WRC **WATER RESEARCH CENTRE**

TECHNICAL REPORT **TR61**

COST INFORMATION FOR WATER SUPPLY AND SEWAGE DISPOSAL

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Technical Report TR 61

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COST INFORMATION FOR WATER SUPPLY AND SEWAGE DISPOSAL

Water Research Centre

Price: Free to WRC Members; £25.00 to non-Members

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CONTENTS

PART I—OUTLINE OF THE STUDY

PART II—THE APPROACH IN DETAIL

PART III—THE RESULTS

PART IV—USERS' DIGEST

Page

APPENDICES

FOREWORD

The project to produce cost functions of water and sewage services, primarily for use in national and regional planning, was partly funded by the Central Water Planning Unit, and started in 1974.

In October 1975, some initial results were presented at an informal discussion meeting of the Institution of Civil Engineers (1). Arising from this meeting a Project Review Group was formed to assist in the dialogue with the many potential users including the Regional Water Authorities. This was constituted as follows:-

Mr. L. E. Taylor	Asst. Director, CWPU (Chairman)
Mr. A. R. Bovington	Director of Resource Planning, AWA (representing the Directors of Resource Planning)
Mr. W. J. F. Ray	Asst. Director of Operations, New Works, TWA (representing the Directors of Operations)
Mr. D. L. Perridge	DOE
Mr. R. Peet	(up to October 1976) CWPU (Secretary)
Mr. D. B. Males	(after October 1976) CWPU (Secretary)
Mr. M. J. Rouse	WRC Project Representatives
Mr. R. Gregory	
Mr. R. W. Bayley	
Mr. J. C. Ellis	

The following WRC staff were directly involved in the project:-

Mr. R. W. Ayling
Mr. R. W. Bayley
Miss S. L. Brown
Mr. R. F. Critchley
Mr. J. C. Ellis
Mr. R. G. Giles
Mr. R. Gregory (Project Leader)
Mr. N. J. Harwood
Dr. G. Hoyland
Mr. N. K. Lambert
Mr. M. J. Rouse

Assistance was received from many other colleagues.

ACKNOWLEDGEMENTS

The study could not have been undertaken without the widespread help of the Water Authorities, Water Companies, National, Regional and Local Government Departments, Consulting Engineers and Contractors in England, Wales, Scotland and Northern Ireland. Their major contribution was the provision of the raw cost data, mostly in the form of bills of quantities.

A number of people known for their special expertise within the Water Industry were consulted during the later stages of the study for their views on some of the cost functions being developed. The Centre and the Project Review Group were grateful for the forthright and constructive comments received, many of which helped in refining the cost functions.

PART I—OUTLINE OF THE STUDY

1. SUMMARY

This report presents the results of a study to produce cost functions suitable for preparing reliable estimates for national and regional planning purposes. It is hoped that many of the results will prove useful also for the selection of alternative processes, for testing engineers' estimates and in identifying research priorities.

The report is in four parts. Part I provides the background to the study, states the objectives, describes the general approach and discusses the applicability of the results. Part II offers a more detailed account of the model-building approach, and provides an introduction to the statistical techniques used in developing the cost functions. Part III contains the detailed set of results, together with typical performance relationships where these are necessary. Finally, those cost functions of most pertinence to national planning are summarized as a Users' Digest in Part IV.

It is tempting to turn directly to Part III or even Part IV. However, the reader is strongly recommended to spend some time with Parts I and II, as this will help in gaining a fuller appreciation of the scope and limitations of the results.

2. INTRODUCTION

2.1. BACKGROUND

In 1967, the Water Research Association (WRA) published in report TP 60 (2) the results of its analysis of a broad sample of cost information provided by its Members via a questionnaire. At about the same time, costs of sewage treatment were collected from local authorities and consultants by Bradley, leading to the results published in 1969 by Bradley and Isaac (3). Both surveys involved the equivalent of about six to twelve months' work by one person.

The results of these two surveys were widely used. The TP 60 results were adapted to provide much of the cost basis of the Water Resources Board (WRB) regional and national studies of water resources in England and Wales (4). In particular, they were used in the preparation of unit costs for the Northern Technical Working Party Report (5). The Bradley and Isaac cost relationships formed the major input in the evaluation of the CIRIA Sewage Cost Optimization Model (6).

The CIRIA study in fact highlighted the need for better sewage treatment cost data, for alternative information in those areas not covered by Bradley and Isaac and others was very scanty. Similarly, the preparation of the WRB report (4) drew attention to the need to update and extend the TP 60 study, for by this time the earlier results had grown out of date - partly through changes in technology, but mainly because of the difficulty of coping with the steep inflation rates of the 1970s. Consequently WRB discussed a contract with WRA immediately prior to the reorganization of the Water Industry in 1974. This resulted in the setting up of the present project, part financed by the Central Water Planning Unit, involving 12.5 man years of effort spread over two and a half years. The work has now been completed, and this report contains a comprehensive account of the approach taken and the results achieved.

2.2. OBJECTIVES

The major objective of the study was to produce cost functions for all major capital construction items in water and sewage services, primarily for use in national and regional planning. The functions were to be based on larger data samples and studied in greater detail than had been possible in earlier work. One important feature was to be the provision of a mechanism whereby the cost functions could readily be updated.

It was hoped that many of the results would prove useful also for selecting alternative treatment processes, for estimation of assets, for testing engineers' estimates and for identifying research priorities. However, it was recognized from the outset that the results from a statistically based study of this sort could not compete with the accuracy attainable by a well-informed and experienced engineer with good local data. It is in situations where the proposals are broadly defined and have not been developed in detail by engineers that the study was thought to be of greatest potential use.

There is some ambiguity about the notion of updating a cost function. In this study, a cost estimate refers to a base point in time (1976, Quarter 3), and a mechanism is provided which allows that estimate to be updated to, say, 1979 prices. A more fundamental interpretation is of updating the cost function itself, by collecting additional data as time progresses and re-estimating the function statistically. Although there is no difficulty in principle in doing this, it would require a continuing high level of effort to extract and organize the data needed for all the cost areas. This aspect is discussed further in Chapter 5 (Conclusions and recommendations).

3. THE GENERAL APPROACH

3.1. SOURCES OF DATA

It was decided that the basic source of capital cost data should be contractual documents, namely copies of priced, accepted bills of quantities (BoQs). Early in the project, therefore, all the Water Authorities and Water Companies were advised of the project, and their assistance sought in the provision of appropriate documents. A number of the larger consultants active in the areas of interest were also approached at this stage. Requests for raw data were followed wherever possible by a personal visit by a member of the project team to select and copy the data.

Some selectivity was introduced into the data collection. By examining the Water Engineers' Handbook for works under construction and planned, and by consulting various technical journals, it was possible to identify Water Authority Regions and Water Companies likely to possess substantial amounts of recent cost data. Also, as the study proceeded, particular schemes were chosen so that data could be collected for more scarce items of works, or generally to provide a more balanced and representative spread of cases.

It had originally been intended to use final account costs rather than tender figures. However, the first data collection excursions showed that on the water supply side within Water Authorities, detailed final costs were not frequently or easily available. Also, it was felt that final costs would often be more difficult to relate to a specific date for inflation adjustment than would tender costs. Most of the results are therefore based solely on accepted tender costs.

Secondary sources of information included various technical journals, contractors and plant manufacturers. For a number of the more specialist and less common engineering areas such as tunnels, especially those in rock, information was also sought from outside the Water Industry.

Some of the raw data collected in the production of TP 60 (2) was used to supplement the new data, especially in the development of general planning models of water treatment works and reservoirs. The raw cost data collected by Bradley could not be tracked down and was concluded to have been lost for ever. The sewage treatment information is therefore based almost entirely on data collected specifically for this study, especially from Consulting Engineers.

3.2. ADJUSTING FOR INFLATION

The bulk of the cost data used in this study originated in the period from the early 1960s to the mid-1970s, during which time costs more than doubled through inflation. The importance of correcting costs for the effect of inflation was therefore much greater than it had been in the earlier studies, when inflation was running at only a few per cent per year. The approach taken in TP 60 (2) was to include 'date of construction' as one of the explanatory variables in each cost function (this was equivalent to representing inflation by an exponential curve). Frequently this term was not significant, and even when it was it occasionally indicated that costs had actually decreased over the period of the data. This treatment of the time effect severely hampered attempts to apply the TP 60 results in subsequent more inflationary periods.

In contrast, Bradley and Isaac (3) used a cost index developed from published indices and discussions within the Industry. Their intention was to have an index that specifically represented inflation of the cost of sewage works rather than the cost of civil engineering construction generally. This 'deflation' approach, whereby costs are corrected for the effect of inflation to some base year prior to developing the cost functions, was seen to be the only practicable alternative in view of the highly varied inflation rates over the last few years. However, it was thought neither appropriate nor necessary to start developing new specialist indices. Such a task, if done thoroughly, would have absorbed far more effort than was available, and the scope and variety offered by existing published indices was felt to be adequate. The results of the study have largely supported this view.

During the development of each cost function, several indices were tested; some of those most commonly used are plotted in Figure 3-1. Appendix B provides a listing of the values of all the indices used in this study, and should be referred to for past values of the indices. For convenience, the indices are given abbreviated titles throughout the main body of the report (for example, the New Construction Wholesale Price Output Index is referred to simply as the New Construction Index).

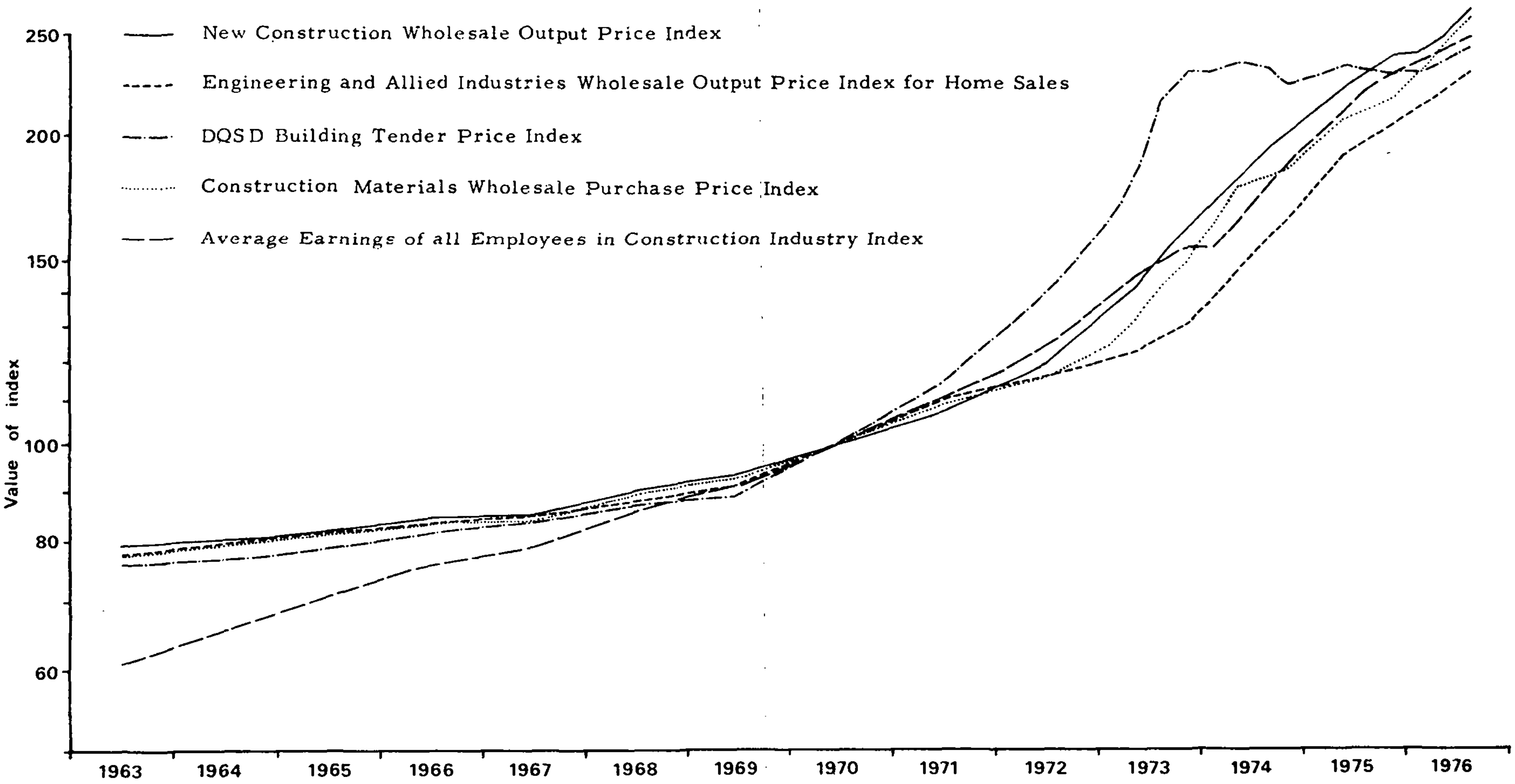

Figure 3-1. The indices most commonly used for cost deflation

The final choice of index was based on three considerations:-

(i) The model developed using the preferred index should not have a substantially larger prediction error than those built using other indices.

(ii) The prediction errors should not show a systematic pattern when plotted through time (see Section 8.3.1).

(iii) The index should be appropriate to the subject and hence acceptable to the user. Thus, a 'cost of construction' index would be preferred to a 'cost of imported cattle-feed' index, even if the latter led to a model with more suitable statistical properties.

Using these guidelines, a variety of indices were examined, including composite indices based on relevant weightings of the indices adopted in the compilation of the National Economic Development Office price adjustment formulae (Baxter and Osborne). Inevitably there were occasions when no one index stood out as the obvious choice, particularly when the data sample was small. There were, however, other cases in which this statistical treatment revealed substantial differences between indices. The index finally adopted for each cost function is stated, along with the other results, in Part III. It should be noted that no single index was consistently more suitable than any other.

Most of the indices found useful were 'output' indices rather than 'input' indices. An input index is concerned with the effect of time on the costs solely of the resources utilized in producing an article, whereas an output index is concerned with the effect of time on the selling price of an article. Thus the output index takes account of the overheads and profits associated with the manufacture of the article in addition to the costs of the resources. It also makes allowance for the effect of market forces on the selling price.

The three input indices used in the study were of a global nature; for example, the Construction Materials Index is based on a weighting of costs of all materials used in the construction industry. It was considered that this form of index might be too general to reflect the true pattern of cost increases in a restricted field of construction activity. To test this theory, a specialized index was prepared for use in the sewerage area. It was compiled from individual material indices (as specified in the NEDO price adjustment formulae, civil engineering), using weights based on those adopted by several authorities for use in sewerage schemes. However, when this index was tested along with the standard input indices, it was found to offer no advantages.

It might be thought that, although the chosen index in a particular case is the best of those examined, there is no guarantee that some hitherto untested index might not be even better. This is not so. If the residual errors show a totally random pattern when plotted through time, there is no way of improving statistically on this. There may well be practical reasons for preferring another index, but these would not be reinforced by the statistical evidence.

During the early modelling work, all tender costs were for simplicity deflated from the tender date. However, attempts at reducing prediction error led to the distinction being drawn between fixed and variable price contracts, with the predicted mid-term contract date being used for correcting the former. (This procedure had previously been adopted in TP 60 (2) for impounding reservoirs.) The appropriate date for price adjustment is not solely related to the conditions and duration of the contract but also to the contractor's anticipated cash flow and the rate of inflation he will face. Some effort was spent on developing a more detailed model of inflation taking account of factors such as these. However, it did not prove possible to arrive at any practical recommendations because of the difficulty of testing alternative deflation strategies. Consequently, the mid-point rule for fixed price contracts was followed throughout the study (except when stated otherwise).

3.3. MODEL-BUILDING

The whole study has been statistically based, in contrast to a synthetic approach whereby a scheme is built up theoretically element by element. The approach followed broadly similar lines in all subject areas, and is outlined briefly in this section.

Firstly it was necessary to establish the cost for each case in the data sample. In the simplest modelling areas, the BoQs referred to just one item, such as a tank or a pump. Often, however, the BoQs for one contract might refer to a number of different major structural items of interest, and it was necessary to identify the costs relating to each individual item. This was generally complicated by the presence of costs additional to those specific to the items of interest. These relate mainly to the conditions of the contract in civil engineering and building contracts, and might in mechanical and electrical engineering contracts also relate to other costs which are concerned with the general provision of the plant. By and large, these costs are not especially associated with any one of the component items. They were therefore assumed to be proportional to the costs of each item. Consequently, unless otherwise stated, the costs used for developing each cost function were adjusted proportionally to take account of these 'conditions of contract' costs. It should also be noted that costs of design, management and supervision by the client have not been included.

Having established the cost for each data case, a list of factors likely to affect cost in that area was drawn up, and data was collected for as many of these as possible. The cost of each item was corrected for inflation as described in Section 3. 2, and a statistical relationship was then sought between cost and the explanatory factors using multiple linear regression on the logged data. This would produce a multiplicative power model taking the following general appearance:-

$$\text{deflated cost} = \alpha(\text{factor } 1)^{\beta}(\text{factor } 2)^{\gamma} \quad \ldots$$

The validity of each model was established by a number of statistical tests (see Chapter 8).

In some cases the factors in the equation were directly related to the function of the unit (for example, the volume of a service reservoir) and so were immediately useful for planning purposes. In others the most satisfactory cost relationship reflected the physical structure of the unit (for example, the volume of a circular sedimentation tank), and so some sort of performance relationship would also be needed (see Section 4. 2).

In most areas, the first cost function to be established was a total cost, or 'global', model. Often an attempt was made to improve on this by splitting total cost into two or more sub-costs and building separate models for each. Examples of this are:-

(i) The separate models in Section 10.3 for tunnels and shafts;

(ii) The borehole sub-models in Section 11.1.1 for setting-up, drilling, casing, grout, screen and pack costs.

This 'hierarchic' approach of developing progressively more detailed cost functions is described in more detail in Section 7.1.

An exception to this general approach arose when, as for most of the sewage treatment areas, the data was obtained from separate and often unrelated civil engineering and mechanical engineering BoQs. It was then not possible to form 'total cost' data, and separate models for civils and mechanicals costs had necessarily to be derived.

The strong statistical content of the study makes it impossible to present the results fully without recourse to a number of basic statistical terms. For this reason a non-technical introduction has been provided in Chapter 8 to the main statistical techniques and ideas underlying the project. The reader is strongly recommended to read this before proceeding to the results in Part III.

4. THE RESULTS

4.1. PRESENTATION OF THE RESULTS

The results of the study are presented in detail in Part III. Because of their sheer volume it was important that they should be laid out in as consistent a manner as possible. The layout ultimately adopted is defined in Chapter 9 at the start of Part III. Each section begins with details of the modelling approach particular to that subject area, such as the indices examined, the explanatory variables used, and the items included in the definition of 'total cost'. The cost function is then presented, with statistical details such as the uncertainty in each coefficient and the overall correlation coefficient. The model is then illustrated graphically. If it is of lesser importance, only one figure is given - a scatter diagram of cost against the main explanatory variable. If it is of greater importance it is given a fuller graphical treatment. Finally, the raw data is listed in Appendix A at the end of the report.

To aid use of the results, those cost functions most useful for broad planning purposes have been repeated in abbreviated form in Part IV - Users' Digest.

Some of the earlier cost functions to be developed were briefly written up and circulated to the Project Review Group and various selected people in the Water Industry. The resulting comments helped in the development of these results and in the cost modelling in other areas. Also, some of the preliminary results were conveyed to Members of the Centre who made specific requests. It is now advised that any provisional information of this sort be destroyed in the light of these more recent and comprehensive results.

4.2. USE AND LIMITATIONS OF THE RESULTS

Estimating the cost of schemes from these results requires values to be inserted for the explanatory factors in the cost equations. In many cases these factors are physical characteristics of the individual components which make up the total schemes, and the planner will usually have to use performance relationships to 'size' each component. To aid the planner, information on performance has been given where appropriate in Part III. Every attempt has been made to provide good performance data based on the knowledge at WRC. However, typical values for average conditions cannot be a substitute for good local knowledge of conditions at site or on works.

A typical cost function consists of an equation relating cost at 1976, Quarter 3, to one or more explanatory factors. The substitution of particular values into the equation therefore provides an estimate at 1976 prices. If it is required to update this estimate to, say, 1979 Quarter 1 prices, the value of the appropriate index must be obtained (or estimated) for 1979 Q1. The 1979 Q1 estimate is then calculated by:-

$$\text{cost at 1979 Q1 prices} = \text{cost at 1976 Q3} \times \frac{\text{index at 1979 Q1}}{\text{index at 1976 Q3}}$$

If the cost function contains only one explanatory variable, the 1976 Q3 estimate for any scheme may be read off directly from the appropriate scatter diagram. However, if the function contains more than one variable there is no substitute for doing the arithmetic.

The scatter diagrams of Part III show that, in nearly every case, the residual scatter about a model is substantial. This was to be expected when the aim from the outset was to construct empirical models strictly on a statistical basis. The cost functions presented in Part III embody all the systematic effects which could be detected within the available data. In any modelling area there are many other factors (state of market, peculiarities of site, regional effects, types of structure, etc.) which account for the individual deviations from the recommended model. What each model offers is an objectively determined average value which the planner can then adjust, using his experience to assess the individual peculiarities of a particular application. The statistical approach ensures that this is so; for by basing the models on actual past data, they reflect the real world rather than assert what ought theoretically to happen.

The uncertainty associated with any cost function is summarized by the confidence interval multipliers supplied amongst the statistical details. The way these should be used is explained in Section 8.1, but it may be helpful to give another example here. Suppose the estimated cost for a particular scheme is £30 000, and the 80% multipliers for that cost function are 0.75 and 1.33. This would mean that there was an 80% chance that the actual cost for such a scheme would fall within the range £22 500 to £40 000. It is important that estimates are not quoted without their corresponding confidence intervals, lest more reliance is placed in them than perhaps is justified. For example, it would be foolish to prefer the above scheme purely on statistical grounds to an alternative scheme estimated at £33 000 with an 80% confidence interval ranging from £24 750 to £44 000.

When a cost prediction is formed by summing separate sub-cost estimates, there is no longer a simple way of calculating confidence intervals. (In particular, it is not valid to add the 80% confidence limits (say) for the separate sub-cost estimates to form a grand 80% interval.) There is in fact no exact method available. However, an approximate procedure is described in Section 8.4.1, and an empirical simulation approach which has been applied to total cost estimates in the water and sewage treatment areas is summarized in Section 8.4.2.

One limitation of statistically-based models is that there is no justification for extending them beyond the range of data from which they were built. The minimum and maximum values of the variables appearing in each cost function are stated, and the function should be used with extreme caution outside this region. One special form of this restriction deserves special mention. On a number of occasions, a variable that was expected to influence cost failed to be detected because it did not vary sufficiently over the data sample. The resulting model in such cases is therefore only valid within that limited range of values. Two examples of this occur in the boreholes and service reservoir areas:-

(i) The function for Type 2 boreholes does not contain diameter as a variable, because although diameter varied between 0.46 and 0.91 m in the sample the majority of the values fell well within this range. The model should therefore not be used outside these limits.

(ii) Length, breadth and height of service reservoirs did not explain variations in cost significantly better than did the single variable volume, because the length/breadth ratio and height were fairly constant from reservoir to reservoir. This implies that service reservoirs have in the past been built to a fairly standard pattern; the recommended cost function reflects this pattern, and would consequently be liable to provide a less

> reliable estimate for a structure deviating markedly from the current practice.

A further restriction is in the types of design for which a cost function is applicable. In some cases, as for example with rapid gravity filters, the wide variations in design do not appear to influence cost significantly. In other areas, however, it is important to note which types of design or condition are represented by the cost function. The tunnels and shafts models, for example, which could only be prepared for soft ground conditions, should not be used for hard rock tunnelling. Limitations of this sort are discussed in the individual results sections in Part III.

5. CONCLUSIONS AND RECOMMENDATIONS

(a) The major objective of the project was to provide good bases for the estimation of capital costs for planning purposes. This has largely been met.

(b) The level of prediction accuracy for capital costs is better than that previously available in the Water Industry. It is now comparable to that achieved by similar exercises in some other industries. It is unlikely that appreciable improvements can be made in prediction accuracy, other than by developing regional models (see (e) below), without taking a radically different approach. That would have to be based on resource measurement, which would involve an order of magnitude greater effort than has been required for this study.

(c) Insufficient operating cost data was available during the project for cost models to be developed. Instead, typical operating cost information is presented. There is a need for further work on operating costs.

(d) As cost functions have been developed from data extracted from bills of quantities, only established processes on water and sewage treatment works have been fully covered. Capital cost functions for those new processes considered to have wide application (e. g. belt presses) will be developed as data becomes available.

(e) In the development of some of the cost functions (e. g. sewerage) a regional effect has been observed. To evaluate this fully it would be necessary to collect a much larger data sample. This has not been possible within the current project.

Experience in the use of the cost functions may highlight the need for the regional effects to be quantified. WRC could carry out this modelling work provided Members were themselves prepared to undertake the data extraction from bills of quantities. WRC would advise on the data collection and provide standard coding sheets to ensure consistency in interpretation of the bills of quantities.

(f) In Chapter 3, two aspects of updating are discussed: dealing with inflation, and keeping up to date with changes in design and construction practice. In general, published cost indices have taken account very well of time-related effects, but in one or two cases a time effect has remained. This does not necessarily imply that the existing cost indices are inadequate, for it may not have been possible to account fully for contract type and adjustment date. It will be necessary for WRC to receive some feedback periodically in order to assess the ability of the recommended cost indices to cope with future inflation.

(g) The rate at which cost functions will need to be updated to reflect changes in design and construction practice (including the building of units in a size outside the range of the currently available data) can only be determined from experience. It is quite likely that, with a larger sample of data, additional explanatory variables will become significant. For example, if data on Type 2 boreholes with a greater diameter range were available, diameter would probably become a highly significant variable. Again, it is important that WRC receives the feedback necessary to ensure that the cost functions can be developed to cover changing requirements.

(h) Frequently, cost information is requested in the form of unit costs. In view of the economies of scale generally exhibited in these studies (causing unit costs to reduce with size), WRC feels it more appropriate to present the results as total cost functions.

(j) Work on cost data at WRC is continuing at a very much reduced manpower level. Effort will be concentrated on:-

(i) assisting Members in the use of this report;

(ii) obtaining better operating cost data, particularly on water and sewage treatment works;

(iii) developing cost functions for important new processes;

(iv) assessing whether or not the recommended cost indices deal adequately with future inflation;

(v) remodelling existing cost functions where the data range is shifting or expanding.

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PART II—THE APPROACH IN DETAIL

7. THE MODEL-BUILDING PROCEDURE

7.1. LEVELS OF MODELS

Suppose a model is required for the capital cost of constructing a sewage treatment works. At the simplest, or highest, level, the model might simply relate the total cost to the population to be served. Such a 'global' model could only be expected to give a very rough estimate, but for certain broad planning purposes that might be all that was required. Alternatively, the model might consist of a collection of sub-models or 'building bricks', each predicting the cost of separate processes or components within the works. This would yield a more precise forecast in return for a more detailed specification of the projected works. The model would therefore be of interest to planners at a more local level, whereas its greater detail might be irrelevant to the regional or national planner.

The variety of possible models which could be constructed for a particular area can be visualized as a hierarchy of models like Figure 7-1. Moving down the hierarchy, total cost is successively broken down into more detailed constituents, each of which is separately modelled. The object of descending a level is to gain

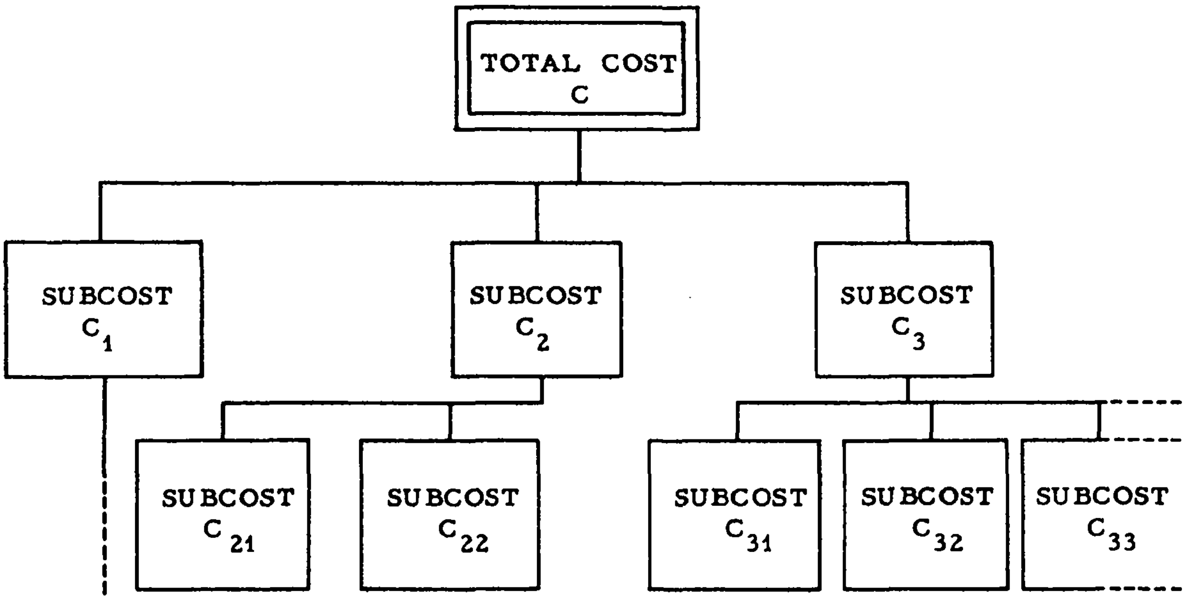


Figure 7-1. A hierarchy of models

precision or flexibility, but this potential benefit must be weighed against the following considerations:-

(i) Is the data available?

(ii) How much effort is needed to assemble it?

(iii) Are the models likely to improve very much on the previous ones?

(iv) Who is going to be interested in models at this level ?

(v) Will the user have the necessary input when he wants to use the models?

The answers to these questions varied widely from area to area. With sewerage, for example, it proved impossible to develop a collection of sub-models which could improve on the original global model. With groundwater development, on the other hand, models were produced at no fewer than four levels, as illustrated in Figure 7-2 (although not all of these were finally adopted).

As a general rule the approach was to begin at the top of the hierarchy by building a simple global model, and to descend to more detailed sub-models only if this seemed worthwhile and the global model fell short of the desired accuracy.

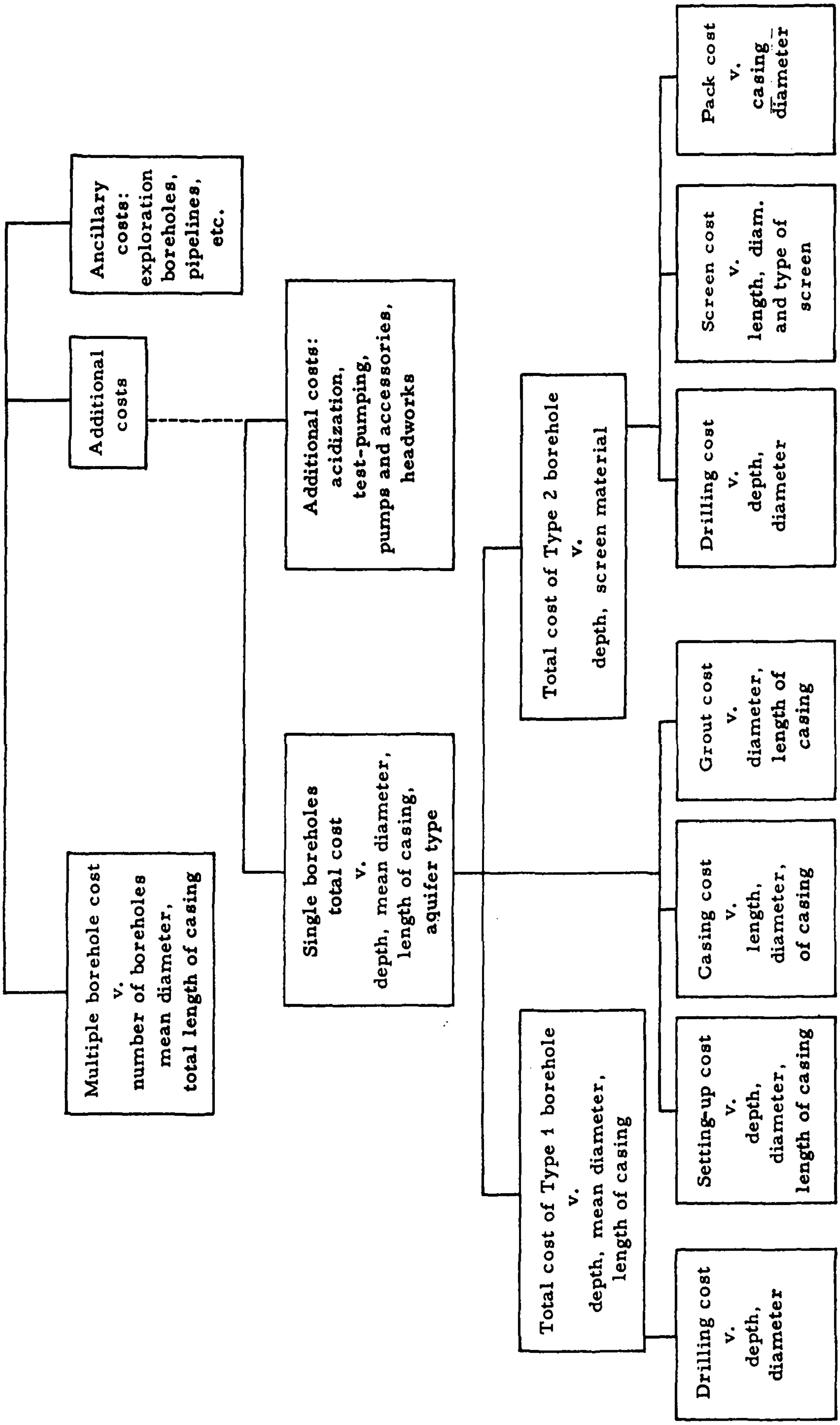


Figure 7-2. The four modelling levels for groundwater development

7.2. COMMON POINTS OF PROCEDURE

7.2.1. DATA ABSTRACTION

Most data was obtained in the form of copies of bills of quantities, or equivalent and related documents of accepted tenders. In all the cases where costs were produced from such raw data, the method used for abstracting the data was generally similar. Following the collection of the raw data the first task was to isolate the cost of each major structural item of interest in a BoQ. Usually one bill represented just one item (although one item could be covered by more than one bill). Sometimes, however, a bill referred to more than one item. In such cases, the costs which clearly related to specific items were first determined, and then the remaining value of the bill was distributed proportionally over these sub-totals. A few BoQs were virtually useless as sources of data, when for example the costs of many items of a scheme were distributed through all the bills, with perhaps one bill containing all concrete work, another all the form working, another all excavation, and so on. Similarly, lump sum contracts could be of little value.

Some of the bills referred to work such as preliminaries and items meeting the conditions of contract, which could not be related to any specific structural item of the scheme. In mechanical and electrical engineering contracts these would include the costs of installation, painting, spares, instruction manuals, overheads and profits. It was generally assumed that such costs were associated with the purchase of the major structural items of the scheme, and that they should be distributed amongst them proportionately. Unless otherwise stated, therefore, costs reported in Part III have already been adjusted to take account of these 'conditions of contract' costs. It should also be noted that the costs of design, supervision and management by the client are not included.

In addition to the costs, data relating to the physical characteristics of each item also had to be assembled. Such information as number, dimensions and type were taken from drawings, specifications and other descriptive documents.

The costs and related descriptive data abstracted from the available contracts were then collated to determine the size of the data sample for each type of structural item. From this it could be judged how successful the subsequent model-building work was likely to be, and whether or not more BoQs should be collected.

7.2.2. MODEL DEVELOPMENT

In all cases the models were developed using linear regression analysis, a non-technical introduction to which is given in Section 8. 2. In the early stages of the study a number of different model structures were investigated: it was found that a multiplicative structure (i. e. additive in the logarithms of the explanatory variables X_1, X_2, etc.) was the most appropriate. Thus the general form assumed for each model was

$$\text{deflated cost} = \alpha X_1^{\beta} X_2^{\gamma} X_3^{\delta} \quad \ldots$$

An index thought to be appropriate was used to correct costs for the effect of inflation prior to estimating the model.

Considerable care was taken over validating the models. Two aspects discussed in Section 8.3 were given special attention: testing whether the residual scatter about a fitted model was Normally distributed with constant variance, and testing whether the selected index was removing the effect of cost inflation satisfactorily. It was sometimes necessary to try several indices before finding one which provided a fair reflection of inflation in that area.

One point arose repeatedly. A factor widely believed by experienced observers to influence cost would fail to achieve significance. This could happen for several reasons:-

(i) the factor did not vary sufficiently within the sample (e. g. 'height' in the water towers data);

(ii) the factor was highly correlated with another factor already in the cost function (e. g. 'depth' and 'screen length' in the Type 2 boreholes data);

(iii) the effect was swamped by the large amount of residual scatter (e. g. 'pipe type' in the sewerage data);

(iv) the factor was subjective or difficult to quantify (e.g. 'surface condition' in the water mains data).

In cases (i) and (ii) little could be done without collecting more data. Sometimes it was possible to overcome (iii) by finding further explanatory variables which would reduce the scatter sufficiently for the factor of interest then to emerge. Another approach, used successfully in the sewerage and water mains models, was to combine a number of minor or subjective factors into one composite variable, termed the 'over-under' factor. This then succeeded in entering the cost function even though all its component factors had individually failed.

The remainder of this part of the report provides some discussion of the central statistical ideas underlying the project. Readers to whom this will be familiar, or who are willing to take it on trust, are invited to turn now to Part III - The results.

8. STATISTICAL BACKGROUND

A number of statistical terms are used in this report which will probably not be familiar to all readers. Their use is inevitable. The cost functions have been derived empirically using statistical methods. In every case the actual data shows a considerable degree of scatter about the fitted cost function. It is particularly important that these obvious limitations are expressed in an objective and unambiguous manner, and this can only be done in statistical language. The aim of this chapter is therefore to provide a statistical background to the rest of the report. This is attempted in three parts. Section 8.1 contains a list of statistical terms and their definitions; Sections 8.2 and 8.3 then provide brief non-technical introductions to a number of statistical topics which are of central importance to a full appreciation of the results. Finally, Section 8.4 discusses methods of forming confidence intervals about a combined cost estimate from several models. This is necessarily rather more technical and may be omitted with little loss.

8.1. SOME STATISTICAL DEFINITIONS

(i)	Variable:	a measurable factor of interest (e.g. cost of a scheme; depth; date of construction; volume excavated).
(ii)	Data, Sample:	the starting point of a statistical study; the collected values of all variables under consideration.
(iii)	Population:	the entire set of possible values of a variable; sometimes finite (e.g. the heights above sea level of all UK reservoirs), sometimes conceptually infinite (e.g. the set of all conceivable wetted surface area values for circular sedimentation tanks).
(iv)	Histogram:	a diagram showing the way a sample of data values is distributed between its extremes; sometimes called a frequency diagram.
(v)	Statistic:	any summary measure calculated from a data sample, like sample mean or standard deviation (see (vi), (vii)).
(vi)	Mean:	the familiar 'average'; a statistic which locates the 'centre', in one sense, of a data sample.
(vii)	Standard deviation:	the most commonly used measure of 'spread'. For a Normally distributed variable (see (xxiv)), roughly 95% of the values in a sample will lie within two standard deviations of the mean. The square of the standard deviation is known as the variance.
(viii)	Outlier:	an extreme data value suspiciously far away from other members of the sample.
(ix)	Coefficient of variation:	a proportional measure of spread, usually expressed as a percentage, and defined as standard deviation divided by the mean. If the standard deviation is 0.55 and the mean is 11.0 the coefficient of variation is 5%.

(x)	Confidence:	if five randomly chosen items have treatment rates of 8, 10, 11, 13 and 10 litres/sec respectively, the mean, 10.4, is the best estimate of the true underlying mean for all such items; but it is very unlikely that the true mean will be exactly 10.4. The confidence interval is a statistical device which gives information on how far from 10.4 the true mean might conceivably be. In this example, an 80% confidence interval for the true mean (assuming that treatment rates are Normally distributed) is 10.4 ± 1.46. The numbers 8.94 and 11.86 are 80% confidence limits and the figure of 80% is the confidence level with which the statement is made that the true mean lies in that interval. The idea of confidence intervals applies to any statistic calculated from a data sample, and plays a crucial role in the interpretation of the results from this study.
(xi)	Multipliers:	a term used in this report to denote the quantities by which an estimate must be multiplied to obtain a specified confidence interval. For example, if 80% multipliers in a particular instance are 0.67 and 1.5, and the estimate is 21.0, an 80% confidence interval for the true value is 14.0 to 31.5. In cases where multipliers are not given, they can be calculated from the 'standard error of the residuals', s (see (xvii)), by the equations lower multiplier = 10^{-ts}, upper multiplier = 10^{+ts}. Approximate values for t are 1.3 for 80% limits and 2.0 for 95% limits.
(xii)	Function, Model:	terms used interchangeably in this report to mean a statistically derived relationship relating one variable (usually cost) to other explanatory variables.
(xiii)	Simple regression:	a statistical technique for deriving a model relating cost (say) to just one explanatory variable.
(xiv)	Multiple regression:	an extension of simple regression to deal with more than one explanatory variable.

8.1. Some statistical definitions

(xv)	Regression coefficients:	the calculated numerical values in a regression equation; in the simple regression model cost = 12.3 + 4.5*volume, the regression coefficients are 12.3 and 4.5.
(xvi)	Parameters:	numerical values relating to an underlying population. For the whole population of example (xv), the true relationship might be cost = 13.1 + 3.9*volume. The numbers 13.1 and 3.9 are population parameters.
(xvii)	Standard error:	a term preferred to standard deviation (see (vii)), though meaning exactly the same, when referring to uncertainties in an estimate of a population parameter. In (xv) the standard error of the 4.5 coefficient might be 0.3, leading to a 95% confidence interval of 3.9 to 5.1.
(xviii)	Significance:	the essence of statistics is to use the information in a sample to make inferences about the underlying population. Contrary to popular belief no theory can ever be proved in statistics. It can only be rejected as being unlikely; and the more unlikely it is estimated to be the greater is the statistical significance of the rejection. The statement that a term in a regression equation is significant at the 1% level means that the improvement brought about by its inclusion could not have occurred by chance on more than one occasion in a hundred in the long run. The theory, or hypothesis, that the variable has no real effect is thus rejected at the 1% level.
(xix)	F-statistic:	calculated when testing the significance of a variable in a regression model. The larger it is, the greater the significance; for a sample size of 40, an F-value of about 4.1 is significant at the 5% level.
(xx)	Correlation coefficient:	a quantity which indicates the overall goodness of fit of a regression model; usually denoted by R. It lies between -1 and +1. The closer the value is to zero, the lower is the correlation; an R of +1 or -1 indicates a perfect fit.

(xxi) Coefficient of determination: the square of the correlation coefficient; R^2. It lies between 0 and 1, and measures the proportion of the original variance (see (vii)) which is 'explained' by the regression model. It is usually expressed as a percentage.

(xxii) Residual: the difference between an actual value (cost, say) and its estimate from a regression model. Whether or not a model may be taken to be satisfactory depends largely upon a study of the residuals.

(xxiii) Cusum chart: a graphical device for highlighting changes in a variable's underlying mean; 'cusum' is short for 'cumulative sum'. The cusum of the numbers

1, -2, 1, 0, 1, -1, 2, 1, 2, 1, 0, 2,
is 1, -1, 0, 0, 1, 0, 2, 3, 5, 6, 6, 8;

when these values are plotted in sequence the cusum shows a marked change in slope after the sixth observation, revealing a shift in the mean value at about that point.

(xxiv) Normal distribution: a symmetrical bell-shaped distribution of great importance in statistical theory and practice. The validity of the confidence limits quoted in this report rests on the assumption that the residuals from the various regression models are Normally distributed.

(xxv) 'Omnibus' variable: (a device developed specifically for this study) a single variable Z which combines all the explanatory variables in a regression model so that the model is compressed into two dimensions and can be demonstrated graphically. For example, suppose

$$\underline{\text{cost} = 67.8\,(\text{diam})^{0.6}(\text{depth})^{0.3}}$$

and mean depth = 2.2.

The 'omnibus' variable is defined as

$$Z = \text{diam}*\frac{\text{depth}}{2.2}^{0.3/0.6}$$

$$\text{i.e.} \quad Z = \text{diam}*\frac{\text{depth}}{2.2}^{0.5} .$$

This allows the model to be rewritten as

$$\underline{\text{cost} = 85.9*Z^{0.6}}.$$

8.1. Some statistical definitions

The variable Z can be thought of as 'diameter adjusted to include the effect of depth'. If Z is calculated for each item of data, both the model and the data can then be represented on a scatter diagram of cost against Z. This indicates how much 'unexplained' scatter there is about the model.

8.2. LINEAR REGRESSION

8.2.1. SIMPLE LINEAR REGRESSION

Figure 8-1 shows a scatter diagram of capital cost C of a type of water treatment. works (corrected to a base year) against the corresponding throughput rate, T.

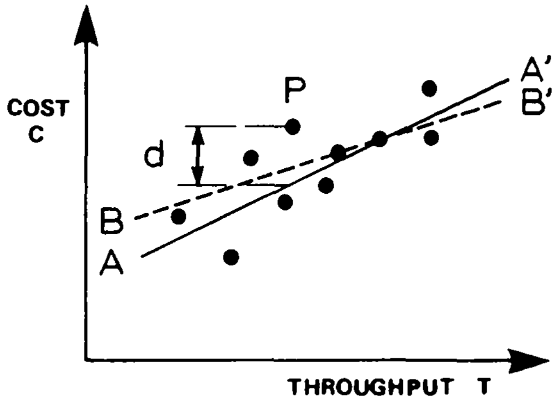


Figure 8-1. A hypothetical scatter diagram of cost v. throughput

It is reasonable to expect that higher throughputs will be associated with higher costs, and this is borne out by the diagram. Nevertheless, the points by no means fall on a straight line and if half a dozen people were invited to draw by eye their estimated 'best' line through the data, half a dozen different lines would result. It is therefore necessary to decide upon an objective criterion for fitting a line through the data, and this is provided by the method of simple linear regression. For various reasons which it is unnecessary to discuss here, the criterion used is the method of 'least squares'. This proceeds as follows. Suppose a line AA' is drawn through the data. The deviation of a point P from the line is d, and this will sometimes be positive, sometimes negative. The quantity d^2 is the squared deviation of P from the line, and this can be calculated for all data points and summed to give the total squared deviation about the line. It is evident that if a different line were drawn, BB', the total squared deviation would be unlikely to be the same as that about AA'; and if it were less, that BB' would intuitively be a 'better' line than AA'. The method of least squares provides the line which minimizes the sum of squared deviations about the line, and so is in that sense the 'best' line through the data.

The regression line will be of the form

$$C = \alpha + \beta T,$$

where α and β are respectively the intercept and slope of the line. One useful property of the line is that it passes through the mean of the data, that is, the point at which both C and T take their mean values. Another consequence of the least squares procedure is that the mean of the deviations d over all the data is zero.

It is natural to ask how successful the regression model is in relating cost to throughput. (Note that there is no question of having established a cause and effect relationship between C and T; that can never be done by a statistical argument.) One obvious indication is the size of the deviations d, or residuals as they are usually known. It has already been noted that they have zero mean. The standard error (see Section 8.1 (xvii)) of the residuals measures their degree of spread about the line, and therefore provides a useful measure of the uncertainty associated with a regression model. The residual standard error is also instrumental in calculating confidence limits for prediction using the model.

Another more immediately useful statistic is the correlation coefficient R. If the points lie perfectly on a straight line R will be +1 (if C and T increase together) or -1 (if C decreases as T increases). If there is little or no association between the two variables, R will be close to zero. The quantity R^2, known as the coefficient of determination, is often quoted: this is equal to the proportion of the variance of C which is 'accounted for' by the model. Figure 8-2 shows an assortment of scatter diagrams with their corresponding R values.

8.2.2. MULTIPLE LINEAR REGRESSION

In the example of Figure 8-1, it might be felt that some of the 'unexplained' scatter about the fitted line is due to the influence of another variable - area of tanks, say. The technique of multiple regression can be used in such a situation. The model

$$C = \alpha + \beta T + \gamma A$$

is fitted to the data, again using the least squares principle, to determine the

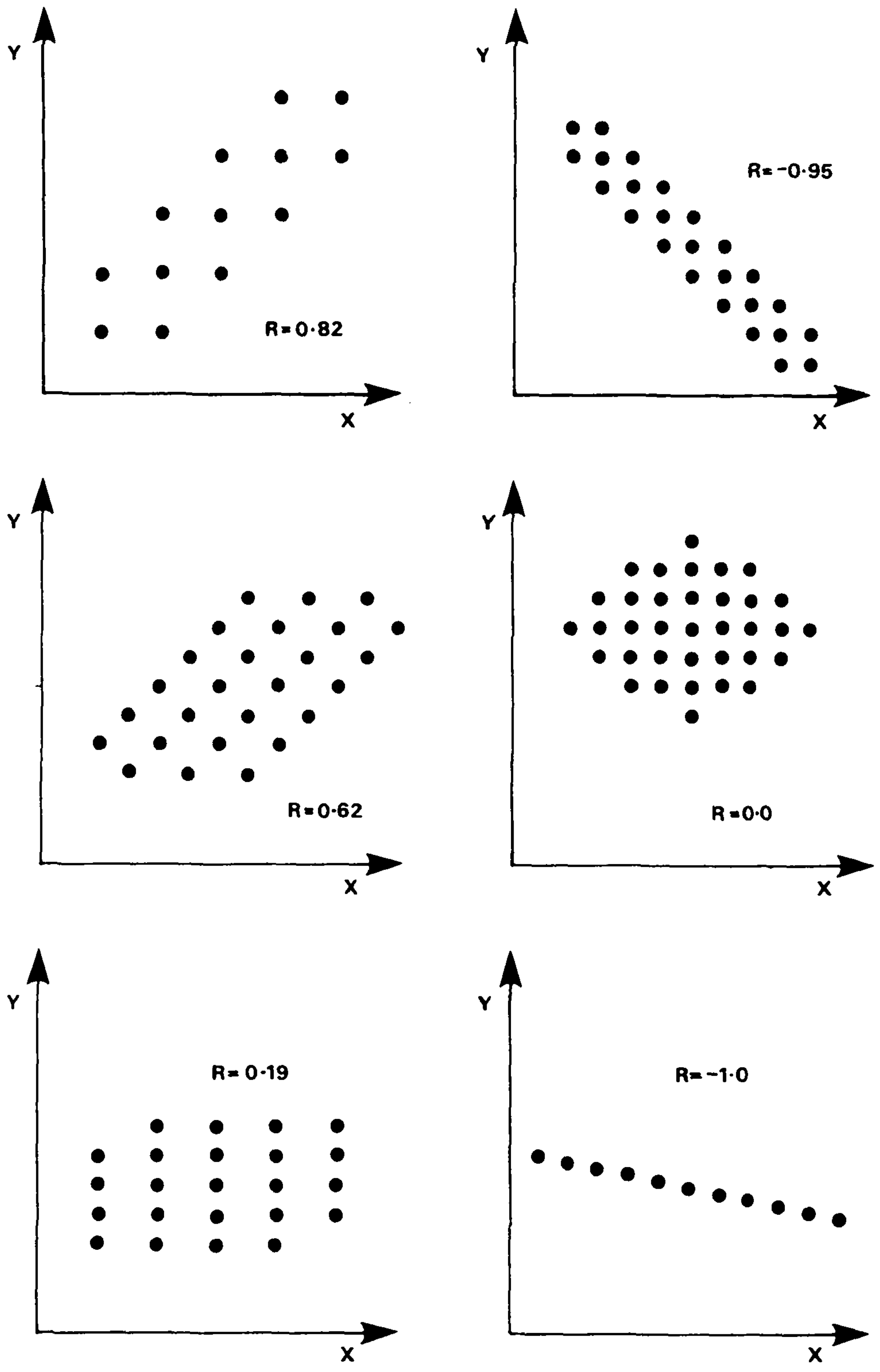


Figure 8-2. Some scatter diagrams and their correlation coefficients

three regression coefficients α, β and γ. It is not always appreciated that this is bound to give a smaller (or at least no bigger) total squared deviation than before: the introduction of another explanatory variable cannot do any harm, because if it did a better solution could be obtained by setting γ to zero and allowing the equation to revert to its earlier simpler form. Thus the important question to ask is whether the total squared deviation is reduced by a significant amount. This can be determined statistically by performing an appropriate F-test; and if the F-statistic is below a particular test value the factor A must be rejected as making no worthwhile contribution to the model. This course must always be pursued even when there are strong grounds (e. g. theory or experience) for believing that A does influence cost, if the objective is to construct a purely empirical model which is statistically valid.

If T and A are only slightly correlated, the new coefficient of T (β) will not be very different from its earlier value. If, however, T and A are highly correlated (as, for example, was found with 'length of pipework' and 'number of manholes' for sewerage schemes) it means that the new variable A is unable to contribute much fresh information not already residing in T, and the best plan almost invariably is to discard either T or A.

The procedure can be extended to include further explanatory variables. With each one, the new augmented model is estimated and a significance test performed to see whether the observed reduction in total squared deviation is more than could be attributed reasonably to chance. If it is, the variable can be retained in the equation.

When the final model has been established, the correlation coefficient R and the standard error of the residuals play exactly the same roles in describing the goodness of fit of the regression model as they do in the simple regression case.

8.2.3. ADDITIVE AND MULTIPLICATIVE MODELS

In Section 8. 2. 1 the discussion was limited to the fitting of a straight line through data like that of Figure 8-1. But it may be that the data is more like Figure 8-3, where the underlying relationship is clearly some form of curve (reflecting economies of scale, perhaps). Several approaches (e. g. polynomial regression, data transformation) were explored during the early development of the study; the one found most effective was the adoption of a multiplicative model structure - an approach also taken in TP 60 (2).

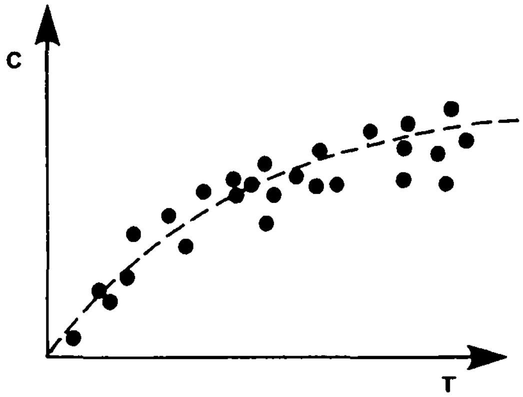


Figure 8-3. Typical non-linear data

Consider the model $C = \alpha + \beta T + \gamma A + \text{error}$, the one discussed in Section 8.2.1 (although the error term was not then mentioned). This is an additive model, and can be estimated directly by multiple regression. Now consider the alternative model $C = \alpha * T^{\beta} * A^{\gamma} * \text{error}$. This has a multiplicative structure but it can be transformed to an additive model by taking logarithms to give:-

$$\log(C) = \log(\alpha) + \beta\log(T) + \gamma\log(A) + \log(\text{error}).$$

A multiple regression of log(C) against the explanatory variables log(T) and log(A) will thus yield estimates of $\log(\alpha)$, β and γ, allowing the multiplicative model to be established.

The taking of logarithms provides a powerful tool whereby a whole new category of models can be examined using multiple regression. However, the capability to fit a wide range of models must be matched by the ability to choose sensibly between them. This raises the important question of how to determine whether a given model is statistically valid, and this is now outlined in Section 8.3.1.

8.3. TESTING AND USING THE MODELS

8.3.1. TESTING THE VALIDITY OF A MODEL

Much of regression theory depends upon assumptions made about the residuals, and an essential part of the model-building process is to examine the residuals after having fitted a model and to see whether or not they meet these assumptions. If they do not, the coefficients in the model could be seriously biased, and any confidence intervals which are constructed will probably be misleading. The assumptions may be illustrated for the simplest case of a linear regression of C on X, when they are that:-

(i) in the long run the average of the residuals is zero; that is, data falls more or less evenly on either side of the true line;

(ii) the residuals have a constant standard deviation which is independent of X; that is, the spread of data about the line is no wider or narrower at different parts of the line;

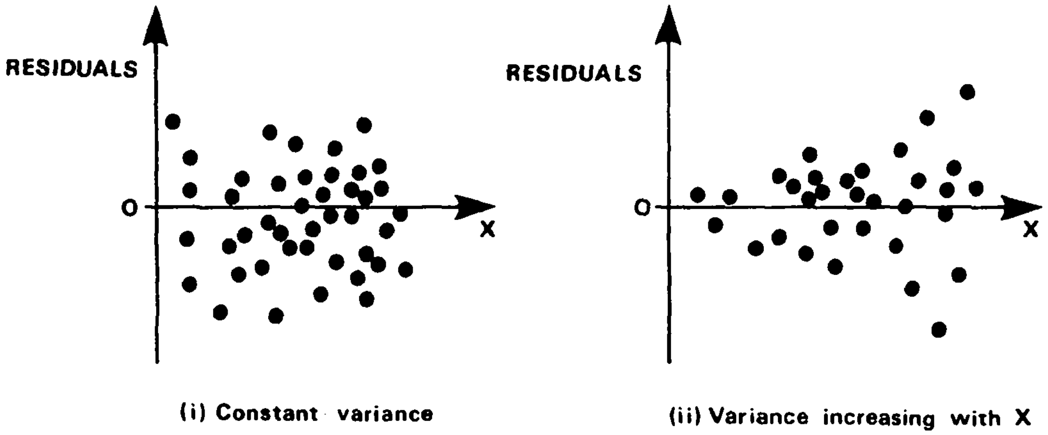
(iii) the residuals are uncorrelated with one another; for example, if the seventh data value happens to be above the line, this should in no way influence whether or not the eighth point is above the line;

(iv) the residuals are Normally distributed.

The first of these assumptions causes no difficulty because it is automatically fulfilled by the least squares method. The second assumption can be examined by plotting the residuals against each explanatory variable in the model. Figure 8-4 (i) shows an acceptable pattern, where the points are scattered haphazardly within a horizontal band. In Figure 8-4 (ii), the spread of the residuals is clearly greater for larger values of X: the model is therefore inadequate and should be rejected.

In the present study, plots similar to Figure 8-4 (ii) almost invariably arose when additive models were fitted to the untransformed data. When the variables were logged, a substantial improvement would be noted, showing that a multiplicative structure was the more appropriate. This conclusion extends over all cost areas.

The third assumption requires that the residuals show no tendency to be interrelated. Systematic patterns are most likely to occur when the residuals are plotted in time order. Suppose the index used to deflate a particular set of costs



(i) Constant variance

(ii) Variance increasing with X

Figure 8-4. Typical plots of residuals

does not accurately reflect the way in which those costs change through time. The index might, for example, over-correct during one 18-month period, and begin to under-correct several years after that. This would introduce a systematic error into the model which would produce runs of positively- or negatively-biased residuals. For every cost function developed in this study a cusum chart was constructed of the time-ordered residuals (see Section 8.1 (xxiii)), and in a number of cases this did indicate that the index used was unsatisfactory in some way.

Finally, the Normality assumption can be examined by constructing a histogram of the residuals. Usually there was insufficient data to allow a very rigorous statistical test to be carried out, and a more practical benefit came in the identification of outliers. These can have a dangerous influence on the model, for a number of reasons: they may distort the coefficients; they may make the correlation coefficient spuriously high; or they may unrealistically widen the model's apparent range of applicability. The practice has been to scrutinize any outlier that is exerting an unduly strong influence on the model, and to discard it if a clear physical justification can be made out.

8.3.2. . PREDICTION USING A REGRESSION MODEL

When a regression model has been established, its main use is in prediction. In the simple example discussed in Section 8.1, namely

$$\text{cost} = 12.3 + 4.5*\text{volume},$$

the predicted cost for a volume of ten units would be 57.3. However, by itself this prediction is only of limited use; it will obviously not be exactly right, and it is much more helpful to have an interval within which the actual cost might reasonably be expected to lie. The uncertainty in the prediction arises for two reasons: firstly, the regression line is only an estimate of the true line; secondly, even if the true line could be known perfectly there will still be scatter about it. This gives rise to a confidence region bounded by two hyperbolic curves, as shown in Figure 8-5.

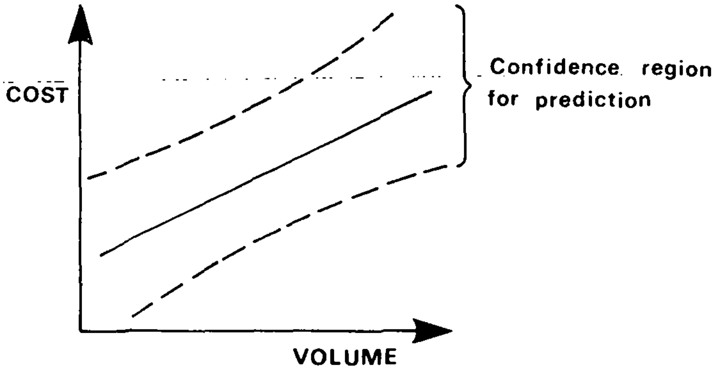


Figure 8-5. Confidence region for prediction using additive model

It will be noticed that the region is narrowest at the centre of the volume range, and widens in either direction as the data from which the model was estimated becomes more sparse. However, the curves are in general rather shallow, and for many practical purposes it is sufficient to use a pair of parallel lines bounding the regression lines. The confidence level may of course be chosen at any level. The higher it is set, the less chance there is that an actual cost will fall outside the predicted interval, but the more likely it is that the interval will be thought unacceptably large. The figure of 80% was felt to provide a reasonable compromise to this difficult dilemma.

If (as is the case in this study) the regression has been fitted to the logged variables, the confidence limits must be 'anti-logged', giving the characteristic appearance of Figure 8-6. Because the model now has a multiplicative structure, the limits should be thought of as multipliers (e.g. 0.79, 1.26) rather than quantities to be added or subtracted (e.g. ±3.4). Thus, the approximate 80% confidence limits quoted with each cost function in Part III are expressed in this manner.

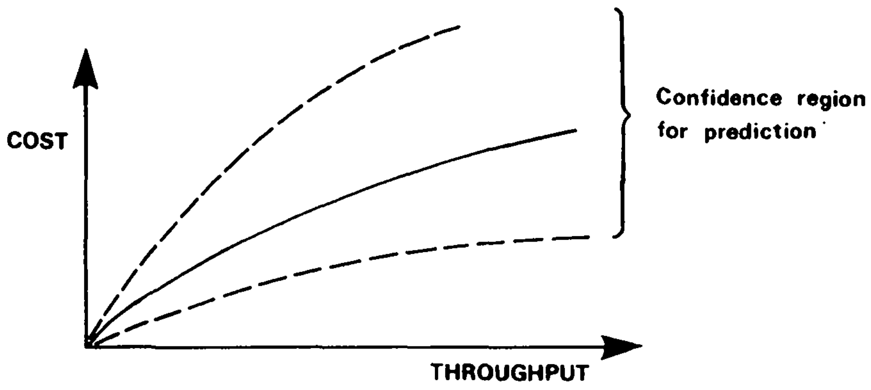


Figure 8-6. **Confidence region for prediction using multiplicative model**

The principle of placing a confidence region around a cost prediction applies equally to a multiple regression model. However, the business of calculating it becomes very laborious and there is no practical alternative to the approximate limits already mentioned. These under-estimate the correct limits for predictions near the extremes of the data, but the model should in any case be used with considerable caution in such regions.

8.3.3. DEMONSTRATING A COST FUNCTION GRAPHICALLY

When a cost function has been finally established it is important to demonstrate how well (or badly) it fits the data from which it was built. This provides a commonsense verification of the confidence limits (roughly a fifth of the cases should fall outside the 80% limits), and helps to define the range over which the model can be applied. If the function has only one explanatory variable - diameter, say - there is no difficulty: the function, its confidence limits and the original data can all be shown on the one scatter diagram of cost against diameter. The problem arises when there are two or more explanatory variables (for example, there are three in the multiple borehole model: number of boreholes, diameter, and length of casing). Here there must be some sacrifice of information if three or more dimensions of data are to be compressed into the two dimensions provided by a scatter diagram. A number of approaches were tried. None was wholly satisfactory; nevertheless, the device eventually adopted - the 'omnibus' variable - seems to have the fewest disadvantages.

The omnibus variable is formed by taking the most important explanatory variable and adjusting it by appropriate multiples of the other explanatory variables so that all the separately identified effects are rolled into the one composite factor. This effectively reduces the cost function to a single variable model, so that it can then be demonstrated by a simple scatter diagram of cost against the omnibus variable.

In the case of multiple boreholes, number of boreholes was the most significant variable in the equation. Diameter and length of casing had average values of 0.586 and 30.9 m respectively. The omnibus variable was therefore defined as

$$
\begin{aligned}
Z &= \mathrm{NOBHS}*\left(\frac{\mathrm{DIAM}}{0.586}\right)^{\frac{1.26}{1.16}}*\left(\frac{\mathrm{CASLEN}}{30.9}\right)^{\frac{0.63}{1.16}} \\
&= 0.278*\mathrm{NOBHS}*\mathrm{DIAM}^{1.08}*\mathrm{CASLEN}^{0.54},
\end{aligned}
$$

so that the full model

$$\mathrm{COST} = 2.08*\mathrm{DIAM}^{1.26}*\mathrm{CASLEN}^{0.63}*\mathrm{NOBHS}^{1.16}$$

could be written equivalently as

$$\mathrm{COST} = 9.18*Z^{1.16}.$$

For a scheme which happens to have DIAM and CASLEN equal to their average values of 0.586 and 30.9, the omnibus variable is simply equal to NOBHS, the number of boreholes. For schemes where diameter and length of casing are, say, above average, the omnibus variable will reflect the implied additional cost by being greater than the NOBHS value; conversely, it will be less than NOBHS for easier schemes.

A second, more simply understood, scatter diagram is presented for each cost function, plotting predicted cost against actual cost (on a log/log scale). If the model were perfect, all the points would lie on a 45° straight line. The extent of the scatter about the line therefore indicates the limitations in the cost function's predicting ability.

8.4. CONFIDENCE LIMITS FOR A COMBINED ESTIMATE

For every recommended cost function presented in Part III, multipliers are provided which allow the 80 and 95% confidence intervals about any estimate to be calculated. Consider, for example, the concrete dams cost function CONCOS = $0.0569*\text{VOL}^{0.95}$ (see Section 11.2B), for which the 80% multipliers are 0.77 and 1.29. For a volume of fill of 100 000 m^3 (VOL = 100), the model gives a predicted cost of £4.52 million. The 80% confidence interval for the actual cost is therefore 4.52*0.77 to 4.52*1.29, namely, £3.48 million to £5.83 million. This is saying that if, conceptually, a large number of dams were built, all with 100 000 m^3 volume of fill, about four fifths of them would cost between £3.48 and £5.83 million (at 1976 Q3 prices).

Suppose now that it is required to estimate the total cost of two concrete dams, with volumes of fill of 100 000 and 150 000 m^3. This is easily obtained as $0.0569(100)^{0.95} + 0.0569(150)^{0.95}$, i.e. £11.16 million. However, it is not possible to combine the corresponding individual confidence intervals in some way to obtain a confidence interval about the overall estimate. This is a consequence of the multiplicative structure which it was necessary to assume for each individual model (see Section 8.3.1); indeed, under these circumstances no exact statistical solution can be found, for reasons outlined in Section 8.4.1 following.

It is possible to use an approximate procedure, also described in Section 8.4.1, which does provide some indication of the uncertainty attached to a particular 'combined estimate'. However, this has the disadvantage that it is laborious to apply, especially when more than two or three models are being combined. This is the case both in water treatment and in sewage treatment, where as many as a dozen component costs might well have to be assembled. A completely different approach was therefore devised for these two areas, using the technique of 'simulation'. This is described in Section 8.4.2, and the results obtained using the approach are presented in Sections 12.1.6 and 13.1.6.

8.4.1. THE STATISTICAL APPROACH

(a) Statement of the problem

For simplicity, suppose that just two cost functions, C_1 and C_2, are being combined to provide a total cost estimate for a particular scheme (the argument can be generalized to more than two functions without difficulty). Associated with each cost function is a multiplicative error: suppose these are denoted by m_1 and m_2.

$$\text{Then estimated total cost} = C_1 + C_2 \qquad \ldots \quad \text{(i)}$$

$$\text{and actual total cost} = C_1 m_1 + C_2 m_2. \qquad \ldots \quad \text{(ii)}$$

It is important to appreciate that the scheme in question will at this stage only be in the planning stage, and not actually have been built. Its cost is estimated by equation (i), but the actual cost is unknown and can be thought of as lying somewhere in the distribution obtained by varying the errors m_1 and m_2 in equation (ii). The quantities m_1 and m_2 are in fact log-Normally distributed: this follows from the assumption discussed in Section 8.3.1, and upheld by thorough checks during the development of the cost functions, that the errors about the log-log models are Normally distributed. Thus 'actual' cost as defined by equation (ii) is the sum of two log-Normal variables. Unfortunately this does not produce a recognizable distribution which can be handled by analytical statistical methods (in the way that, for example, the sum of two Normally distributed variables is itself Normal). There is therefore no exact method of obtaining confidence limits about the quantity $C_1 + C_2$.

(b) An approximate method

It is, however, possible to calculate the mean and standard deviation of $C_1m_1 + C_2m_2$ knowing the distributions of m_1 and m_2, and these form the basis of an approximate confidence interval, as follows.

Suppose that $\log_{10} m_1$ is Normally distributed with mean O and standard deviation σ_1,

and that similarly $\log_{10} m_2$ has standard deviation σ_2.

Making the assumption that m_1 and m_2 are statistically independent, the variable $C_1m_1 + C_2m_2$ has mean

$$\underline{M = C_1(14.2)^{\sigma_1^2} + C_2(14.2)^{\sigma_2^2}} \qquad \ldots \text{(iii)}$$

and standard deviation

$$S = \sqrt{C_1^{\,2}(200.7)^{\sigma_1^2}\{(200.7)^{\sigma_1^2} - 1\} + C_2^{\,2}(200.7)^{\sigma_1^2}\{(200.7)^{\sigma_1^2} - 1\}} \quad \ldots \text{(iv)}$$

(The numbers 14.2 and 200.7 arise as various combinations of 10 and the mathematical quantity e.)

Although the exact distribution of $C_1m_1 + C_2m_2$ cannot be determined, there is some statistical justification (the Central Limit Theorem) for supposing that it is at least approximately Normal. Under this assumption, confidence limits for $C_1m_1 + C_2m_2$ can be formed in the usual way, namely $M \pm 1.3S$(80%) and $M \pm 2.0S$(95%).

It is convenient to turn these additive limits into multiplicative limits by expressing them relative to the estimated cost, $C_1 + C_2$. Thus the 80% multipliers, for example, would be

$$\frac{M - 1.3S}{C_1 + C_2} \quad \text{and} \quad \frac{M + 1.3S}{C_1 + C_2}.$$

If the total cost estimate is formed by summing more than two component estimates, equations (iii) and (iv) are simply extended by similar terms involving C_3 and σ_3, C_4 and σ_4, and so on as necessary.

(c) The independence assumption

In equation (iv) for the standard deviation of the quantity $C_1m_1 + C_2m_2$, the important assumption is made that m_1 and m_2 are statistically independent. What this requires is that the magnitudes of the random multiplicative errors associated with C_1 and C_2 are not influenced by one another. For example, if in a particular scheme the capital item represented by the cost function C_1 happens to be cheaper than predicted (i.e. m_1 is less than 1), this is assumed to have no bearing on whether the other capital item is more or less expensive than predicted by C_2. This is clearly an over-simplification. Whilst there is sure to be some sort of 'swings and roundabouts' effect, it is easy to visualize factors which could tend to bias all component costs away from the average (for example, locally cheap labour, or site difficulties). The presence of factors such as these will make the approximate confidence intervals calculated by the method outlined above too narrow. This is an additional reason, therefore, why the method should be regarded as no more than a rough guide.

The method is illustrated for the case of just two component costs in the following worked example.

(d) Worked example

Suppose the total cost is to be estimated for a proposed water pumping installation (including standby capacity and pumps) for which

design throughput of pumphouse = 18 000 m^3/h,
normal operating capacity = 10 000 m^3/h,
and normal operating head = 60 m.

Two models are required: the water pumping model of Section 10.4.1, and the water pumphouse building model of Section 14.1. The first of these models is:

$$\underset{(\text{£}'000)}{\text{WATCOS}} = 0.0229*\underset{(m^3/h)}{\text{NORMCAP}}^{0.81}*\underset{(m)}{\text{NORMHEAD}}^{0.43},$$

with standard error of 0.216.

This gives a predicted cost of £231 000.

The second model is:

$$\underset{(\text{£}'000)}{\text{WATPUMPCOS}} = 4.00*\underset{('000\ m^3/d)}{\text{THRUPUT}}^{0.79},$$

with standard error 0.227.

The value of THRUPUT to be used is 18*24 = 432, giving a predicted cost of £483 000.

The combined estimate of total cost is therefore £714 000.

The quantity M may now be calculated from equation (iii), using 0.216 and 0.227 as estimates of σ_1 and σ_2, and setting C_1 and C_2 to 231 and 483 (as both equations are in £'000):-

$$\begin{aligned} M &= 231(14.2)^{0.0467} + 483(14.2)^{0.0515} \\ &= 261 + 554 \\ &= \underline{815}. \end{aligned}$$

Equation (iv) for S is in fact less ferocious than it appears. Upon substitution,

$$\begin{aligned} S &= \sqrt{231^2(1.281)(0.281) + 483^2(1.314)(0.314)} \\ &= \sqrt{19208 + 96254} \\ &= \underline{340}. \end{aligned}$$

Approximate 80% confidence limits are therefore $M \pm 1.3S$,

i.e. <u>£373 000 to £1 257 000</u>.

Finally, these can be expressed relative to the estimate of total cost provided by $C_1 + C_2$ (namely 714) to give

$$\frac{373}{714} \quad \text{and} \quad \frac{1257}{714},$$

or <u>0.52 to 1.76</u>.

The advantage of expressing the interval in this way is that the multiples can then be used for assessing other schemes which may be of interest, provided their physical characteristics are fairly close to those of the case worked through in detail.

Although these limits are wide, they are narrower than the 80% limits of (0.52, 1.93) and (0.49, 2.06) for the two component models. This is a customary feature of multiplicative confidence intervals when combining estimates.

8.4.2. THE SIMULATION APPROACH

When two or more cost estimates are taken from multiplicative (or log-log) models and summed to form an estimate of total scheme cost, there is no exact statistical method available for calculating confidence intervals about that estimate. An approximate method is described in Section 8.4.1, but this is very unwieldy when dealing with more than a small number of component items.

A completely different approach is to generate the distribution of possible actual costs empirically by the method of 'simulation'. Consider again equation (ii) of 8.4.1(a):-

$$\text{actual cost} = C_1m_1 + C_2m_2 \qquad \ldots \text{(ii)}$$

This may be rewritten as

$$\text{actual cost} = C_1 10^{e_1} + C_2 10^{e_2} \qquad \ldots \text{(v)}$$

where e_1 and e_2 are Normally distributed errors with zero means and standard deviations σ_1 and σ_2 respectively. The simulation proceeds as follows. Random values are selected for e_1 and e_2 from their two parent Normal distributions (this is most easily done by computer). These are substituted into equation (v) to obtain a hypothetical 'actual cost'. This process is then repeated a number of times, each time using fresh random values for e_1 and e_2. In this way a histogram of actual costs can be built up which gradually becomes smoother as the simulation progresses. Finally, when the actual costs distribution is sufficiently well established, confidence intervals can be determined directly from the histogram.

This method has been used in the total costing of both water treatment and sewage treatment schemes. The details are given in Sections 12.1.6 and 13.1.6 respectively. In both cases, 1000 simulated values of total cost were generated from the component error distributions for each treatment standard over a range of works capacities. Considerable reliance can therefore be placed in the representativeness of the results.

However, the approach does make one over-simplification: in common with the statistical approach described earlier, it assumes that the errors associated with each separate cost estimate are statistically independent. The consequences of this have already been discussed in Section 8.4.1(c); the general conclusion is that the quoted intervals are probably too narrow. Nevertheless, they still provide a very useful, quantitative measure of the uncertainty attached to each total cost estimate.

PART III—THE RESULTS

9. LAYOUT OF THE RESULTS

The detailed results follow a structure which, apart from minor details, is the same for all cost areas. Each section begins with two basic parts:-

A. The modelling approach;
B. The results.

If more than one major cost function has been developed for that area, categories C, D, etc. are added as necessary. For example:-

A. The modelling approach;
B. The results - total costs;
C. The results - civil engineering;
D. The results - mechanical engineering.

In these circumstances it has still usually been possible to collect details of the modelling approach for all cost functions under the one heading, A. Sometimes, however, it has been necessary to include detailed modelling comments within individual parts of the results.

Each set of results is sub-divided by the following headings:-

(i) Detailed modelling approach (if relevant);
(ii) Data summary;
(iii) The recommended cost function;
(iv) Other cost functions (if relevant);
(v) The data.

Items to be found under each of these headings are detailed below, together with some general comments which apply throughout all the results.

(i) Detailed modelling approach

Sometimes there are points of procedure peculiar to one function within the section, or there may be a particularly important proviso to be made concerning the use of the model. Matters of this sort are discussed under this heading.

(ii) Data Summary

The minimum, maximum, mean, standard deviation, units of measurement and code label (e.g. DIAM, DEP, CIVCOS, TYPE) are presented for the deflated cost, for all the variables which were found to be significant, and sometimes for certain other variables of interest. The units in the table are carried through to all subsequent functions in that results section. The code labels are used to simplify the writing of the cost functions.

The number of cases of data and the index used for deflation are stated below the table.

The summary statistics are supplemented by 'mini-histograms' for all the main variables. Each of these covers a range containing the minimum and maximum values recorded in the preceding table, and provides a snapshot of how that variable is distributed. The frequency ('vertical') scale for the mini-histograms is the same throughout the report. The mini-histograms are particularly useful in cases where the distribution is markedly skew, or has some other irregularity which distorts the familiar roles played by mean and standard deviation. (For example, the common assumption that roughly 95% of the data lies within two standard deviations of the mean is true only for Normally distributed data.)

(iii) The recommended cost function

The equation is given defining the recommended cost function; it is boxed for clarity. The variable labels and units are always defined in the preceding data summary; as the cost function usually appears within a page of the table it was thought unnecessary to repeat these details. The equation coefficients are not quoted to more than three significant figures; this makes for ease of computation, and in any case the precision gained by more figures would be largely spurious owing to the substantial prediction errors.

A number of statistics are provided which help in assessing and interpreting both the cost function as a whole and its individual components. These are all defined and discussed in Chapter 8. However, some explanation is needed of the column headed 'significance level'. Suppose the variable DIAM were marked as $<0.1\%$ This means that the inclusion of DIAM in the cost function is significant at less than the 0.1% level: in other words, there is less than a 1 in 1000 chance that the reduction in scatter attributable to that variable came about by chance. (The symbol $\ll$ has been used to mean 'very much less than'.)

In cases where the function contains more than one explanatory variable, an omnibus variable is required for the graphical presentation. For completeness the equation for this is given. However, it should be stressed that the omnibus variable is purely a device for showing graphically how well the variations in cost are accounted for by the model, and there is no necessity for the reader ever to calculate it.

The cost function is illustrated by one main scatter diagram - either cost v. explanatory variable, or cost v. omnibus if there are two or more explanatory variables. This diagram plots the data, the cost function, and the 80% confidence interval for prediction. In addition, four subsidiary diagrams are provided if there is sufficient data to warrant them. These are:-

(a) The log-log equivalent of the main diagram. Because the cost function was developed using linear regression on the logged data, it appears in this diagram as a straight line. (This is how the cost functions were presented in TP 60 (2).)

(b) A scatter diagram of the residuals v. the logged explanatory variable or omnibus variable. Note that the residuals are defined in terms of the log model, namely $\log_{10}$(actual cost) - $\log_{10}$(predicted cost). This diagram is included as a check on the assumption that the residuals have a similar degree of scatter about all parts of the zero line.

(c) A histogram of the residuals. This should look roughly Normal (i.e. bell-shaped) for the quoted confidence limits to be valid.

(d) A scatter diagram of $\log_{10}$(predicted cost) against $\log_{10}$(actual cost). This is another way of looking at how well the function fits the data: if the fit were perfect, the points on the diagram would all lie on a 45° straight line, and so the extent of the scatter about the line is an indication of the cost function's predicting ability.

(iv) Other cost functions

In cases where subsidiary cost functions have been developed, these are presented with an abbreviated form of the statistical back-up. Sometimes, minor cost items are given without repeated explicit mention of the base year. It can be assumed in all such cases that the figures refer to 1976 Q3.

(v) The data

The raw data from which the cost functions were developed is listed in Appendix A at the end of the report. Variables which were not significant have usually been omitted; it was felt that the limited benefit gained by their inclusion would be more than offset by the lengthening of the report. In any case, lesser variables of this sort were often not available for all the data cases.

The data appears in the listing in increasing order of the explanatory variable (or omnibus variable if there is more than one explanatory variable). This is to facilitate the identification of points on the various scatter diagrams.

Each listing ends with the following three columns:-

(a) Deflated cost;
(b) Estimated cost;
(c) Percentage error.

There are two ways of defining percentage error. Suppose deflated or actual, cost is £10 000 and estimated cost is £7 500. Then the estimated cost is 25% below the actual cost, but equivalently the actual cost is 33⅓% above the estimated cost. In other words, the error is either -25 or +33⅓% depending on the standpoint. It was decided that users of the report would find the latter definition more helpful, because when planning a scheme it is the estimate which is the fixed point of reference, and the actual cost which is the 'unknown quantity'. The figure in the listings is therefore defined by:-

$$\text{percentage error} = \frac{\text{deflated cost - estimated cost}}{\text{estimated cost}} * 100\% .$$

10. PIPEWORKS AND PUMPING

10.1. SEWERAGE

A. The modelling approach

The total cost of a sewerage scheme or contract was defined to be the total accepted tender price. No allowance was made for additional costs such as design, supervision, permanent reinstatement as carried out by the highway authority, compensation, easement, land acquisition, or any public utility or other cost not featured in the tender document but paid directly by the client. However, some typical costs for permanent reinstatement of highways are given in part C following.

Each total cost was subdivided into 15 cost categories as follows:-

C1	site clearance;
C2	sewers - excavation, supply, lay and backfill;
C3	sewers - fittings;
C4	sewers - break-out and temporary reinstatement of surface;
C5	sewers - alterations to existing;
C6	sewers - provisional items;
C7	manholes - excavation, supply, construction;
C8	manholes - fittings;
C9	manholes - provisional items;
C10	manholes - alterations to existing;
C11	public utility works as detailed in the contract;
C12	accommodation works;
C13	unrelated construction works;
C14	preliminaries (including contingencies and dayworks);
C15	special construction techniques or works.

For each BoQ that had been collected the sub-totals in the 15 categories were determined. The physical characteristics of each BoQ were specified by assembling for each pipe length within the contract the following details:-

(i) contract number;
(ii) pipe diameter;

(iii) pipe description (material, bedding, etc.);
(iv) system and construction;
(v) ground condition;
(vi) surface type;
(vii) length;
(viii) depth to invert;
(ix) excavation cost per metre;
(x) pipe supply and lay cost per metre;
(xi) bedding cost per metre;
(xii) total cost per metre.

This mass of data had to be condensed in various ways to provide suitable summary variables for use in the subsequent cost modelling. From this preliminary work the following were obtained:-

(i) the proportions of total cost for each BoQ falling into the 15 cost categories, and the mean proportions over all contracts;
(ii) mean depth and total length of each diameter of pipe appearing in a BoQ, and the mean diameter and total length of all pipes in specified depth ranges;
(iii) a summary of the sewer data grouped by diameter and pipe material within each BoQ;
(iv) mean depth and diameter and total length of pipes in each of 18 surface categories (various grades of rural, suburban and urban) within BoQs;
(v) an overall weighted measure of surface condition for each BoQ.

Cost functions were sought at four different levels of detail:-

level 0: a global model for total cost;
level 1: a global model for total cost modified by spreading provisional and general costs (C6, C9 and C14) over the other sub-costs and then removing C13 and C15 from the total;
level 2: separate sub-models for sewers (C2), reinstatement (C4), manholes (C7) and the remainder;
level 3: a further breakdown of the sewers cost into sub-models for each diameter/type/ground combination within a BoQ.

The level 0 model was only developed for comparison with the level 1 model, and this confirmed that the level 1 definition of total cost was the more appropriate. The effort expended on the levels 2 and 3 models brought disappointing results. The level 2 sewer cost function was only a little better than the level 1 global model, whilst the models for reinstatement and manholes were both poor. At level 3, there was an unacceptable amount of scatter in the cost v. depth relationships between pipes of a common diameter, type and ground condition. A variety of ideas were tried in an attempt to make further progress, but it was eventually concluded that no advance could be made on the level 1 global model with the present data.

During the development of the level 1 model, four indices were tried: the Construction Materials Index, the DQSD Index, the New Construction Index, and an appropriate weighting of Baxter indices. Using the testing criteria discussed in Part II, the DQSD Index was found to be the most suitable.

Four explanatory variables were considered in developing the level 1 global model:-

(i) total length of pipework in scheme;
(ii) mean diameter of pipes in scheme;
(iii) mean depth of scheme;
(iv) number of manholes in scheme.

Of these variables, only length and diameter were at first significant. Number of manholes was rejected because of its high correlation with length of scheme (longer schemes have proportionally more manholes): once length was included in the equation, number of manholes could offer little independent information. More surprise was occasioned by the failure of depth to be significant. However, the scatter diagram shown in Figure 10-1 demonstrates that, for the data sample studied, there is a tendency for larger diameters to be associated with greater depths. The relationship between depth and diameter is clearly rather tenuous. Nevertheless, the correlation is sufficiently high ($R = 0.6$) for it to be very difficult to distinguish statistically between the separate effects of depth and diameter on cost from the available data. Thus, once diameter was included in the model, depth did not provide a further significant reduction in scatter.

10.1. Sewerage

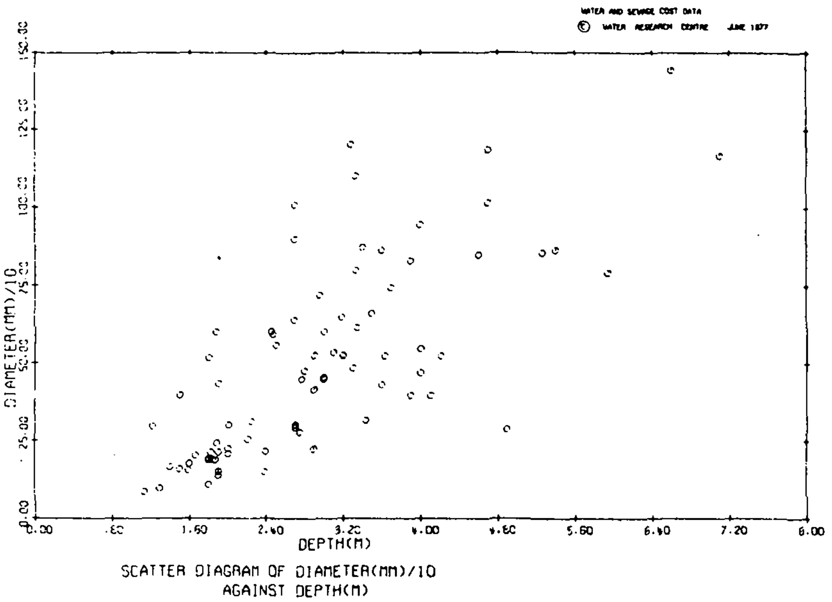


Figure 10-1. Scatter diagram of diameter against depth

When this initial model was circulated, concern was voiced not only at the absence of depth in the equation, but also that no mechanism had been provided for adjusting the model to take account of other factors (e.g. pipe material, ground condition, surface type) known to be important, even though this could not be demonstrated statistically. It is worth repeating the point made in Part I that the cost functions developed in this study are all intended to be empirical, derived purely by statistical methods from the available data. In the case of sewerage, efforts were made to obtain a wide spread of these other factors, but practical difficulties limited the available choice of contracts. Consequently there is frequently insufficient variation in a factor to allow its effect to be detected. Also there is often a range of conditions (e.g. surface types) within a typical contract, and the average of these over the contract may obscure the real variations.

Nevertheless, practical experience overwhelmingly indicates that scheme costs are radically affected by variations in factors of this sort. Accordingly, this engineering attitude was used as the basis of a more intuitive approach to provide an 'over-under' factor, O-U. Twelve contributory factors were identified, and to each of these was attached a series of possible weightings, or scores. Thus, for example, 'surface condition' ranges from 1 (open land) to 6 (difficult or restricted area).

The factors are as follows:-

(i) depth range;
(ii) diameter range;
(iii) per cent hard reinstatement;

(iv) surface condition;
(v) general vicinity of site;
(vi) ground conditions;
(vii) water table;
(viii) pipe material;
(ix) pipe bedding;
(x) manhole construction;
(xi) pipe laying/construction technique;
(xii) scheme type.

The possible weightings associated with each factor are defined in Table 10-1.

Table 10-1. Definition of the 'over-under' factor for sewerage schemes

Contributory factor	Range	Weighting	Comments
1. Depth range (m)	No excavation	Score 1 point for every depth range featured in contract	Diversity of depths might indicate an increase in complexity of the scheme, and necessitate a variety of excavation and pipe-handling techniques.
	≤ 1.0		
	1.0 ≤ 1.5		
	1.5 ≤ 2		
	2 ≤ 3		
	3 ≤ 4		
	4 ≤ 6		
	> 6		
2. Diameter range (mm)	≤ 200	Score 1 point for every diameter range featured in contract	Diversity of diameters might indicate an increase in complexity of the scheme, and necessitate a variety of excavation and pipe-handling techniques.
	200 ≤ 300		
	300 ≤ 600		
	600 ≤ 900		
	900 ≤ 1200		
	1200 ≤ 1500		
	1500 ≤ 1800		
	> 1800		
3. % hard reinstatement	0 ≤ 20	1	Taken to be any reinstatement in roads or similar paved areas, and based on length* (diameter + 0.5 m) summed for each pipe length.
	20 ≤ 40	3	
	40 ≤ 60	5	
	60 ≤ 80	7	
	80 ≤ 100	9	

Table 10-1 (continued)

Contributory factor	Range	Weighting	Comments
4. Surface condition (i.e. site location)	O: open land S: scrubland, wooded areas A: agricultural land P: private property R: residential roads M: main roads X: difficult/ restricted area	1 2 3 4 5 6 7	The terrain over which the pipe is laid may affect costs associated with:- (i) accommodation works; (ii) reinstatement; (iii) clearance; (iv) access.
5. General vicinity of site	U: urban S: suburban R: rural	5 3 1	The vicinity of the site will affect costs associated with:- (i) site access; (ii) restrictions on site operations.
6. Ground conditions	CL, OL ML, MH, CH, OH SF, SP SC, SW, GS Pt Rs (rock soft) BF (backfill - made ground) RH (rock hard)	1 2 3 4 5 6 7 8	The soil coding is derived from Casagrande's soil classification. The inclusion of ground type is necessary as excavation cost is known to depend upon soil conditions.
7. Water table	D: dry W: wet but not flooded F: dewatering required	1 2 7	Contractor rates are normally expected to allow for intermittent pumping, but continuous dewatering is considerably more expensive.

Table 10-1 (continued)

Contributory factor	Range	Weighting	Comments
8. Pipe material	Steel, spun iron, ductile iron	9	The costs of installing and providing pipes may depend on:- (i) physical characteristics, i.e. size, weight; (ii) material costs; (iii) laying and handling costs.
	Plastics	7	
	Asbestos cement	5	
	Concrete	3	
	Clayware	1	
9. Pipe bedding	Concrete bed and surround	6	
	Concrete bedding	5	
	Granular bed and surround	3	
	Granular bedding	2	
	Backfill only	1	
10. Manholes	Concrete (P/C)	1	There are distinct differences in the cost of constructing manholes according to the technique used.
	Backdrops	4	
	In situ concrete or brickwork	7	
	Segmented	10	
11. Construction method	Construction in single or dual trenches	1	
	Suspended on supports or not in trench	2	
	Pipe jacking	3	
	Construction in tunnels or headings	5-7	
12. Scheme type	S: storm	1	
	F: foul	4	
	C: combined	7	
	T: strong trade effluent†	10	†where special pipes or materials are required.

The sum of the 12 scores for a contract constitutes the O-U factor, and is an attempt to summarize how easy or difficult the contract is, and hence whether it is likely to be cheaper or more expensive than the average. The assessment of the individual weights is, of course, a matter of engineering judgement. However, sensitivity analyses carried out during the development of O-U indicated that its ability to account for some of the residual scatter about the model is not critically affected by the precise relative weightings. It should be stressed that the final ranges of weights set out in Table 10-1 were *not* determined statistically by any sort of 'best-fit' procedure; they purely attempt to reflect a consensus of the engineering attitudes and views encountered during the development of the study.

When the O-U factor was introduced into the cost function it was found to be highly significant. It also brought a bonus: with O-U in the model, the residual scatter was reduced sufficiently for depth to emerge as a significant variable in addition to diameter. However, a warning must be issued against attempting to use the O-U factor to determine the *separate* effects of its constituent items. The O-U factor has been constructed to represent the overall combined effect of all the variables listed in Table 10-1, and only in this sense is it statistically significant. Use of the O-U factor to attempt to assess the marginal effects of individual components, or groups of components, would therefore be statistically invalid.

At no point during the development of these models had it been possible to test for regional differences, as the bulk of the contracts originated from the North-West, and the remainder were not sufficiently concentrated to allow any worthwhile comparisons. However, a further collection of 32 sewerage BoQs was provided by the Transport and Road Research Laboratory towards the end of the study. Not only did this allow the model to be re-estimated from a broader, more representative sample, but because the contracts came predominantly from the South-East it was also possible to seek a regional effect. This was done by fitting a model of the same form as before to the pooled data (80 BoQs) and then grouping the residuals according to planning regions. This revealed a significant difference between the means of the North-West and the South-East sets of residuals, indicating that North-West contracts were cheaper than those in the South-East. However, it was thought unwise to include this effect in the quoted model because there is no guarantee that other equally significant effects do not exist for other regions. For the moment, therefore, the model must be used with the proviso that some part of the error is associated with regional variations, the identifying of which would need to be the subject of a further study.

B. The results

(i) Data summary

Table 10-2. Sewerage data summary

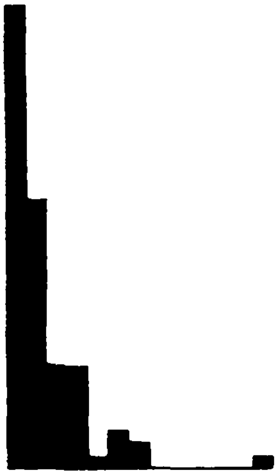
Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	2.5	2050	267	380
Total length of pipework	LEN	m	45.0	30 000	3190	4490
Mean diameter of pipework	DIAM	mm	86.0	1440	500	309
Mean depth of pipework	DEP	m	1.14	7.10	2.95	1.22
'Over-under' factor	O-U	-	18	56	36.8	8.77
Omnibus variable (see Section 8.3.3)	Z1	-	39.0	36 900	3450	5570

Note:
1. Number of cases: 80.
2. The DQSD Index was used for deflation.
3. Mean diameter for a scheme is obtained by weighting individual pipe diameters by their lengths.
4. Mean depth is obtained by weighting individual pipe depths by their corresponding areas (i.e. length*(diameter + 0.5 m)).

Mini-histograms for the main variables of interest:-

COST

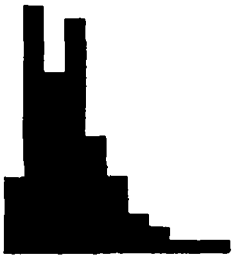
LOG COST



LEN

10.1. Sewerage

DIAM



DEP

O-U

(ii) The recommended cost function

The recommended function for sewerage is:-

$$COST = 0.0000213 \ast LEN^{0.94} \ast DIAM^{0.72} \ast DEP^{0.57} \ast (O\text{-}U)^{0.97}$$

The statistical details of the function are as follows:-

Number of observations : 80
Multiple correlation coefficient (R) : 0.96
Coefficient of determination (R^2) : 92%
Standard error of residuals (in $\log_{10}$ model) : 0.193

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
LEN	0.939	0.039	594	≪0.1%
DIAM	0.722	0.121	35.6	≪0.1%
DEP	0.575	0.203	7.99	<1.0%
O-U	0.973	0.226	18.5	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	**Lower**	Upper
80%	0.56	1.78
95%	0.41	2.43

The omnibus variable is defined as:-

$$Z1 = 0.000103*LEN*DIAM^{0.77}*DEP^{0.61}*(O-U)^{1.04}.$$

Figures 10-2 and 10-3 show the five standard diagrams in support of the model.

(iii) Other cost functions

Section 10-1A contains an account of cost functions which were developed at other levels of detail. As none of them offered any advantage over the recommended global model, it was felt unnecessary to discuss them further here.

If the information needed to construct the over-under factor is not available, its average value of 37 should be used. This simplifies the cost function to:-

$$\boxed{COST = 0.000717*LEN^{0.94}*DIAM^{0.72}*DEP^{0.57}}$$

It should be remembered that the omission of O-U from the model increases the standard error, and so the previously quoted confidence limits are slightly optimistic if this equation is used.

(iv) The data

The sewerage data is listed in Table A-1.

Figure 10-2. Sewerage

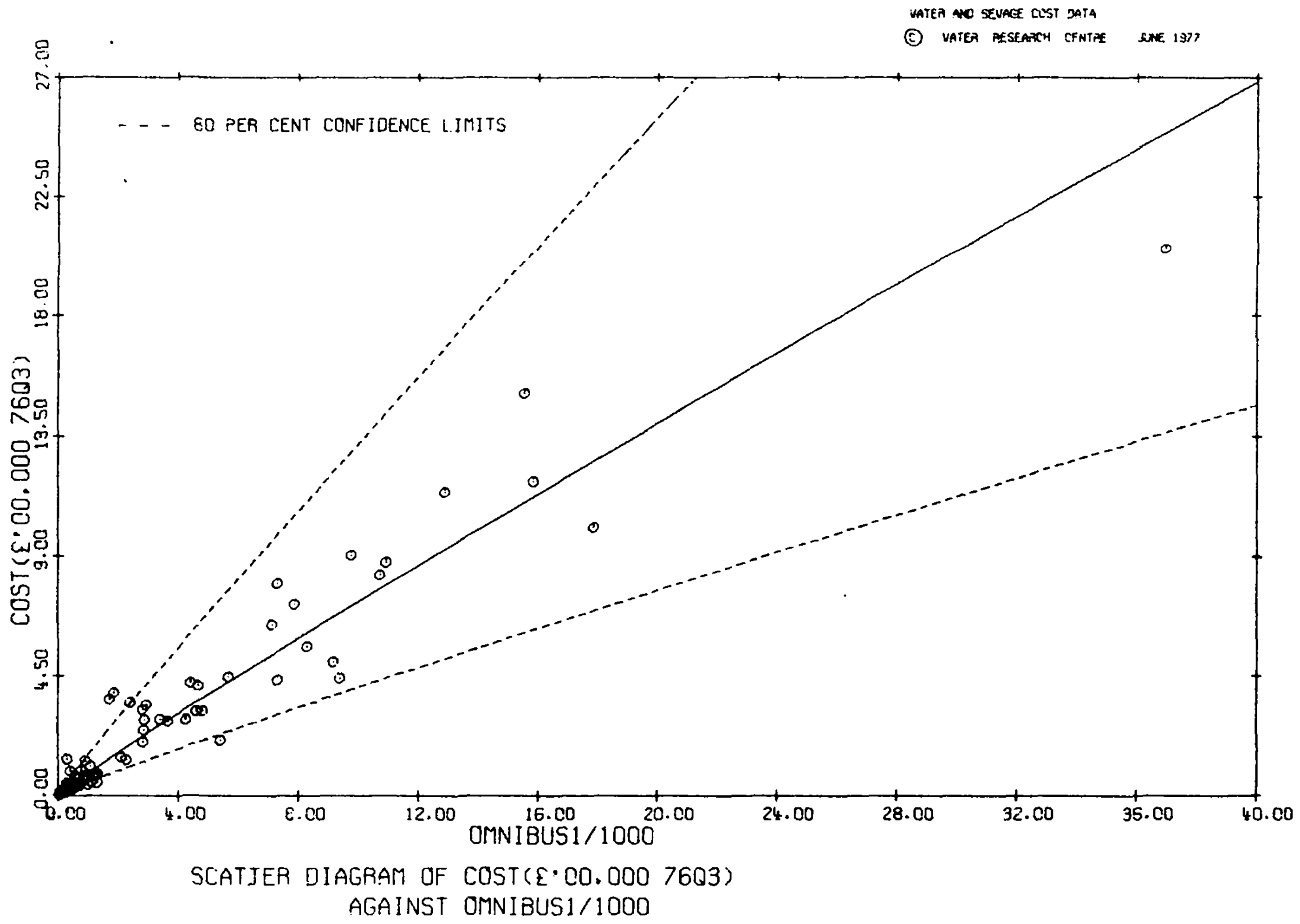
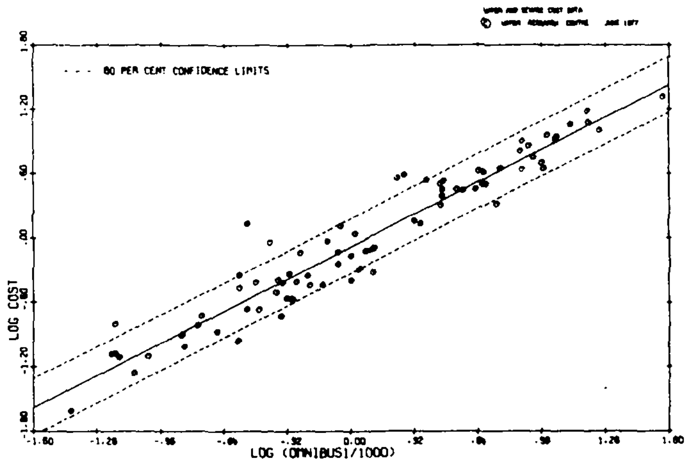
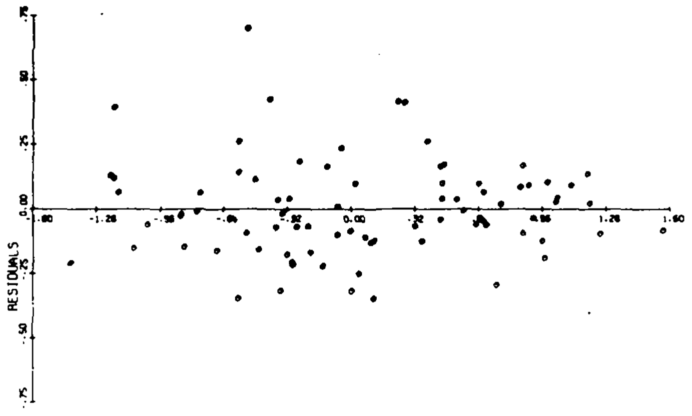


Figure 10-3. Sewerage

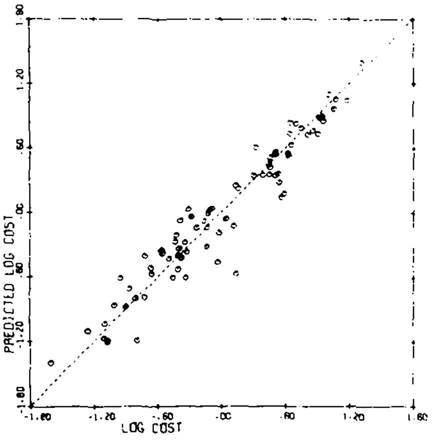


SCATTER DIAGRAM OF LOG COST
AGAINST LOG (OMNIBUS1/1000)



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG (OMNIBUS1/1000)

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. Permanent reinstatement of highways

In general the data collected for sewerage and water distribution schemes did not include the cost of any final or permanent reinstatement of the public highway. A number of highway authorities were therefore approached with requests for information regarding their charges for permanent reinstatement of trenches. Six of the authorities always charged on the basis of incurred costs plus on-costs, and felt that they were unable to provide suitable cost data. The other nine authorities to a greater or lesser extent all utilized schedules of charges for recouping some or all of the cost of permanent reinstatement. These could not be compared directly, as they were generally based on the type of road surface rather than the depth of

Table 10-3. Typical construction costs in permanent reinstatement of highways

Reinstatement item	Range of costs	Mean cost	Number of cases
	(£ 1976 Q3/m^2/25 mm depth)		
Hot rolled asphalt wearing course†	2.3 - 4.6	3.4	7
Hot rolled asphalt base course†	2.1 - 3.5	2.7	7
Lean mix concrete	0.6 - 2.0	0.9	6
Reinforced concrete pavement	0.3 - 2.7	1.2	6
Tar or bitumen macadam surfacing	1.2 - 2.4	1.6	8
Tar or bitumen macadam regulating course	1.2 - 2.0	1.5	6
Compacted hardcore	0.3 - 0.6	0.4	4
	(£ 1976 Q3/m^2)		
Fine cold asphalt surfacing	2.0 - 5.7	3.3	4
Surface dressing	0.5	0.5	2
Reinstatement of maintained verge	0.7 - 1.4	1.0	6
Relay of paving slabs	1.7 - 8.8	3.1	9
Tarmacadam/bituminous macadam footpath	3.4 - 8.0	4.9	8
	(£ 1976 Q3/m)		
Relay of kerbs	1.6 - 6.3	3.7	7

† Most authorities revert to 'actual costs' for contracts over a specified size.

road construction. However, by making suitable approximations where necessary Table 10-3 could be assembled, showing the variations in charges encountered for a number of items of work. All the figures refer to 1976 Q3 prices, though it should be emphasized that several of the authorities were in the process of updating schedules that were acknowledged to be out of date.

10.2. WATER MAINS

A. The modelling approach

The majority of the schemes analysed in the study of water distribution costs consisted of three or more separate contracts. These covered the installation of pipework and fittings, the supply of pipework and the supply of fittings. In some instances the supply contracts were further sub-divided, with some materials being obtained from stocks previously acquired. Almost the only exception to this arrangement related to the use of plastic pipes, and these were invariably installed on a 'supply and lay' basis with only valves being subject to a 'supply only' contract. For this reason two models were developed, the first to estimate the installation cost of a scheme, and the second to estimate the combined installation and materials costs of a scheme - that is, the total cost.

No allowance was made for additional costs such as design, supervision, permanent reinstatement as carried out by the highway authority, compensation, easement, land acquisition, or any public utility or other cost not featured in the tender document but paid directly by the client. However, some typical costs for permanent reinstatement of highways are given in Section 10.1C.

No attempt was made to subdivide the installation cost of a scheme into cost categories, as experience gained during the development of the sewerage model had suggested that there was little benefit to be gained from this.

Cost details of the distribution schemes were assembled as follows:-

(i) contract identification number;
(ii) signing date;
(iii) duration as specified;
(iv) type of contract (fixed or variable price);
(v) installation cost (less unrelated construction costs and their proportion of preliminaries and general costs);
(vi) pipe supply cost;
(vii) signing date;
(viii) type of contract;
(ix) fittings supply cost;
(x) signing date;
(xi) type of contract.

10.2. Water mains

The physical characteristics of each scheme were specified by assembling for each pipe length within the contract the following details:-

(i) contract identification number;
(ii) pipe diameter;
(iii) pipe length;
(iv) pipe depth;
(v) pipe material type;
(vi) pipe use.

This data was condensed to provide suitable summary variables for use in the subsequent cost modelling. From these preliminary calculations the following were obtained for each contract:-

(i) total length of water pipes;
(ii) total length of non-water pipes;
(iii) mean diameter of water pipes, weighted by length;
(iv) mean depth of water pipes, weighted by length;
(v) mean depth of water pipes, weighted by (length*(diameter + 0.5 m));
(vi) volume of excavation, defined as the sum over all water pipes of length*(diameter + 0.5 m)*(depth + 0.2 m);
(vii) percentages of pipe materials used, firstly based on length (see Figures 10-4 and 10-5) and secondly on length*diameter;
(viii) mean depth and total length of each diameter of pipe appearing in the contract, and the mean diameter, mean depth and total length of all pipes in specified depth ranges.

The explanatory variables assembled under (i) to (vii) above were used to develop two models, one for installation cost and one for total cost of a scheme.

For the installation cost model, volume of excavation, length, mean depth and pipe material were significant explanatory variables. In an attempt to reduce the residual scatter, an 'over-under' factor, O-U, similar to that used successfully in the sewerage work, was developed. This did bring about a significant improvement when introduced into the model.

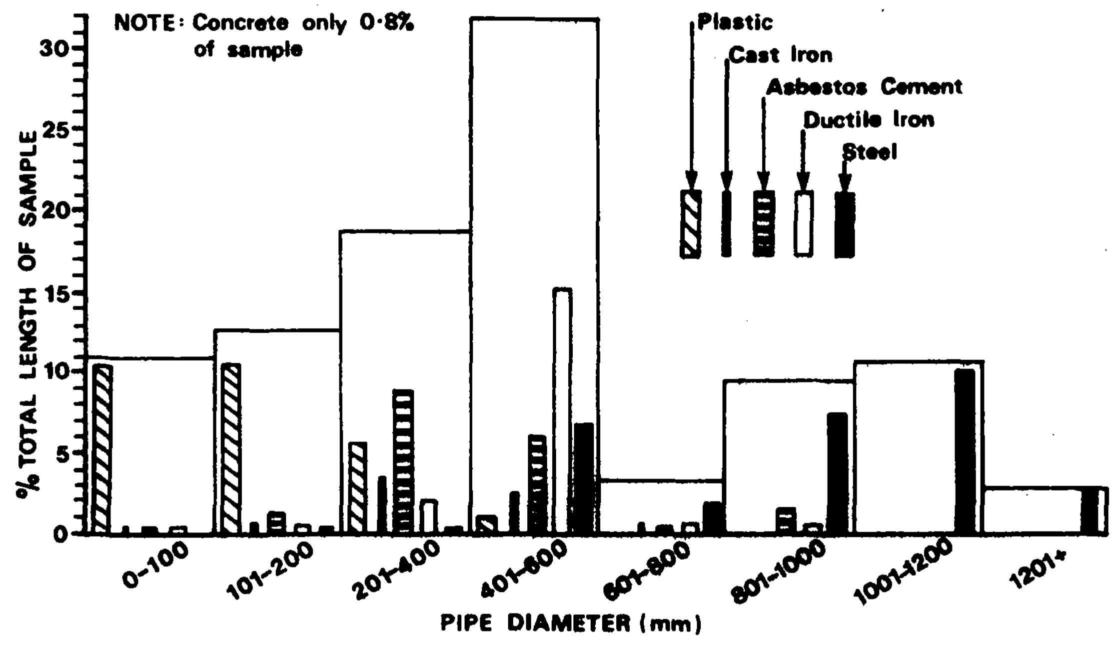


Figure 10-4. Percentages of total length of sample falling in different diameter ranges and material types for water mains installation cost data

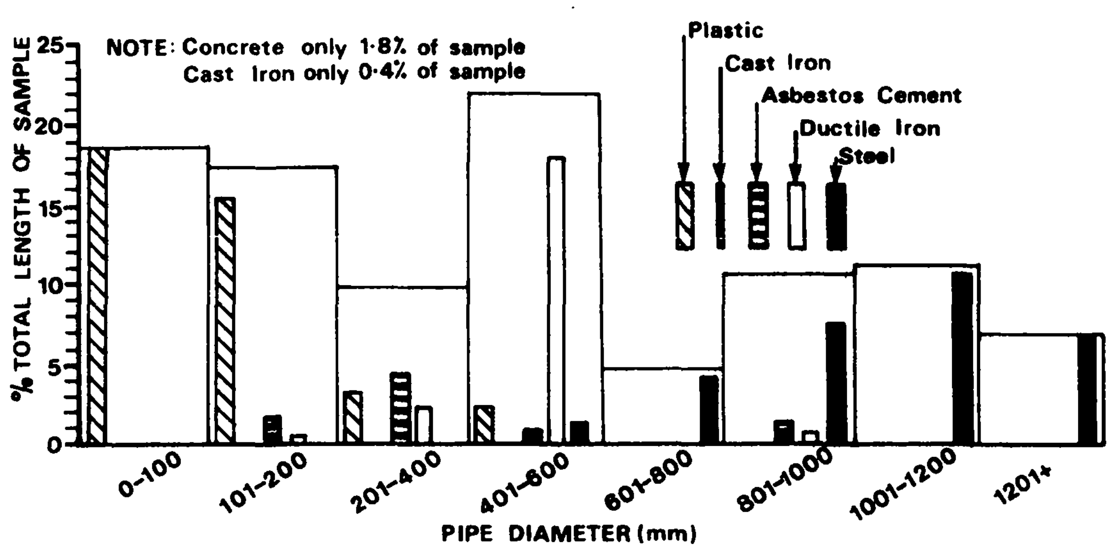


Figure 10-5. Percentages of total length of sample falling in different diameter ranges and material types for water mains total cost data

10.2. Water mains

A similar approach was taken in modelling total cost. Initially a cost function was developed which contained length, mean diameter and the proportion of steel pipe length (but not, this time, the O-U factor). However, this was not entirely satisfactory. A study of the model residuals plotted against diameter showed a tendency for the model to under-estimate costs at higher diameters. This suggested that the formulation of the diameter term in the model was inappropriate. Furthermore, Figure 10-5 indicates that the data sample contains a predominance of steel pipes in the larger diameter ranges. It was thought possible, therefore, that the steel proportion variable had appeared in the model solely because of its correlation with diameter. This hypothesis was tested by replacing the old diameter term DIAM^{α} by a new term of the form

$$\mathrm{DIAM}^{\alpha(\mathrm{DIAM}/(\beta + \mathrm{DIAM}))},$$

so that the diameter coefficient could itself increase with diameter (see Figure 10-6). This formulation successfully removed the earlier inadequacy shown by the diameter term, and, as suspected, the steel proportion variable was no longer significant and so dropped out of the equation.

Following this new development, the installation cost model was re-examined to determine whether there was similar scope for improvement. However, it was found that the conventional DIAM term was wholly adequate. Thus it seems as though only when material costs are included does total cost increase proportionally more sharply at high diameters.

Regional differences in the costs of water distribution schemes were examined by studying the model residuals grouped according to economic planning regions. This revealed some differences between the planning regions; however, it was not possible to quantify the effect fully with the present data sample. For this reason no attempt was made to incorporate regional effects in the cost functions.

During the development of the two models the DQSD Index and Construction Materials Index were tried. The DQSD Index was found to be more suitable for the installation cost model, and the Construction Materials Index for the total cost model.

Because of the limited amount of detailed pipeline data contained in the water distribution BoQs, it was not considered feasible to develop cost functions other than at the global level.

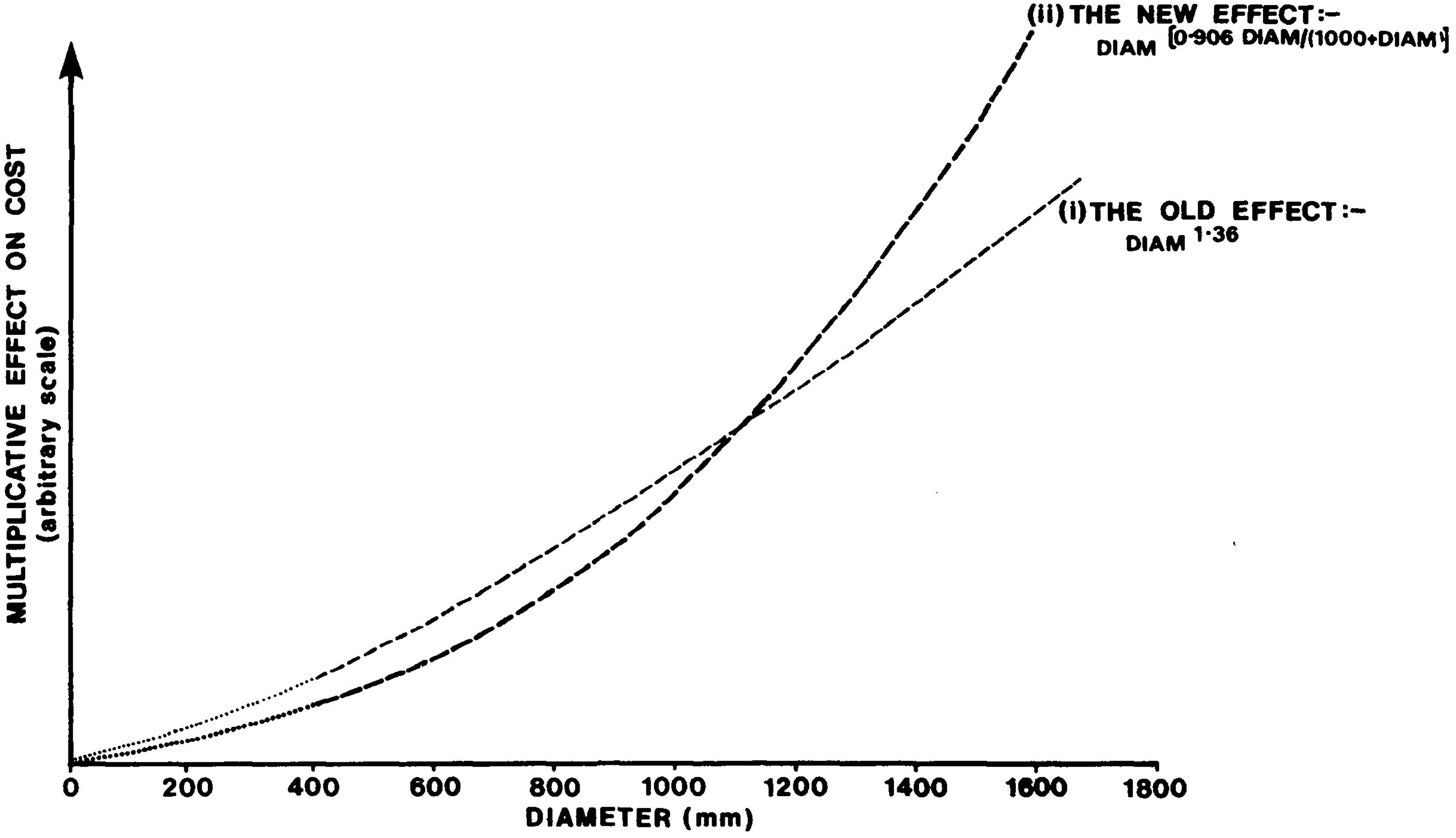


Figure 10-6. The marginal effect of diameter on cost for the recommended and earlier water mains total cost models

10.2. Water mains

The warnings given about the use of the O-U factor for the sewerage cost model hold equally for water distribution schemes. The O-U factor is based on a subjective assessment of the various features of a scheme likely to make it cost more or less than the average. It is only statistically valid in its entirety, and it cannot be used to determine the separate effects of its constituent elements.

Details of the variables making up the O-U factor are tabulated in Table 10-4.

Table 10-4. Definition of the 'over-under' factor for water distribution schemes

Contributory factor	Range	Weighting	Comments
1. Depth range (m)	Not in trench	Score 1 point for every depth range featured in contract	Diversity of depths might indicate an increase in complexity of the scheme, and necessitate a variety of excavation and pipe-handling techniques.
	≤ 1.0		
	1.0 ≤ 1.5		
	1.5 ≤ 2		
	2 ≤ 3		
	3 ≤ 4		
	4 ≤ 6		
	> 6		
2. Diameter range (mm)	≤ 100	Score 1 point for every diameter range featured in contract	Diversity of diameters might indicate an increase in complexity of the scheme, and necessitate a variety of excavation and pipe-handling techniques.
	100 ≤ 200		
	200 ≤ 300		
	300 ≤ 600		
	600 ≤ 900		
	900 ≤ 1200		
	1200 ≤ 1500		
	1500 ≤ 1800		
	>1800		
3. % hard reinstatement	0 ≤ 20	1	Taken to be any reinstatement in roads or similar paved areas, and based on length* (diameter + 0.5 m) summed for each pipe length.
	20 ≤ 40	3	
	40 ≤ 60	5	
	60 ≤ 80	7	
	80 ≤ 100	9	

Table 10-4 (continued)

Contributory factor	Range	Weighting	Comments
4. Surface condition (i.e. site location)	O: open land S: scrubland, wooded areas A: agricultural land P: private property R: residential roads M: main roads X: difficult/ restricted areas	1 2 3 4 5 6 7	The terrain over which the pipe is laid may affect costs associated with:- (i) accommodation works; (ii) reinstatement; (iii) clearance; (iv) access.
5. General vicinity of site	U: urban S: suburban R: rural	5 3 1	The vicinity of the site will affect costs associated with:- (i) site access; (ii) restrictions on site operations.
6. Ground conditions	CL, OL, ML MH, CH, OH SF, SP SC, SW, GS Pt Rs (rock soft) BF (backfill - made ground) RH (rock hard)	1 2 3 4 5 6 7 8	The soil coding is derived from Casagrande's soil classification. The inclusion of ground type is necessary as excavation cost is known to depend upon soil conditions.
7. Water table	D: dry W: wet but not flooded F: dewatering required	1 2 7	Contractor rates are normally expected to allow for intermittent pumping, but continuous dewatering is considerably more expensive.

Table 10-4 (continued)

Contributory factor	Range	Weighting	Comments
8. Construction method	Construction in single or dual trenches	1	
	Suspended on supports or not in trench	2	
	Pipe jacking (short length)	3	
	Construction in tunnels or headings	5-7	
9. Scheme type	Trunk mains - raw	6	
	Trunk mains - treated	5	
	Trunk/ distribution	4	
	Distribution main - existing area	2	
	Distribution main - new area	1	
10. External corrosion protection	Cathodic protection	5	
	Concrete surround	4	
	Bitumen sheathing	3	
	Sleeving	2	
	None	1	
11. Internal corrosion protection	Cement mortar	3	
	Bitumen	2	
	None	1	

Table 10-4 (continued)

Contributory factor	Range	Weighting	Comments
12. Pressure rating (ft)	Over 500 ft	6	
	500 or less	5	
	400 or less	4	
	300 or less	3	
	200 or less	2	
	100 or less	1	
13. Control cabling	Yes	3	
	No	1	
14. Land drainage; length of pipes as % of water pipes	0 - 25%	1	
	25 - 50%	2	
	51 - 75%	3	
	76 - 100%	4	
	100 + %	5	
15. Crossings	Ten or more minor road crossings	Score 1	Up to a maximum of 10.
	Major road/rail crossing using special techniques	Score 2 for each	
	Major river or canal crossing	Score 4 for each	

B. The results - installation cost

(i) Data summary

Table 10-5. Water mains (installation cost) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Installation cost (corrected to 1976 Q3)	COST	£'000	18.3	2500	323	463
Volume of excavation	VOL	'000 m^3	1.33	146	23.8	28.2
Mean diameter	DIAM	mm	146	1830	660	350
Mean depth	DEP	m	0.94	3.22	1.84	0.499
Proportion of ductile iron pipelength + 1	PRODI	-	1	2	1.24	0.413
'Over-under' factor	O-U	-	27	62	38.9	7.13
Omnibus 2 (see Section 8.3.3)	Z2	-	1.73	424	35.5	71.2

Note:
1. Number of cases: 51.
2. The DQSD Index was used for deflation.
3. Volume of excavation for a scheme is obtained by summing length*(diameter + 0.5 m)*(depth + 0.2 m) for each pipelength.
4. Proportion of ductile iron pipework is obtained by weighting individual ductile iron pipelengths by their diameters.

Mini-histograms for the main variables of interest:-

COST

LOG COST

VOL

DIAM

DEP

PRODI

O-U

(ii) The recommended cost function

The recommended function for water mains installation cost is:-

$$\boxed{COST = 0.000343*VOL^{0.81}*DIAM^{0.82}*DEP^{-1.15}*(O-U)^{1.77}*PRODI^{-0.60}}$$

The statistical details of the function are as follows:-

Number of observations : 51

Correlation coefficient (R) : 0.94

Coefficient of determination (R^2) : 89%

Standard error of residuals (in $\log_{10}$ model) : 0.168

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.808	0.064	161	$\ll 0.1\%$
DIAM	0.824	0.144	32.8	$\ll 0.1\%$
DEP	-1.15	0.265	18.8	$\ll 0.1\%$
O-U	1.77	0.363	23.9	$\ll 0.1\%$
PRODI	-0.597	0.195	9.35	<1.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.61	1.65
95%	0.46	2.17

The omnibus variable is defined as:-

$$Z2 = 0.00000119{*}VOL{*}DIAM^{1.02}{*}DEP^{-1.42}{*}(O\text{-}U)^{2.20}{*}PRODI^{-0.74}.$$

Figures 10-7 and 10-8 show the five standard figures in support of the function.

(iii) Other cost functions

If the information needed to construct the over-under factor is not available, its average value of 39 should be used. This simplifies the cost function to:-

$$\boxed{COST = 0.229{*}VOL^{0.81}{*}DIAM^{0.82}{*}DEP^{-1.15}{*}PRODI^{-0.60}}$$

It should be noted that the previously quoted confidence intervals are slightly optimistic if this form of the function is used.

(iv) The data

The water mains installation cost data is listed in Table A-2.

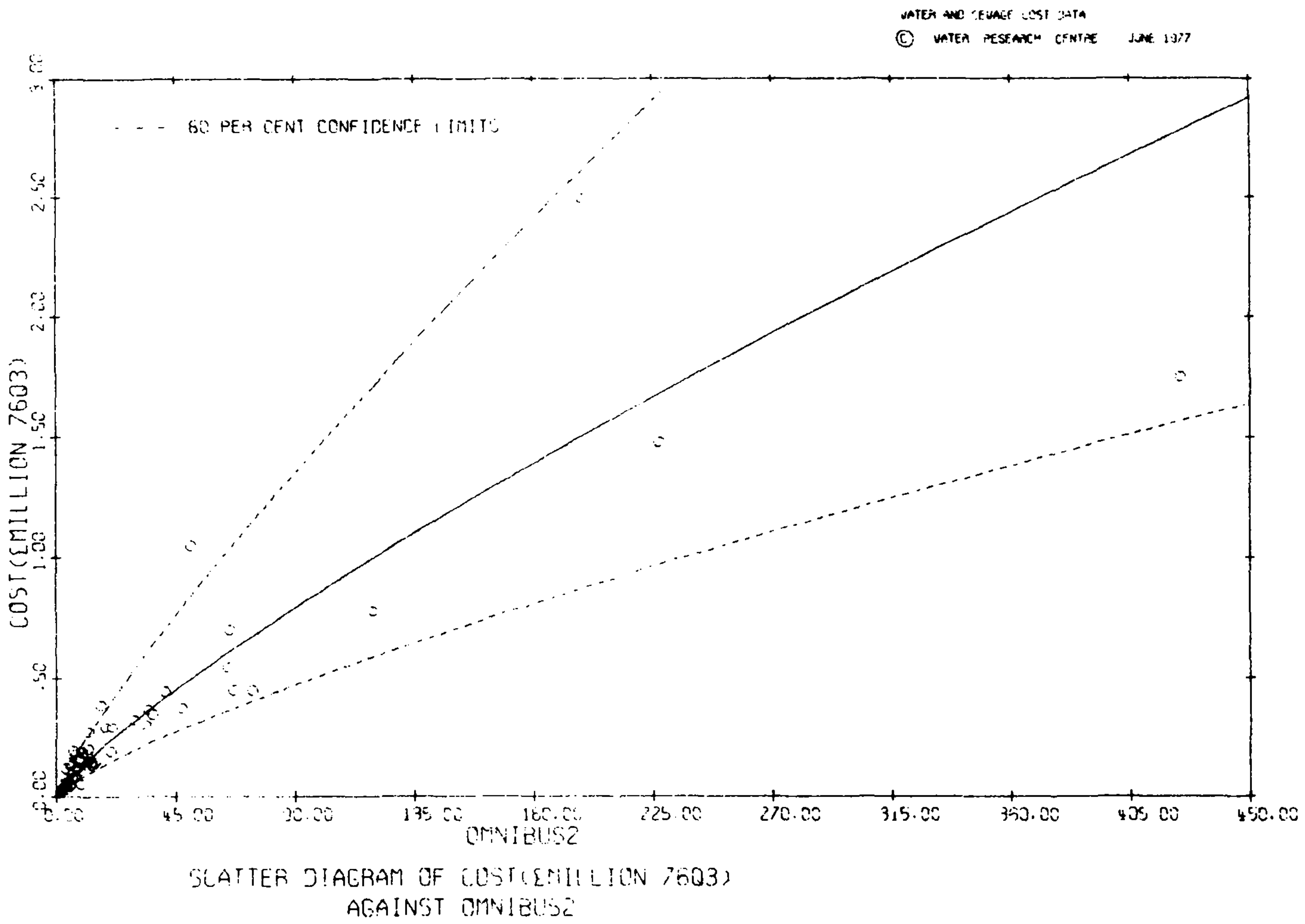
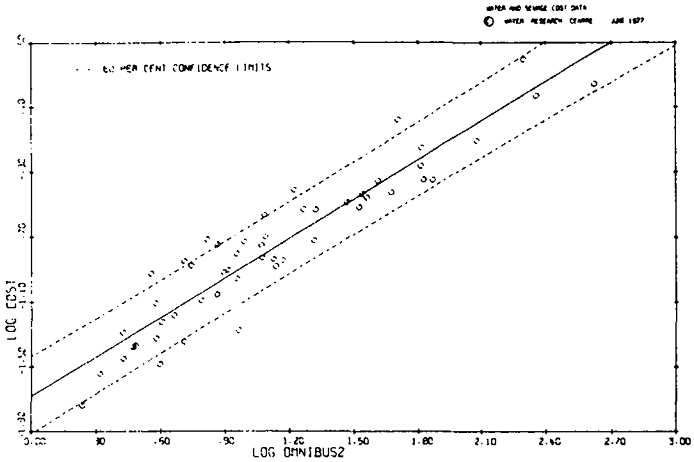


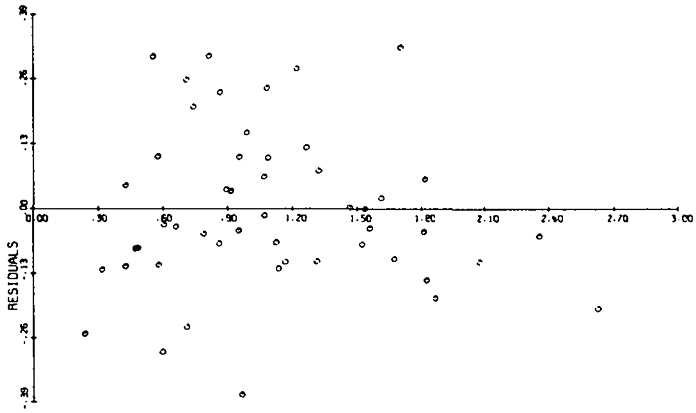
Figure 10-7. Water mains (installation cost)

10.2. Water mains

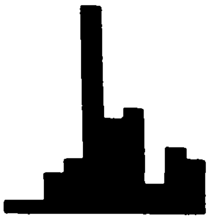
Figure 10-8. Water mains (installation cost)



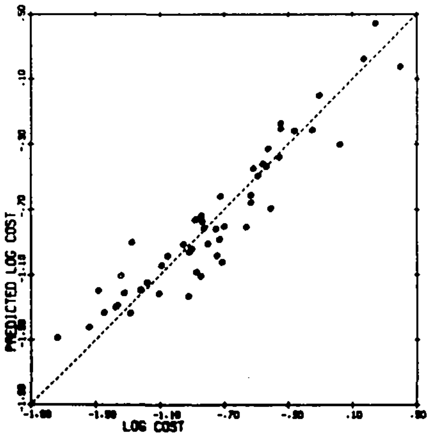
SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS2



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS2



HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - total cost

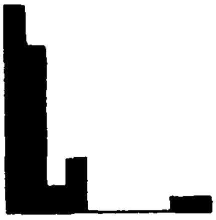
(i) Data summary

Table 10-6. Water mains (total cost) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Installation and materials cost (corrected to 1976 Q3)	COST	£'000	70.3	4770	721	1040
Total length of pipework	LEN	m	744	45 500	8970	8730
Mean diameter of pipework	DIAM	mm	126	1830	695	410
Omnibus 3 (see Section 8.3.3)	Z3	-	922	236 000	20 000	47 000

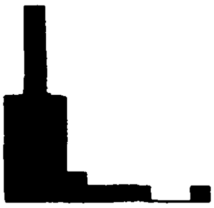
Note:
1. Number of cases: 37.
2. The Construction Materials Index was used for deflation.
3. Mean diameter for a scheme is obtained by weighting individual diameters by their lengths.

Mini-histograms for the main variables of interest:-



COST

LOG COST



LEN

DIAM

10.2. Water mains

(ii) The recommended cost function

The recommended function for water mains total cost is:-

$$\boxed{\text{COST} = 0.0702 * \text{LEN}^{0.73} * \text{DIAM}^{0.91*(\text{DIAM}/(1000 + \text{DIAM}))}}$$

The statistical details of the function are as follows:-

Number of observations	:	37
Multiple correlation coefficient (R)	:	0.95
Coefficient of determination (R^2)	:	91%
Standard error of residuals (in $\log_{10}$ model)	:	0.146

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
LEN	0.726	0.068	115	≪0.1%
$\text{DIAM}^{\left(\frac{\text{DIAM}}{1000 + \text{DIAM}}\right)}$	0.906	0.053	296	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.64	1.55
95%	0.51	1.98

The omnibus variable is defined as:-

$$\text{Z3} = 0.0430 * \text{LEN} * \text{DIAM}^{1.25*(\text{DIAM}/(1000 + \text{DIAM}))}.$$

Figures 10-9 and 10-10 show the five standard diagrams in support of the function.

(iii) The data

The water mains total cost data is listed in Table A-3.

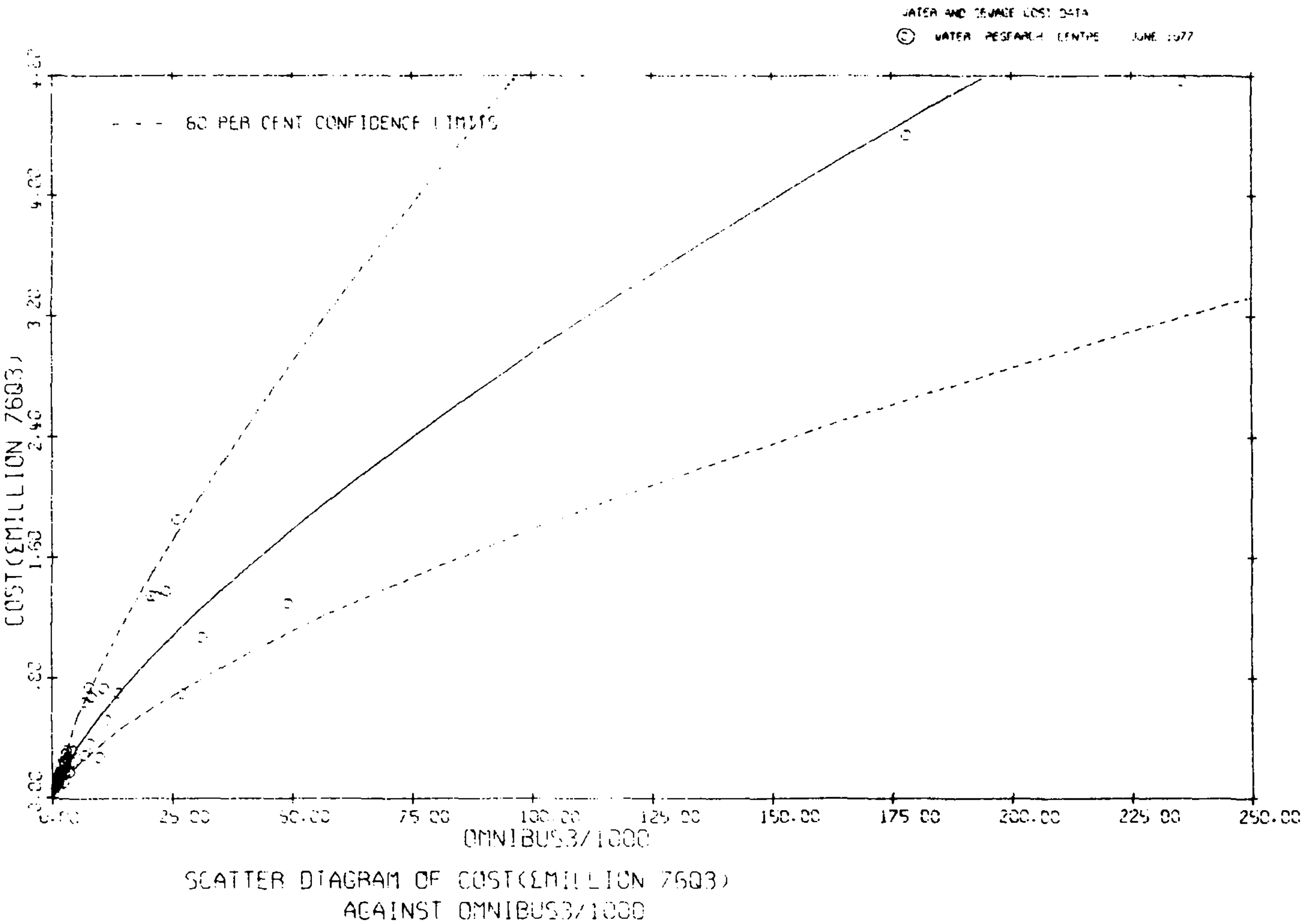
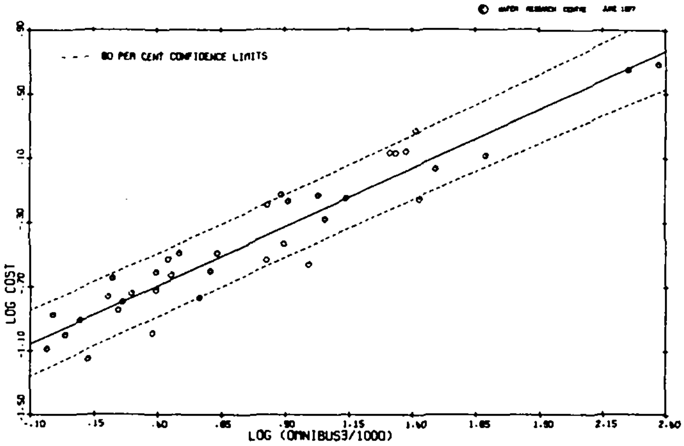


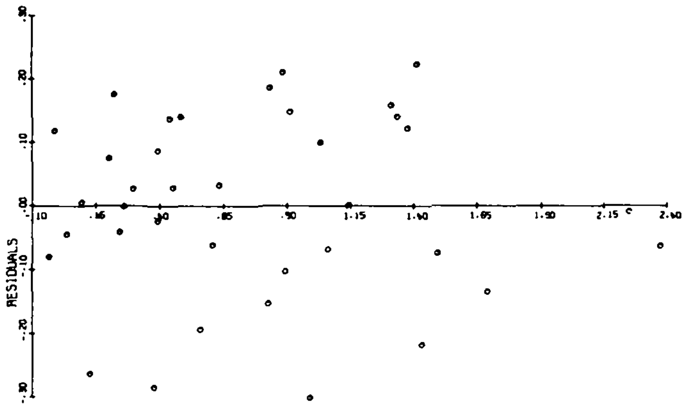
Figure 10-9. Water mains (total cost)

10.2. Water mains

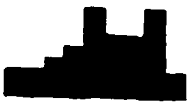
Figure 10-10. Water mains (total cost)



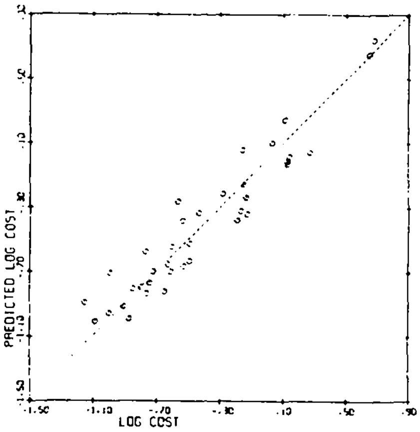
SCATTER DIAGRAM OF LOG COST
AGAINST LOG (OMNIBUS3/1000)



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG (OMNIBUS3/1000)



HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

10.3. TUNNELS AND SHAFTS

A. The modelling approach

Because of geological uncertainties tunnels are high risk projects, and almost invariably the settlement of the final account involves a high proportion of variations and claims. However, it was necessary to use tender BoQs in developing the cost functions presented in this section, and so caution must be exercised when using these models to estimate final costs. Other qualifying comments are given in part H.

Most of the available data was in the form of BoQs for soft ground shield-driven tunnels. More than half the cases were of tunnels driven through the London clay. A limited amount of data related to hard rock tunnelling, but not enough to allow a model usefully to be estimated. The soft ground tunnels usually had a short section of bolted concrete liners and much longer sections of wedge-block lining. The secondary linings, fittings in the shafts, internal pipework and other items of this sort largely depend on the use to which the tunnel is to be put. This exercise was therefore limited to the cost of excavation and primary lining of soft ground tunnels and shafts.

To begin with, separate models were sought for tunnels and shafts, as tunnel driving via a shield and shaft sinking are essentially different operations. Three explanatory variables were considered for each category: length, excavated diameter, and excavated volume. (For the tunnels model, depth was also considered but this proved to have no discernible effect on costs.) The variables diameter and volume refer to the excavated dimensions and not to the dimensions of the finished lined tunnel. Thus, in the case of a 100-inch (2.54-m) diameter tunnel the excavated diameter might be 111 inch (2.82 m), and this would be the figure defining the tunnel diameter.

Cost was related to volume alone, and to length and diameter together. In the tunnels case, diameter was not found to be a significant variable when tried with length; this is probably because the variation in diameter for the sample was insufficient for a diameter effect to appear. The most satisfactory model was therefore the one based on volume alone. For the shafts model, however, it was found appropriate to retain both length and diameter rather than to use volume.

10.3. Tunnels and shafts

Ground condition is another factor which exerts a major influence on cost. Unfortunately, this varied very little over the data: ground conditions were fairly good for most of the contracts, and ground freezing and compressed air working each only appeared in one contract. The unit costs for these items are listed in Table 10-12 but it must be stressed that these are not necessarily representative and should only be taken as a rough guide.

A complete scheme in general consists of a number of tunnels and shafts. The total cost can be estimated by applying the above models individually to each item and summing the separate estimates. There is one difficulty with this approach: there is no simple way of combining the confidence limits about each estimate to obtain a grand confidence interval about the total cost estimate. However, the approximate procedure described in Section 8.4.1 may be used.

In the tunnelling contracts examined, it was found that the tunnel and lining itself accounted for about 60% of the contract and the shafts for about another 10%. The remainder was for secondary lining (for tunnels carrying treated water), internal pipes and 'general and preliminary' items. In view of the relatively small shafts component, it seemed feasible to develop a global model embracing both tunnels and shafts. Using the same variables as before, but now defined for whole schemes, a satisfactory model was developed containing the single explanatory variable volume. Estimates made using this model are compared in part E with those obtained by summing separate estimates from the tunnels and shafts models.

The Construction Materials Index was chosen for deflation.

B. The results - tunnels

(i) Data summary

Table 10-7. Tunnels data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost (corrected to 1976 Q3)	TUNCOS	£ million	0.0154	2.68	1.01	0.850
Excavated volume of tunnel	VOL	'000 m^3	0.500	89.7	29.1	25.5
Length of tunnel	LEN	m	39	14 400	4630	4170
Diameter of excavation	DIAM	m	2.29	4.83	3.05	0.613

Note:
1. Number of cases: 18.
2. The Construction Materials Index was used for deflation.
3. TUNCOS is the cost of tunnel excavation and primary lining (assuming wedge-block lining), but excluding costs of secondary lining, internal pipes and general and preliminary items.

Mini-histograms for the main variables of interest:-

TUNCOS

LOG TUNCOS

VOL

(ii) The recommended cost function

The recommended function for tunnels is:-

$$\boxed{\text{TUNCOS} = 0.0408*\text{VOL}^{0.95}}$$

The statistical details of the function are as follows:-

Number of observations : 18
Correlation coefficient (R) : 0.98
Coefficient of determination (R^2) : 96%
Standard error of residuals (in $\log_{10}$ model) : 0.145

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.952	0.051	343	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

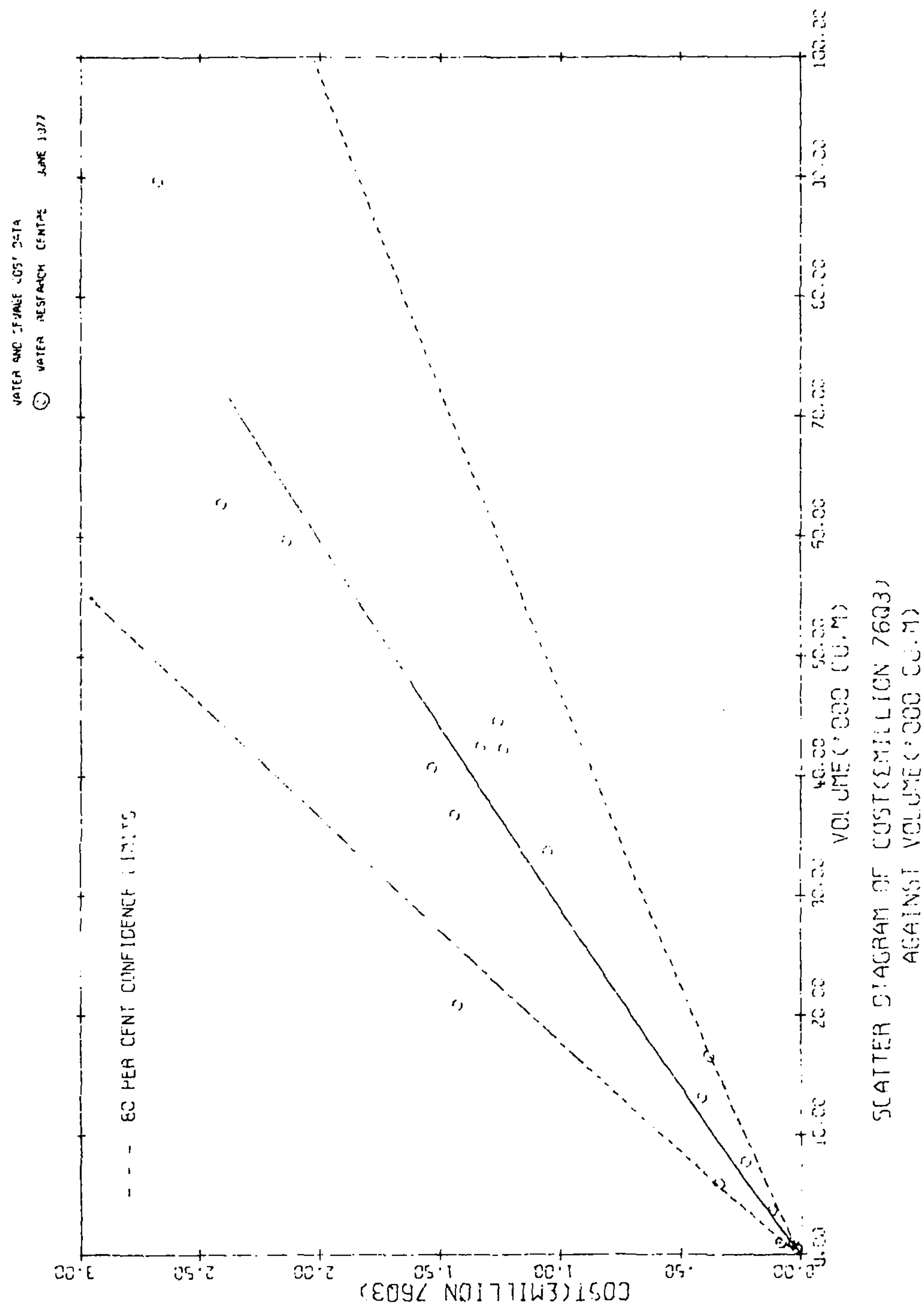
Confidence level	Lower	Upper
80%	0.64	1.56
95%	0.49	2.03

Figures 10-11 and 10-12 show the five standard diagrams in support of the function.

(iii) The data

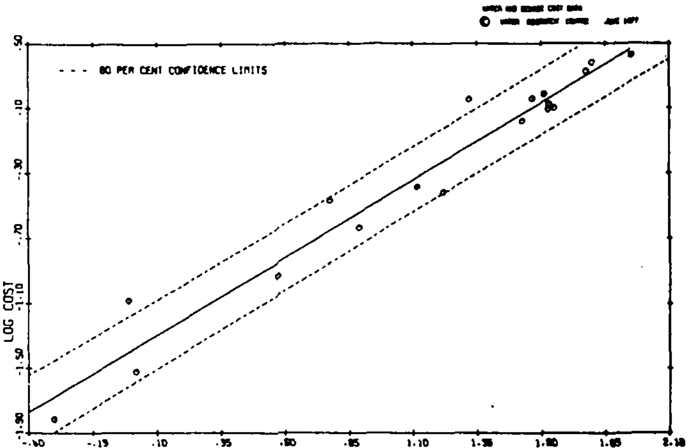
The tunnels data is listed in Table A-4.

Figure 10-11. Tunnels

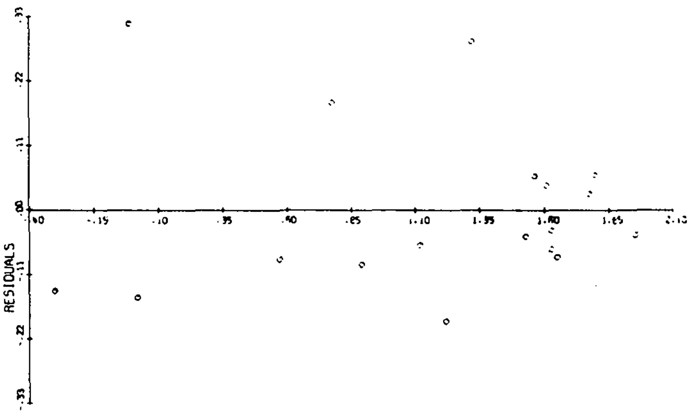


10.3. Tunnels and shafts

Figure 10-12. Tunnels

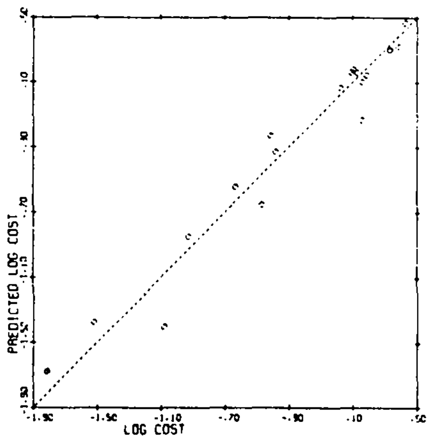


SCATTER DIAGRAM OF LOG COST
AGAINST LOG VOLUME



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG VOLUME

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - shafts

(i) Data summary

Table 10-8. Shafts data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	SHAFCOS	£'000	16.3	268	72.9	52.3
Excavated diameter of shaft	DIAM	m	3.66	11.3	5.78	2.23
Depth of shaft	DEP	m	13.7	84.1	34.2	12.7
Omnibus 4 (see Section 8.3.3)	Z4	-	13.1	144	42.2	26.8

Note:
1. Number of cases: 45.
2. The Construction Materials Index was used for deflation.
3. SHAFCOS is the shaft excavation and lining cost, and excludes shaft fittings cost.

Mini-histograms for the main variables of interest:-

SHAFCOS

LOG SHAFCOS

DEP

DIAM

(ii) The recommended cost function

The recommended function for shafts is:-

$$\boxed{\text{SHAFCOS} = 0.194*\text{DEP}^{1.05}*\text{DIAM}^{1.22}}$$

The statistical details of the function are as follows:-

Number of observations	:	45
Multiple correlation coefficient (R)	:	0.96
Coefficient of determination (R^2)	:	92%
Standard error of residuals (in $\log_{10}$ model)	:	0.080

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DEP	1.05	0.085	155	≪0.1%
DIAM	1.22	0.086	204	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.79	1.27
95%	0.69	1.45

The omnibus variable is defined as:-

$$Z4 = 0.25*\text{DIAM}*\text{DEP}^{0.86}.$$

Figures 10-13 and 10-14 show the five standard diagrams in support of the function.

(iii) The data

The shafts data is listed in Table A-5.

Figure 10-13. Shafts

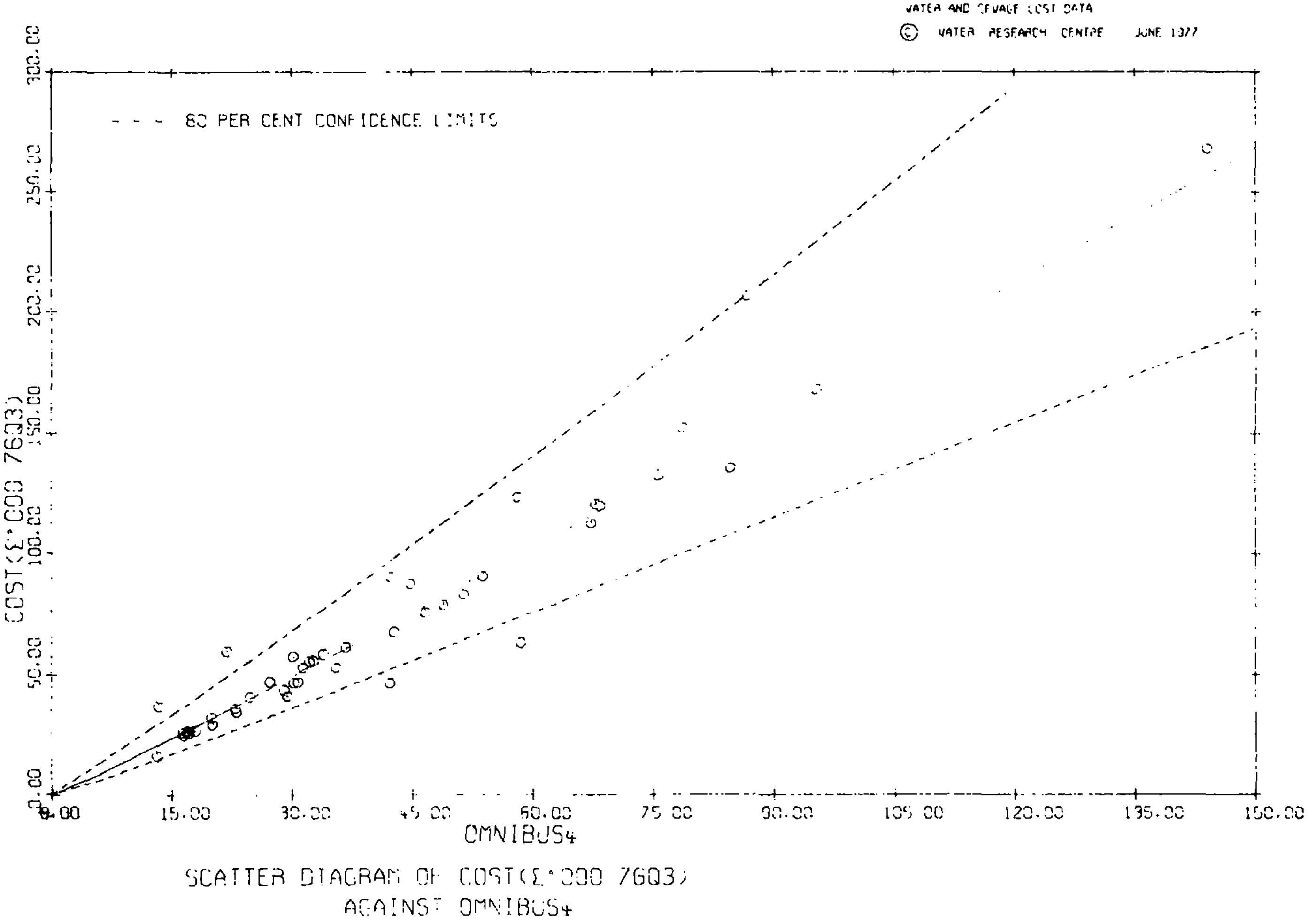
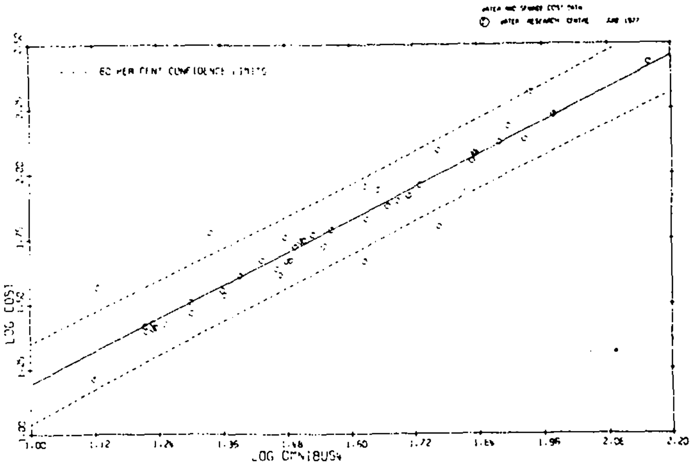
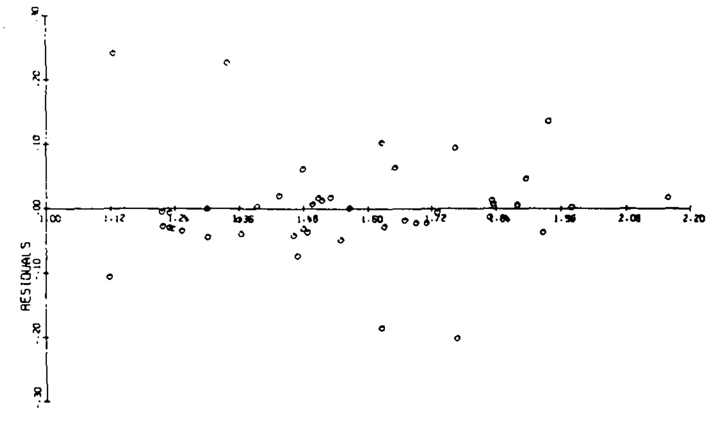


Figure 10-14. Shafts

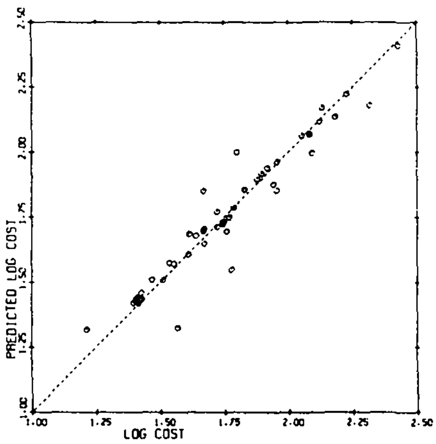


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS¥



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS¥

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

D. The results - global model

(i) Data summary

Table 10-9. Global model data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total tunnels and shafts cost (corrected to 1976 Q3)	COST	£ million	0.148	4.23	1.92	1.35
Combined excavated volume of tunnels and shafts	VOL	'000 m^3	4.75	131	54.7	40.6

Note:
1. Number of cases: 9.
2. The Construction Materials Index was used for deflation.
3. VOL is the sum of the excavated volumes of the individual tunnels and shafts making up a contract.
4. COST is the cost of the individual tunnels and shafts making up the contract (assuming wedge-blocked lining), but excluding costs of secondary lining, shafts fittings, internal pipes and general and preliminary items.

Mini-histograms for the main variables of interest:-

COST

LOG COST

VOL

(ii) The recommended cost function

The recommended function for tunnels and shafts is:-

$$\boxed{\text{COST} = 0.0265 * \text{VOL}^{1.07}}$$

The statistical details of the function are as follows:-

Number of observations : 9
Correlation coefficient (R) : 0.99
Coefficient of determination (R^2) : 97%
Standard error of residuals (in $\log_{10}$ model) : 0.083

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	1.07	0.067	257	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.76	1.31
95%	0.64	1.57

Figure 10-15 illustrates the global cost function.

It will be noticed that the coefficient of VOL is 1.07. This means that the estimated cost for a scheme with an excavated volume of 100 000 m^3 (say) is 2.10 times that for a scheme with an excavated volume of 50 000 m^3. This runs counter to the common sense view that there should be a discernible economy of scale. It is inevitable, with the purely empirical approach taken throughout this study, that anomalies of this sort occasionally arise - though in this case the function is not inconsistent with there being an economy of scale, because an 80% confidence interval about the 1.07 estimate is 0.98 to 1.16. In other words, it is quite conceivable that the true (but unknown) value of the coefficient is actually less than one. This is borne out by Figure 10-15, which shows that the curvature of the recommended function is in fact very slight. The following alternative function may therefore be used with little loss of accuracy:-

$$COST = 0.0352*VOL.$$

(iii) Other cost functions

The figure obtained by summing the individual tunnels and shafts cost estimates represents about two-thirds of the total cost of a contract (as discussed in part A), and applies only to tunnels built by the 'wedge-block' method. If bolted concrete segment linings are used the cost tends to be higher, and is higher still with cast iron segments.

A multiplying factor, LINING, has therefore been defined (as below) so that the sum of the individual tunnels and shafts cost estimates can be adjusted to provide an estimate of total contract cost. Three values of LINING have been determined from an examination of the available data, corresponding to the three different types of lining, so that the extra cost of bolted concrete or cast iron segment lining can be included in a prediction of total contract cost.

A 'composite' total contract cost model (i. e. including costs of secondary lining, shafts fittings, internal pipes and general and preliminary items) has accordingly been defined as:-

COST = LINING*(sum of individual TUNCOS and SHAFCOS estimates),

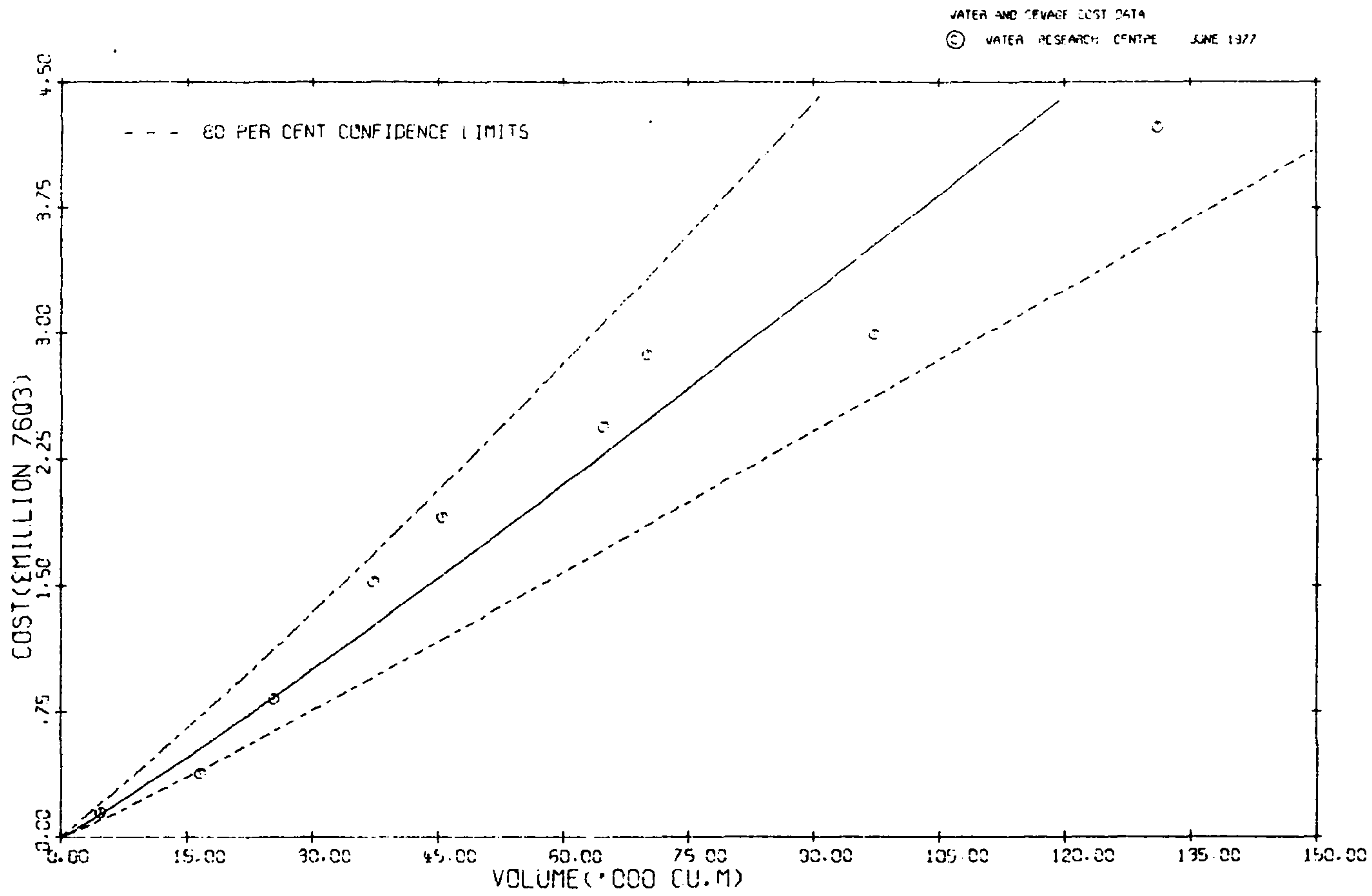
where LINING is 1.43 for wedge-block lining,
1.57 for bolted concrete segment lining,
and 2.00 for cast iron segment lining.

The factor LINING should also be used for estimation of total contract cost if using the global cost function.

(iv) The data

The tunnels and shafts data used in modelling the global function is listed in Table A-6.

Figure 10-15. Global model



SCATTER DIAGRAM OF COST(£MILLION 7603)
AGAINST VOLUME('000 CU.M)

E. Comparison of cost functions

Table 10-10 compares estimates made by the global and the composite cost functions for the nine complete contracts. All the costs presented refer to total contract costs, assuming 'wedge-block' lining; the global model cost estimate was therefore multiplied by 1.43 in each case, and a LINING value of 1.43 was similarly used in determining the composite cost model estimates.

The results demonstrate that the global model is slightly more accurate than the composite model.

Table 10-10. Comparison of the global and composite models

Contract	Number of shafts	Number of tunnels	Actual cost (£'000 1976 Q3)	Global model estimate (£'000 1976 Q3)	Composite model estimate (£'000 1976 Q3)
1	5	1	2730	2250	2500
2	2	1	2180	1820	1880
3	5	2	6050	6990	6690
4	2	3	1180	1210	1410
5	5	1	3490	3280	3390
6	7	1	4100	3580	3750
7	5	2	4270	5080	4980
8	-	1	548	764	845
9	-	2	211	201	263

F. Hard rock tunnelling

Little data is available about hard rock tunnelling for water. Road tunnels tend to be of very much greater diameter and cost details are not always relevant to water engineering requirements. Table 10-11 presents the available data for small rock tunnels; in each case sprayed concrete was used for the lining.

Table 10-11. Cost of hard rock tunnelling

Type of rock	Diameter of tunnel excavation (m)	Length (m)	Cost (£'000 1976 Q3)	Cost/unit volume (£/m^3)
Limestone	2.49	3761	3790	207
Igneous and metamorphic	2.82	1490	3800	408
Limestone	3.05	2652	3870	200
	1.25	2042	515	206

G. Additional costs

The models presented in parts B, C and D have been developed for good conditions in soft ground. In waterlogged strata, ground freezing or compressed-air working is needed. A few of the contracts considered allowed for these practices, but not enough data existed for them to be included in the models. Table 10-12 shows the rates (corrected to 1976 Q3) in those contracts in which either of these techniques was used.

Table 10-12. Rates for ground freezing and compressed air working

Contract	Working	Shaft or tunnel	Diameter (m)	Length (m)	Rate (1976 Q3)
1	Compressed air	T	3.8	2880	£224 000 + £42.64/m
2		S	5.5	17.3	£25 000 + (£110 - £315)/d†
2		S	5.5	15.2	£44 000 + (£110 - £315)/d†
2		T	4.0	203	£315/d
3	Freezing	S	5.5	31.6	£47 930 (lump sum)
3		S	5.5	32.7	£49 080
3		S	5.5	54.5	£68 170
3		S	5.5	68.2	£84 620
3		S	8.2 - 9.0	84.2	£152 400

† Depending on pressure (0 - 36 lb/sq. in.).

H. Special limitations

A number of special restrictions and provisos should be borne in mind whenever applying the cost functions presented in this section. These are discussed in (i) to (iv) below.

(i) As tunnels are high risk projects, final costs are likely to deviate much more from the tendered figures than in most other areas. This lessens the confidence with which the quoted cost functions can be used to estimate final costs.

(ii) London clay is probably the most favourable soft ground tunnelling medium. This has biased the data sample, and the quoted functions will probably under-estimate the influence of poor ground conditions (which may not necessarily require compressed air, freezing or injection). The effect of ground conditions is covered to some extent by the lining factor, but the functions are basically reliable only in the London clay type of soil conditions.

(iii) The data sample for tunnels in clay covered only a limited range of diameters, and within this range diameter was not a significant factor. However, for smaller diameters the problems of mucking and access to excavation at the face would be expected to influence cost, and at higher diameters difficult ground conditions would pose proportionally greater problems. The cost function should not be used, therefore, outside the diameter range spanned by the data.

(iv) Although a volume-based model is presented for tunnels in clay, this could be misleading when applied to, say, a large diameter tunnel of very short length, when there would be a high proportion of mobilization costs.

10.4. PUMPS AND PUMPING

10.4.1. PUMPING PLANT

A. General modelling approach

The costs of pumping plant have been examined for three main applications:-

(i) water pumping for surface water abstraction, long and short distance transfer, treated water distribution and supply boosting;

(ii) borehole pumping for single and multiple installations and schemes;

(iii) sewage pumping for individual pumping stations and for pumping stations within treatment works.

The three applications were modelled separately as there are distinct technical differences between them. The modelling approach was similar in each case, with installed capacity, operating head, number of pumps installed and the installed power being examined as explanatory variables for installation cost. The functions have been developed and presented with the view that, at broad planning levels, installed capacity for the operating and the standby pumps and the operating head will be the only physical dimensions known. Cost functions based on head as well as capacity give substantial improvements, as cost is strongly related to both these variables; they are preferable to functions based on installed power as pump efficiency has to be estimated, and head and capacity known, before power can be calculated.

For both water and sewage pumping, definitions of capacity and power relate to the combined operating and standby pumping plant installed. Thus the user should first determine the required operating plant, and then decide upon and allow for the appropriate standby plant. Capacity and power for the total plant are then used with the appropriate cost functions to estimate costs.

B. The results - water pumping

(i) Detailed modelling approach

Data was collected mainly from tender documents relating to individual pumping or boosting stations, and pumping stations situated on treatment works or reservoir sites. Also, the TP 60 (2) raw data was re-examined.

Total installation cost of pumping plant, total installed capacity, operating head, total number of pumps installed (each inclusive of standby pumps) and total installed power of motors were obtained for 20 cases from the newly collected data. Cost includes cost of installing the motors, pumps and switchgear, but excludes the cost of the building, which is considered in Sections 10.4.3 and 14.1. The Engineering and Allied Industries Index was chosen for deflation of costs.

When cost was related to power only, the function for the new data was found to be very similar to that for the TP 60 data. However, functions based on the other variables were substantially different for the two data sets. The reason for this is that for the new data, 'capacity' is defined as the maximum installed capacity, and 'head' is defined as the maximum operating head, whereas the TP 60 data refers to 'normal capacity' and 'normal operating head'. (In both cases, capacity includes standby as well as operating capacity.) Normal capacity and normal head are probably more appropriate for use in planning than maximum capacity and head. Furthermore, the cost function based on normal capacity and head (for the TP 60 data only) was the one with the better predictive ability. This has therefore been presented as the recommended function for water pumping.

As the definition of 'total installed power' is the same for both data samples, and as the functions relating cost to power only were very similar for both samples, a cost function based only on power was developed using the combined sample and is also presented.

A function relating power to capacity and head was developed for each data sample. The relationship obtained from the TP 60 data in terms of normal capacity and normal head is:-

$$\text{POWER} = 0.0091*\text{NORMCAP}^{0.95}*\text{NORMHEAD}^{0.90}.$$

Correlation coefficient (R) : 0.98

Standard error of residuals (in $\log_{10}$ model) : 0.127

The corresponding relationship obtained from the new data sample in terms of maximum capacity and maximum head is:-

$$\text{POWER} = 0.0136*\text{MAXCAP}^{0.85}*\text{MAXHEAD}^{0.94}.$$

Correlation coefficient (R) : 0.98

Standard error of residuals (in $\log_{10}$ model) : 0.125

In the above equations, POWER is the total installed power (kW),

NORMCAP and MAXCAP are measured in m^3/h,

and NORMHEAD and MAXHEAD are measured in m.

In comparison, the installed power required to pump water at a certain flowrate (capacity) through a particular head can be calculated from the following equation, derived from the definition of installed power of a pump:-

$$\underset{(\text{kW})}{\text{POWER}} = 0.00272*\underset{(m^3/h)}{\text{Capacity}}*\underset{(m)}{\text{Head}}/\underset{(\text{proportion})}{\text{Efficiency}}.$$

This equation was used to estimate the efficiency of each pumping station represented in the data samples; the calculations were based upon maximum capacities and heads for the new data and normal capacities and heads for the TP 60 data. For relatively simple pumping installations, involving discharge at one head or approximately the same head for multiple systems, the average power efficiency was about 64% for both data samples, though the distributions about this average were substantially different. Some of the calculated power efficiencies were apparently far too small or far too large; these referred to multiple pumping installations where various capacities are pumped through different heads. The definition of power given above is not valid for such cases. For example, an installation with a large part of the capacity being pumped through the lowest head will result in an apparently high efficiency if the maximum operating head is used in calculating it. Further work is needed to examine and resolve the problems associated with definitions of power, capacity and head.

(ii) Data summary

Table 10-13 summarizes the data from both the TP 60 and the new data samples (45 observations in all). Details of maximum capacity and maximum head of pumping plant are given for the new data only; details of normal capacity and normal head are given for the TP 60 data only.

10.4.1. Pumping plant

Table 10-13. Water pumping data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Combined data sample (45 cases)						
Total cost of installation (corrected to 1976 Q3)	COST	£'000	2.49	836	98.2	170
Total installed power	POWER	kW	15	6270	840	1470
New data sample (20 cases)						
Total cost of installation (corrected to 1976 Q3)	-	£'000	5.79	836	132	236
Maximum total installed capacity	MAXCAP	m^3/h	82	30 300	3860	7170
Maximum operating head	MAXHEAD	m	13.1	175	99.0	36.0
Total number of pumps installed	-	-	2	8	3.75	2.00
TP 60 data sample (25 cases)						
Total cost of installation (corrected to 1976 Q3)	WATCOS	£'000	2.49	390	71.5	83.7
Normal total installed capacity	NORMCAP	m^3/h	36	16 100	2790	3790
Normal operating head	NORMHEAD	m	13.7	181	68.0	44.6
Total number of pumps installed	NPUMP	-	1	10	3.52	2.14
Omnibus 10 (see Section 8.3.3)	Z10	-	28.9	18 300	2520	3780

Note: The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-

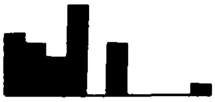
WATCOS

LOG WATCOS

NORMCAP

NORMHEAD

POWER



NPUMP

(iii) The recommended cost function

The recommended function for water pumping is:-

$$\boxed{WATCOS = 0.0229*NORMCAP^{0.81}*NORMHEAD^{0.43}}$$

The statistical details of the function are as follows:-

Number of observations	:	25
Multiple correlation coefficient (R)	:	0.93
Coefficient of determination (R^2)	:	87%
Standard error of residuals (in $\log_{10}$ model)	:	0.216

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
NORMCAP	0.806	0.066	148	≪0.1%
NORMHEAD	0.425	0.149	8.16	< 1.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.52	1.93
95%	0.36	2.80

The omnibus variable is defined as:-

$$Z10 = 0.108*NORMCAP*NORMHEAD^{0.53}.$$

Figures 10-16 and 10-17 show the five standard diagrams in support of the function.

(iv) Other cost functions

There may be occasions when, in the first instance, the operating head is not known by the planner. The following function is then appropriate:-

$$\boxed{\text{WATCOS} = 0.160*\text{NORMCAP}^{0.77}}$$

The statistical details of the function are as follows:-

Number of observations	:	25
Correlation coefficient (R)	:	0.91
80% confidence interval multipliers	:	0.47, 2.12
Standard error of residuals (in $\log_{10}$ model)	:	0.248

A cost function which is less useful, because it is based on power, is given below. It has lower predictive accuracy than the functions presented above because of the need to estimate pumping efficiency before power can be calculated. However, this relationship is based on both the TP 60 and the new data and therefore represents a wider range of conditions.

$$\boxed{\text{COST} = 0.447*\text{POWER}^{0.80}}$$

The statistical details of the function are as follows:-

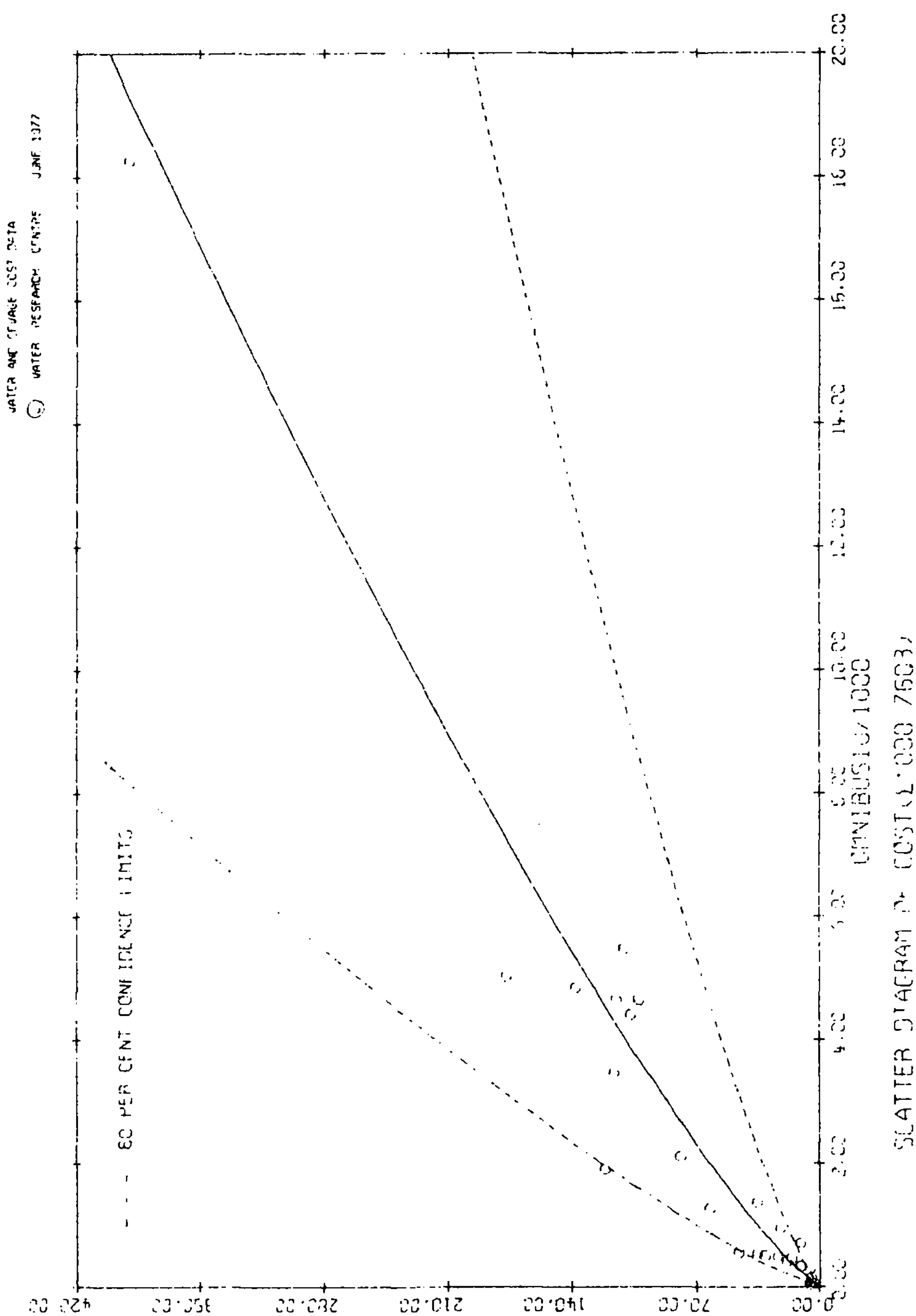
Number of observations	:	45
Correlation coefficient (R)	:	0.90
80% confidence interval multipliers	:	0.46, 2.16
Standard error of residuals (in $\log_{10}$ model)	:	0.257

(v) The data

The TP 60 data used in modelling water pumping costs is listed in Table A-7.

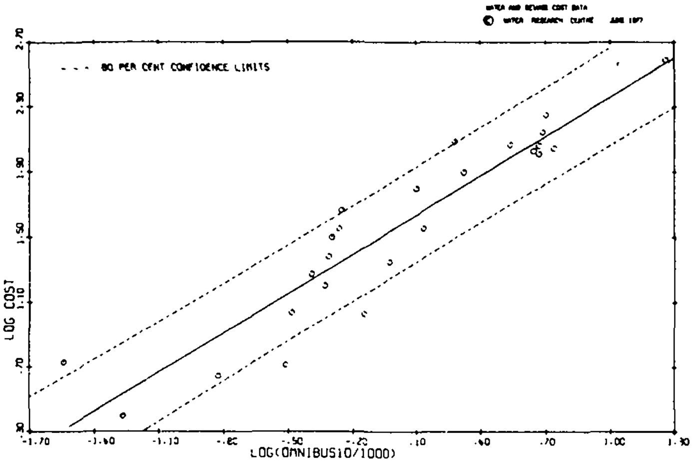
10.4.1. Pumping plant

Figure 10-16. Water pumping

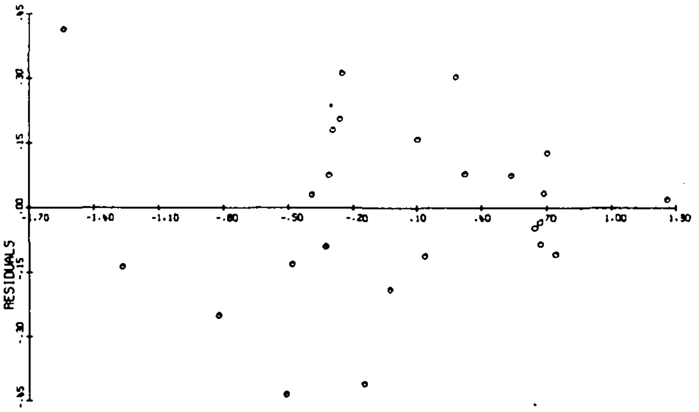


10.4.1. Pumping plant

Figure 10-17. Water pumping

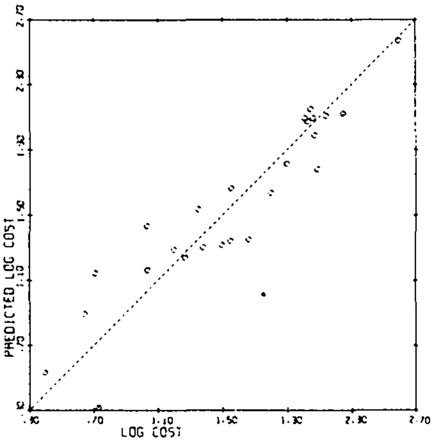


SCATTER DIAGRAM OF LOG COST
AGAINST LOG(OMNIBUS10/1000)



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG(OMNIBUS10/1000)

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - borehole pumping

(i) Detailed modelling approach

The data for borehole pumping came from two sources. Firstly, data was obtained for 17 cases of single and multiple borehole pump installations from the TP 60 questionnaires. Secondly, details of 38 individual pump installations within a recent large borehole scheme were available.

The tender cost of pumping plant installation, the number of pumps and the installed power of the motors were obtained for each of the 55 cases. Cost included the cost of installing pumps complete with motors, rising mains, cables and starters. The Engineering and Allied Industries Index was chosen for deflation of costs.

The borehole yield, on which normal operating capacity was based, and the normal operating head were also available for the TP 60 sample alone, whereas designed normal operating capacity and designed operating head were available for just the new data sample.

The explanatory variable most highly correlated with cost was installed power for each data set. Two separate functions were therefore developed relating cost to installed power only. At first sight these suggested that the data samples were incompatible. However, the considerable difference between the functions was mainly due to the multiple pump installations of the TP 60 sample being consistently more expensive than single pump schemes with the same installed power. When number of pumps was introduced into the TP 60 cost function as a second explanatory variable, the scatter was substantially reduced and the power coefficient came into close agreement with that in the single pumps model. This indicated that the two sets of costs were compatible after all. The data samples were therefore combined and functions based on power alone, and power together with number of pumps, were obtained. The spread of data about the second of these models tended to be greater for the TP 60 data than for the new data; this is probably because the new data all originates from the same scheme.

As the required power has to be calculated from the capacity, the head and an estimate of the pump efficiency, efforts were made to obtain a cost function based on capacity and head. The TP 60 data was not combined with the new data to develop such a function because there was uncertainty over the relationship between the yield, as quoted by TP 60, and capacity. This was borne out by the considerable differences between the cost functions in terms of capacity and head based on the TP 60 and the new data samples. However, as the function based on power and the number of pumps indicates that the costs for the new data sample are typical, the function based on the new data alone with designed capacity and head as explanatory variables has been recommended. It is interesting to note the marked similarity between this function and the recommended function for water pumping (see part B).

As the new data is limited in its range of application the following points should be noted when using the recommended function. Firstly, because the new data is derived from one contract the scatter of the data about the cost function is probably less than can generally be expected; the quoted multipliers for confidence intervals about a prediction should therefore be used with some caution. Secondly, the function is based solely on single pump installations and is therefore strictly valid only for individual pumps.

If, for a particular application, the ranges of the explanatory variables used for the recommended function are not appropriate, one of the other quoted functions, based on installed power, should be used.

(ii) Data summary

Table 10-14 summarizes the data from both the TP 60 and the new data samples (55 observations in all). Details of capacity and head are given for the new data only (38 observations).

Table 10-14. Borehole pumping data summary

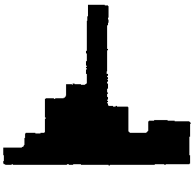
Variable	Label	Unit	Min.	Max.	Mean	St. dev.
New data sample (38 cases)						
Total cost of installation (corrected to 1976 Q3)	BORECOS	£'000	4.22	13.5	7.80	2.46
Designed capacity of pumps	DESCAP	m^3/h	208	417	282	96.9
Designed operating head	DESHEAD	m	14.7	146	75.8	32.7
Installed power	POWER	kW	25.0	149	86.3	34.7
Omnibus 11 (see Section 8.3.3)	Z11	-	107	460	262	91.0
TP 60 data sample (17 cases)						
Total cost of installation (corrected to 1976 Q3)	-	£'000	2.10	86.4	22.0	24.0
Installed power	POWER	kW	15.0	425	153	156
Number of pumps installed	NPUMP	-	1	4	1.94	1.03

Note: 1. The Engineering and Allied Industries Index was used to deflate costs.

2. The recommended function is based solely on single pump installations and is therefore strictly valid only for individual pumps.

Mini-histograms for the main variables of interest:-

BORECOS



LOG BORECOS

DESHEAD

10.4.1. Pumping plant

(iii) The recommended cost function

The recommended function for borehole pumping is:-

$$\boxed{\text{BORECOS} = 0.0135 * \text{DESCAP}^{0.79} * \text{DESHEAD}^{0.46}}$$

The statistical details of the function are as follows:-

Number of observations	:	38
Multiple correlation coefficient (R)	:	0.92
Coefficient of determination (R^2)	:	84%
Standard error of residuals (in $\log_{10}$ model)	:	0.053

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DESCAP	0.787	0.070	127	≪0.1%
DESHEAD	0.457	0.039	140	≪0,1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.85	1.17
95%	0.78	1.28

Note: All the cases used in developing the recommended function are from the same contract; the quoted multipliers for confidence limits should therefore be used with caution.

The omnibus variable is defined as:-

$$Z11 = 0.0812*DESCAP*DESHEAD^{0.58}.$$

Figures 10-18 and 10-19 show the five standard diagrams in support of the function.

(iv) Other cost functions

The TP 60 and the new data sets were combined to produce functions based on power and the number of pumps. These have a wider range of applicability but require the estimation of installed power. The functions are:-

$$\boxed{BORECOS = 0.806*POWER^{0.52}*NPUMP^{0.86}}$$

The statistical details of the function are as follows:-

Number of observations	:	55
Multiple correlation coefficient (R)	:	0.93
80% confidence interval multipliers	:	0.73, 1.38
Standard error of residuals (in $\log_{10}$ model)	:	0.107

$$\boxed{BORECOS = 0.428*POWER^{0.70}}$$

The statistical details of the function are as follows:-

Number of observations	:	55
Correlation coefficient (R)	:	0.82
80% confidence interval multipliers	:	0.61, 1.64
Standard error of residuals (in $\log_{10}$ model)	:	0.166

The first of these two models has substantially the better predictive ability, as is borne out by the statistical details.

(v) The data

The data used in modelling borehole pumping is listed in Table A-8.

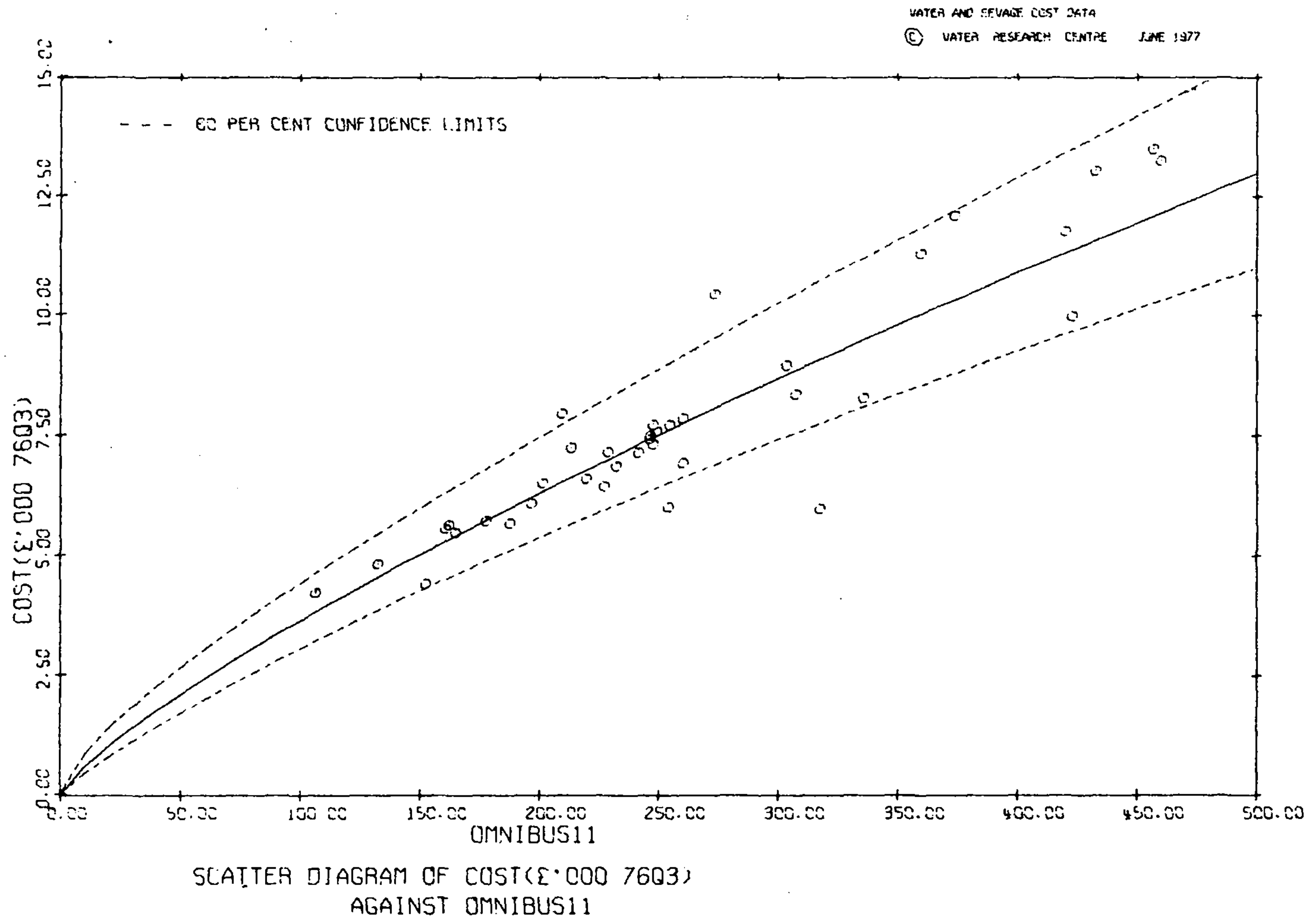
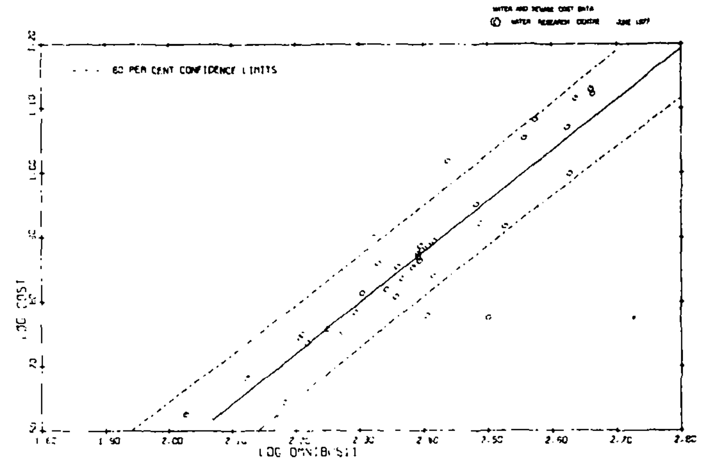


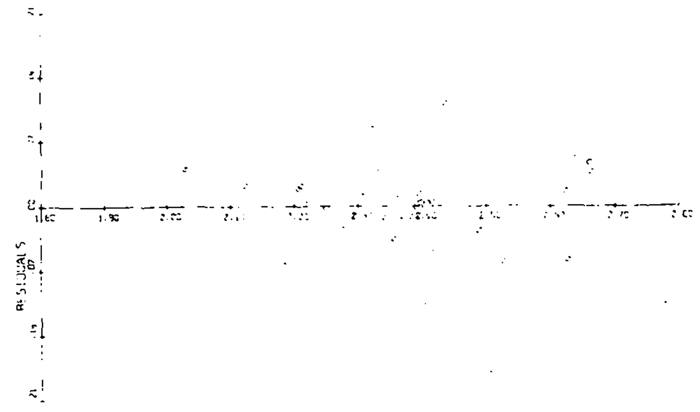
Figure 10-18. Borehole pumping

10.4.1. Pumping plant

Figure 10-19. Borehole pumping

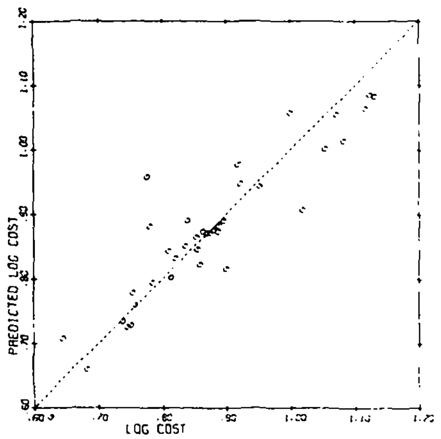


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS11



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS11

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

D. The results - sewage pumping

(i) Detailed modelling approach

Data was collected from tender documents for individual pumping stations, for those forming part of sewerage schemes, and for inlet and main lift pumping stations included in the construction of sewage treatment works. In the majority of cases the civil engineering and building works formed part of a main contract, with the supply and installation of mechanical and electrical plant being subject to separate nominated sub-contracts.

When assembling the cost data, nominated sub-contract costs and their percentage additions were deducted from the total tender sums, this being carried out before the costs of preliminary items, general items and dayworks were distributed over the remaining items.

Similarly, cost data was assembled for the supply and installation of the mechanical and electrical plant, with suitable adjustments being made, where required, for general costs. Where appropriate the costs were further adjusted to allow for the main contractor's additional costs or profits as detailed in the tender documents.

No allowance was made for additional costs such as design, supervision, permanent reinstatement as carried out by the highway authority, compensation, easement, land acquisition, or any public utility or other cost not featured in the tender document but paid directly by the client.

The physical dimensions of the pumping station structures were normally determined from contract drawings. The design characteristics were compiled from the specifications included in the tender documents relating to the mechanical and electrical plant. In many cases it was necessary to differentiate between those characteristics concerned with the final design capacity of the pumping station (e.g. the structure) and those concerned with the initial installed capacity (e.g. the plant). These details were assembled as follows:-

(i) contract identification number;
(ii) pumping station identification number;
(iii) use and location of pumping station;
(iv) volume of substructure (m^3);
(v) volume of superstructure (m^3);

(vi)	total floor area (m^2);	
(vii)	total head (m) (static head and friction losses but excluding station losses);	
(viii)	total installed power (kW)	based on rated power of motors, and including standby motor sets;
(ix)	total design power (kW)	
(x)	total installed capacity (l/s)	based on rated duty of pumps, and including standby sets;
(xi)	total design capacity (l/s)	
(xii)	provision of additional facilities (i.e. intake or generators);	
(xiii)	initial number of pumps installed	including standby pumps.
(xiv)	final number of pumps to be installed	

Because of the common practice of installing pumping plant in phases it was necessary to develop two cost functions. The first function covered the cost of the structure or building housing the plant. For consistency, this has been dealt with in Section 14.3 along with the other models for buildings. The second function covered the cost of the plant. For this a function was sought relating cost to installed capacity, total head, installed power and number of pumps. Experience elsewhere indicated that the most suitable index for deflation was likely to be the Engineering and Allied Industries Index. Subsequent testing confirmed this choice as being suitable. Installed power was not considered to be very suitable for planning use, as numerous assumptions would be required in its derivation. Consequently a cost function was developed by suppressing the power term during the regression analysis. This resulted in a model expressing cost in terms of capacity, head and number of pumps.

10.4.1. Pumping plant

(ii) Data summary

Table 10-15. Sewage pumping data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	SEWCOS	£'000	2.74	96.0	25.0	25.0
Total installed capacity	CAP	l/s	1	1350	196	339
Total head	HEAD	m	1.5	60.9	18.4	12.7
Number of pumps installed	NPUMP	-	1	7	2.43	1.20
Total installed power	POWER	kW	2	354	55.8	70.0
Omnibus 12 (see Section 8.3.3)	Z12	-	0.0109	675	65.1	140

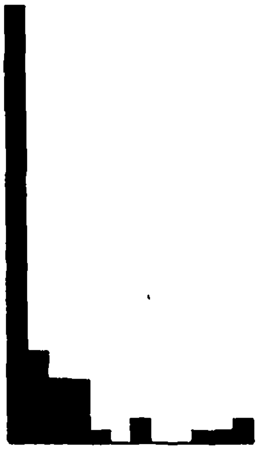
Note: 1. Number of cases: 58.

2. The Engineering and Allied Industries Index was used for deflation.

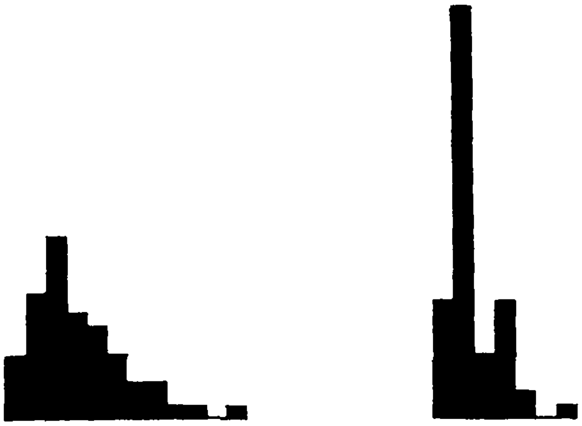
Mini-histograms for the main variables of interest:-

SEWCOS

LOG SEWCOS



CAP



(iii) The recommended cost function

The recommended function for sewage pumping is:-

$$\boxed{SEWCOS = 1.63*CAP^{0.29}*HEAD^{0.19}*NPUMP^{0.89}}$$

The statistical details of the function are as follows:-

Number of observations	:	58
Multiple correlation coefficient (R)	:	0.91
Coefficient of determination (R^2)	:	82%
Standard error of residuals (in $\log_{10}$ model)	:	0.174

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.286	0.038	56.3	≪0.1%
HEAD	0.186	0.073	6.56	< 2.5%
NPUMP	0.891	0.148	36.3	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.59	1.68
95%	0.45	2.23

10.4.1. Pumping plant

The omnibus variable is given by:-

$$Z12 = 0.000983*CAP*HEAD^{0.65}*NPUMP^{3.12}.$$

Figures 10-20 and 10-21 show the five standard diagrams in support of the function.

(iv) Other cost functions

The following function relates cost to total installed power alone:-

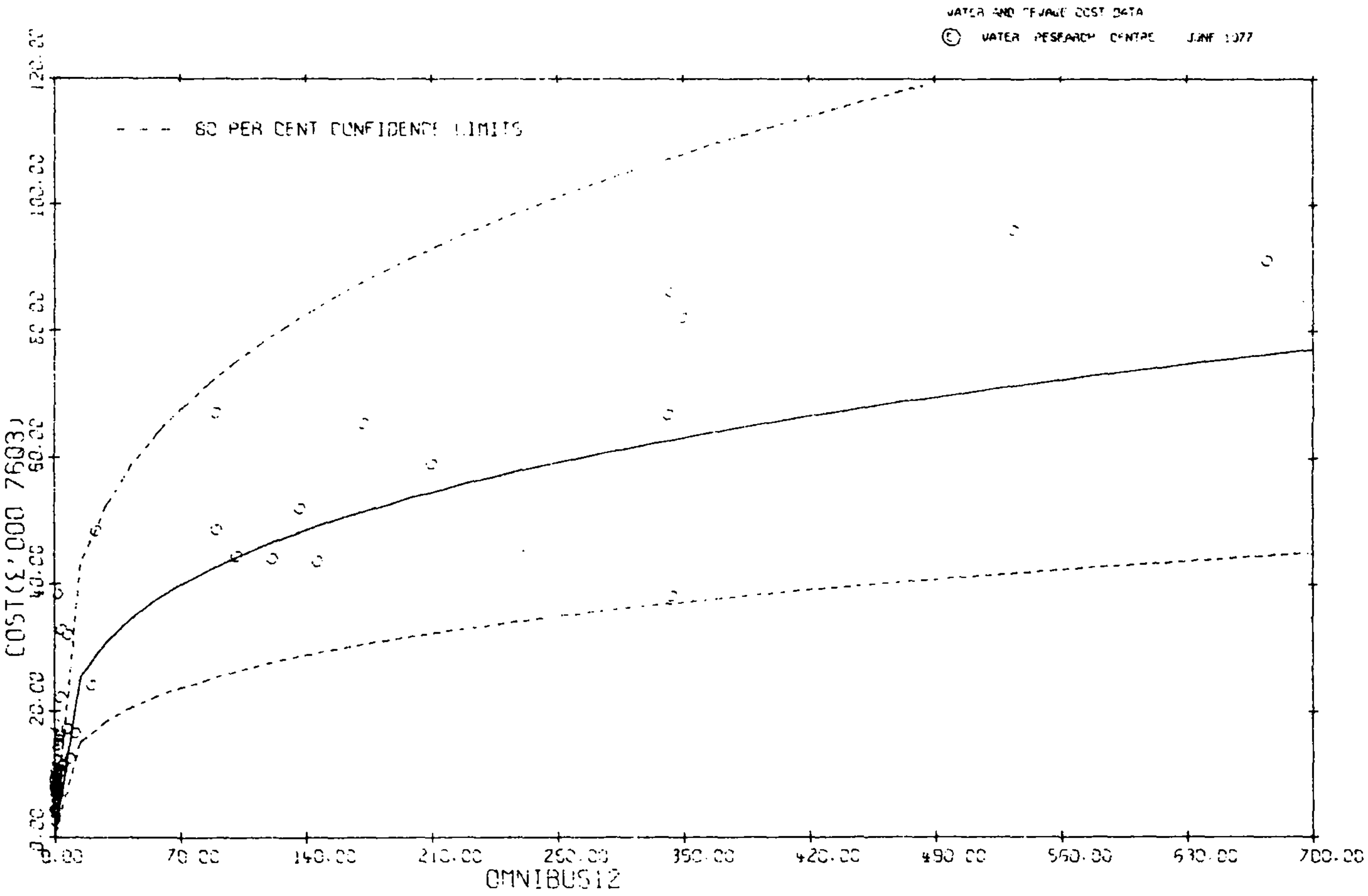
$$\boxed{SEWCOS = 1.79*POWER^{0.66}}$$

The statistical details of the function are as follows:-

Number of observations	:	58
Correlation coefficient (R)	:	0.87
80% confidence interval multipliers	:	0.56, 1.80
Standard error of residuals (in $\log_{10}$ model)	:	0.197

(v) The data

The sewage pumping data is listed in Table A-9.

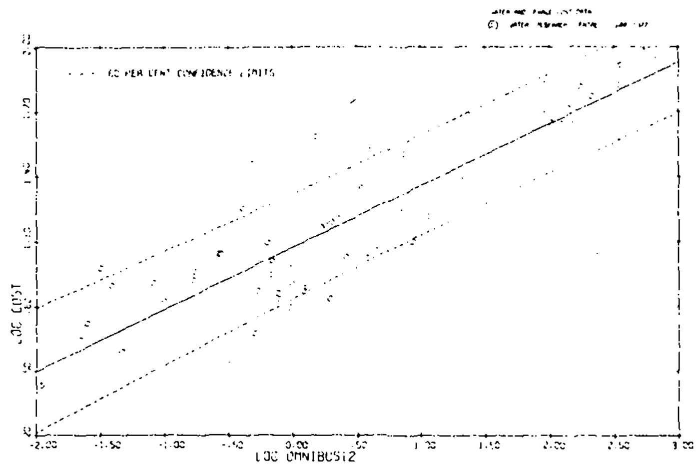


SCATTER DIAGRAM OF COST(£'000 7603)
AGAINST OMNIBUS12

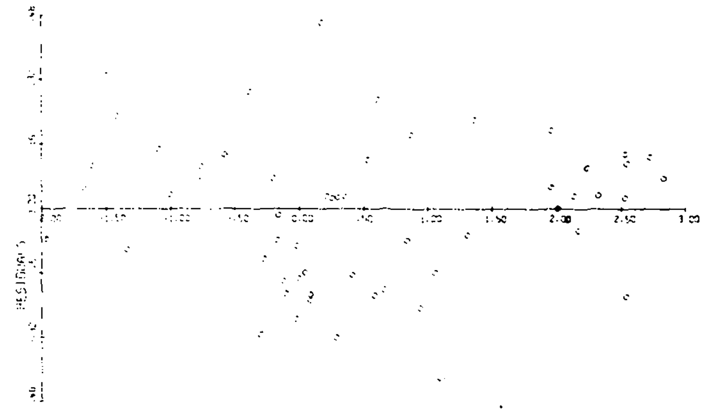
Figure 10-20. Sewage pumping

10.4.1. Pumping plant

Figure 10-21. Sewage pumping

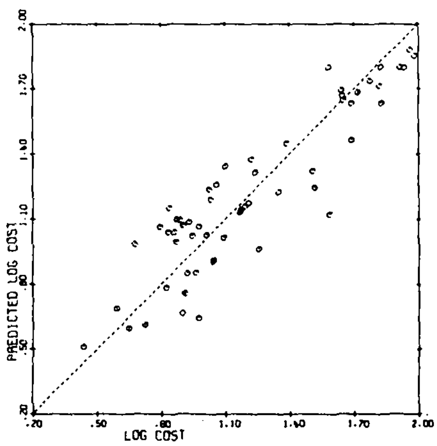


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS12



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS12

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

10.4.2. BUILDINGS AND INTAKES

A. The modelling approach

Data was collected from BoQs and associated documents. A wide variety of intake schemes were represented. From these, six basic components could be identified:-

(i) bankside intake structure;
(ii) interconnecting channels, tunnel or pipeline;
(iii) screening plant;
(iv) pumping plant;
(v) river diversion and/or weir;
(vi) pumphouse and/or screenhouse.

A study of the various intake designs showed that there were four common arrangements of these basic components, as follows:-

Type I: A bankside intake low profile structure that is connected to a pumphouse by an intake aqueduct. The lengths of intake aqueducts vary considerably. Screening plant is situated in the pumphouse.

Type II: A bankside intake house that contains the screening plant and associated switchgear. The intake house is connected to a combined low and high lift pumphouse by a long aqueduct.

Type III: As Type I but with a short connecting aqueduct (or none at all) and constructed in association with weirs, river diversions and other river works.

Type IV: A bankside pumphouse that contains the screening plant and the intake in addition to the pumps.

It was considered that the simplest approach would be to regard each type of intake as a development of a pumphouse, and to express the additional costs as a percentage of the basic pumphouse cost. The total cost estimate would thus be built up as follows:-

(i) decide on the arrangement of the basic components;
(ii) estimate the cost of the pumphouse or screenhouse (Section 14.1);

(iii) estimate the additional cost, if any, of the bankside intake structure and other river works from B following; where necessary allow for river diversions;

(iv) estimate the cost of screening plant (Section 12.2.2);

(v) estimate the cost of pumping plant (Section 10.4.1);

(vi) estimate the cost of the tunnel (Section 10.3) or pipeline (Section 10.2);

(vii) sum all the component cost estimates.

The cost function given in Section 14.1 for water pumphouses requires no additional allowance for housing screening plant or bankside construction. The cost of a screenhouse without pumping plant can still be estimated from the functions relating pumphouse costs to throughput, if no better estimate is available.

The additional costs for intake Types I and II are of similar size, and appear to be independent of scheme size. For intakes of Type III, costs are strongly dependent on the size, number and intricacy of weirs required, and also the need for any river diversion work.

B. Additional costs of pumphouses as intakes

Type I: Examples of the cost of the low profile bankside intake structure, as a percentage of the associated pumphouse cost, are summarized as follows:-

Design abstraction capacity ('000 m^3/d)	27.3	27.3	91	180	182	205	295
Additional cost (%)	36.7	29.8	17.2	25.7	19.3	10.7	39.6

Type II: Examples of the cost of bankside intake houses to contain screening plant and associated switchgear, as a percentage of the associated combined low and high lift pumphouse cost, are summarized as follows:-

Design abstraction capacity ('000 m^3/d)	28.6	182	450
Additional cost (%)	19.8	16.6	26.8

Type III: Examples of the cost of weirs but excluding river diversions constructed in association with bankside pumphouses, as a percentage of the pumphouse cost, are summarized as follows:-

Design abstraction capacity ('000 m^3/d)	45.5	95.5	205
Works included	Combined weir and intake	Weir and intake channel	Two Crump weirs and intake
Additional cost (%)	89.3	47.3	39.3

10.4.3. DIESEL ALTERNATORS

A. The modelling approach

Security of power supply at water supply and sewage disposal works is usually arranged by providing a dual supply from the electricity grid or by providing a standby diesel-alternator system. Costs of dual supplies from the grid will depend very much on the geographical circumstances. Costs of dual fuel systems as might be used for sewage works are also not known.

Raw data was collected from tender BoQs and associated contract documents. Costs were taken at date of tender with no adjustment made for type of contract. Total installed cost was used, as it was not in general possible to distinguish between the cost of supplying the power unit and the cost of installation together with associated equipment. The cost of cranes is not included in total cost, nor is allowance made for any building necessary for housing the plant (see Chapter 14). The Engineering and Allied Industries, Mechanical Engineering and Electrical Engineering Indices were examined; of these, the Engineering and Allied Industries Index was the most suitable for correcting costs.

Total installed cost was found to be strongly related to the power capacity of the generating plant. The number of units installed was another significant explanatory variable. A tendency was noticed for there to be a jump in cost at about 2000 kVA. This might in part be due to a change to a more expensive construction specification and to the provision of more sophisticated ancillary equipment.

From a sample of five diesel generator installations, a linear relationship was established between floor area of the generator hall (AREA) and design capacity (DESCAP). This is as follows:-

$$\underset{(m^2)}{\text{AREA}} = 67 * \underset{(\text{'000 kVA})}{\text{DESCAP}} .$$

B. The results

(i) Data summary

Table 10-16. Diesel alternator data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	8.86	618	182	195
Total installed power	POWER	'000 kVA	0.0710	8.37	1.45	2.05
Number of units	NUNIT	-	1	3	1.50	0.730
Omnibus 9 (see Section 8.3.3)	Z9	-	0.049	6.45	1.47	1.94

Note:
1. Number of cases: 16.
2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST

LOG COST

POWER

NUNIT

(ii) The recommended cost function

The recommended function for diesel alternators is:-

$$\boxed{\text{COST} = 93.9 * \text{POWER}^{0.90} * \text{NUNIT}^{0.83}}$$

The statistical details of the function are as follows:-

Number of observations	:	16
Multiple correlation coefficient (R)	:	0.94
Coefficient of determination (R^2)	:	89%
Standard error of residuals (in $\log_{10}$ model)	:	0.207

10.4.3. Diesel alternators

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
POWER	0.898	0.102	77.7	$\ll 0.1\%$
NUNIT	0.832	0.293	8.07	$< 2.5\%$

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.53	1.90
95%	0.36	2.80

The omnibus variable is defined as follows:-

$$Z9 = 0.687 * POWER * NUNIT^{0.93}.$$

Figure 10-22 illustrates the recommended function.

(iii) Other cost functions

An alternative cost function for use at the broadest planning level where the number of units installed is too detailed a variable, is as follows:-

$$\boxed{COST = 124 * POWER^{0.97}}$$

The statistical details of the function are as follows:-

Number of observations : 16
Correlation coefficient (R) : 0.91
80% confidence interval multipliers : 0.46, 2.19
Standard error of residuals (in $\log_{10}$ model) : 0.253

(iv) The data

The diesel alternator data is listed in Table A-10.

10.4.3. Diesel alternators

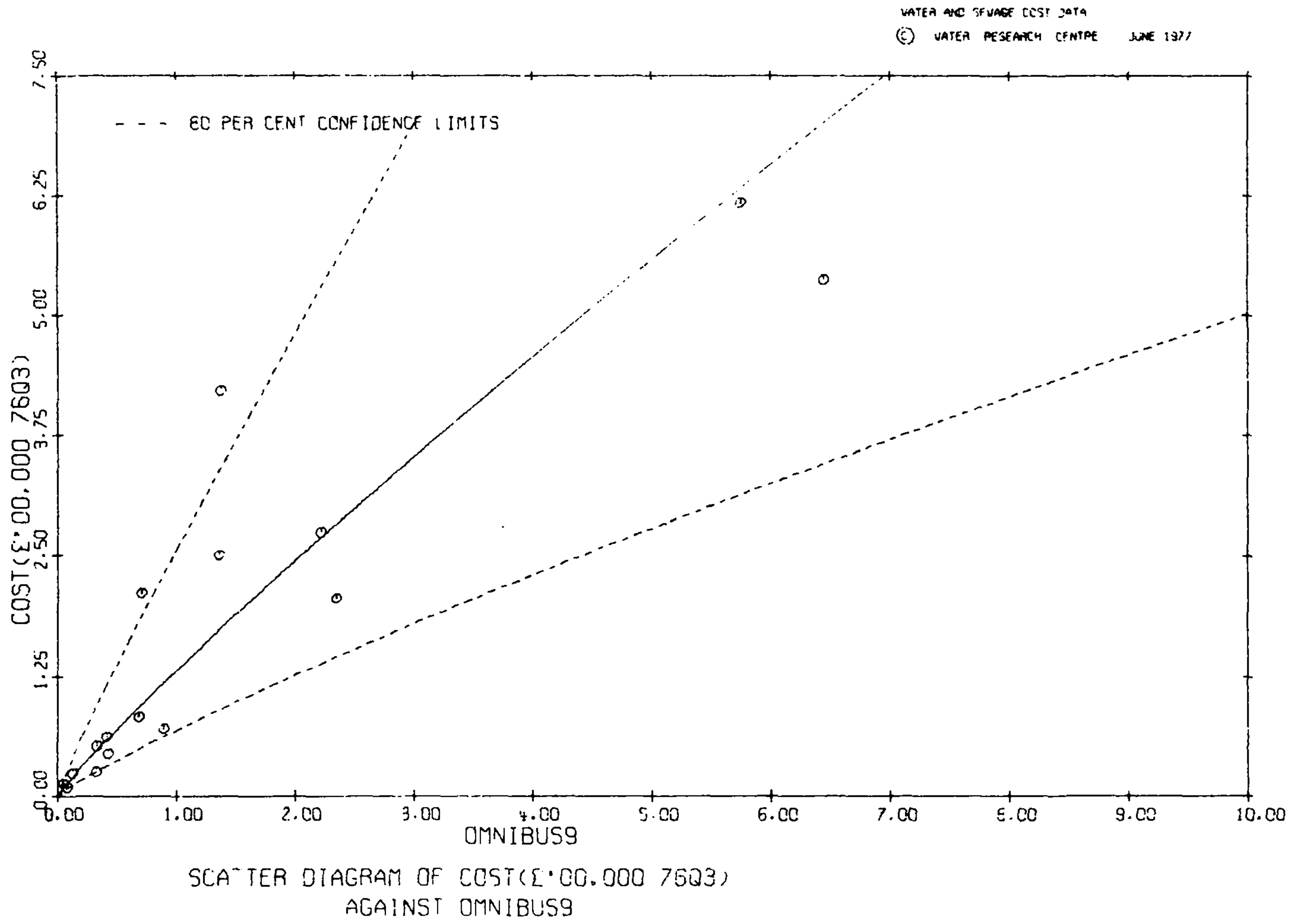


Figure 10-22. Diesel alternators

10.4.4. OPERATING COSTS

The operating cost of pumping water is affected by three main factors:-

(i) the unit cost of power;
(ii) the rate and pressure of water pumping; and
(iii) the pumping efficiency.

The unit cost of power varies with the locality. Given a particular tariff, the engineers can arrange the pumping programme and purchase of grid electricity to give minimum cost operation. Similarly the engineers will exercise some control over the quantity and pressure of pumping. Operating cost is therefore dependent both on plant design and on the operations engineer.

The little information that was collected on water pumping operation indicated that efficiency is not always as high as expected, ranging from about 40 to 80% - although installed power was usually around 70 to 80% (see also Section 10.4.1). The lower actual efficiencies are presumably due to pumping loads lying outside the optimum range of the pump and/or motor. These might therefore tend to be found with small installations based on only one or two operational pumps required for varying pumping loads.

No information was available concerning the labour and maintenance cost of pumping water.

11. RESOURCE WORKS

11.1. GROUNDWATER DEVELOPMENT

11.1.1. SINGLE BOREHOLES

A. The modelling approach

The major aquifers used for public water supplies in the UK are the Chalk and Triassic sandstones. Other minor aquifers such as the Lower Greensand, Upper Carboniferous sandstones, Magnesian Limestone and Lower Jurassic sandstones are also used in certain areas. Of the data collected in this study, 95% was from boreholes in the two major aquifers and the Lower Greensand and the remainder from boreholes in the Magnesian Limestone. However, as the cost models have been developed on the constructional features of the boreholes and not solely on rock type, it is possible to use these models for the prediction of costs in most of the minor aquifers.

It must be emphasized that the models have been developed on a data sample from UK public water supply boreholes, and cannot be used for predicting the costs of boreholes lying outside the range covered by the sample. In particular, the reader should ascertain the limitations on depth and diameter for each model by referring to the data summary preceding that model. The data sample contained no boreholes in the hard sandstones such as the Millstone Grit series. As these are very hard rocks to drill, the models shown here should not be used to estimate costs of boreholes in those rock types.

Data for the single borehole cost study was collected, where possible, from final priced bills; otherwise tender BoQs were used. The data covered the period from 1963 to 1976. Effort was concentrated on producing a model of 'construction cost', i. e. the cost of setting up, drilling, casing, screening and packing a borehole. Costs for acidization and test-pumping, and any other costs not directly related to the construction of the borehole, were therefore subtracted from the contract prices before the cost model was developed. These costs are treated as additional items, since they are not directly related to the physical dimensions of the borehole. Other additional items are the installation of a pump with associated cable, starter and rising main, and the construction of a chamber or kiosk to protect any instrumentation which may be required. Costs of laying water mains and construction of buildings to house larger equipment, e. g. chlorination, are dealt with in Sections 10. 2 and 14. 1 respectively. Information on the costs of all these additional items and on some of the smaller items of instrumentation are dealt with in Section 11.1.1D. The costs associated with land acquisition and provision of electricity have not been included.

During the modelling work five indices were examined: the Average Earnings Index, the Construction Materials Index, the New Construction Index, the Mechanical Engineering Index, and the Steel Output Index.

Boreholes were primarily divided into two types based on their method of construction:-

(i) Type 1: boreholes requiring no screen or pack, e. g. Chalk and most Bunter Sandstone holes; and

(ii) Type 2: boreholes in unconsolidated formations which require screen and a pack, e. g. the Lower Greensand formations.

In some areas the Bunter Sandstone may be quite friable, and a screen and pack may be required before the borehole can be put into supply. In such a case the borehole should be treated as a Type 2 borehole. Occasionally a Chalk borehole may also require support to prevent collapse, and this is most often done with slotted mild steel casing. In such a case the borehole should still be treated basically as Type 1, but the extra cost of the screen should be calculated from the screen cost model presented in Section 11.1.1E(v).

The construction details of each borehole were summarized by total depth, diameter, and the length of permanent steel casing required to screen out any overburden or unproductive sections of the aquifer. Diameter was defined as the diameter over the greatest length of the borehole, or, in cases where the drilled diameter was different for comparable lengths, a weighted average diameter. For Type 2 boreholes the drilled diameter of the borehole was always used. For Type 1 boreholes the drilled diameter was used where available, but if the diameter of the casing was the only known dimension this was used instead. Information on depth, diameter and length of casing was available for both types of borehole. Further information on screen length, diameter and type of material of screen was summarized for Type 2 boreholes only.

Initially, effort was concentrated on developing a global cost function relating cost to depth, diameter, casing length and borehole type. The resulting global model demonstrated the obvious dependence of the costs on borehole type. Separate models for each type of borehole were therefore constructed, thus allowing the coefficients for the variables depth, diameter and casing length to vary between types if necessary. This approach also enabled the variables for screen length, diameter and material to be considered in the Type 2 boreholes model.

A statistical comparison of the residuals about the Type 1 and Type 2 models with the residuals from the original global model showed that the two sub-models had achieved a reduction in residual scatter which was significant at the 1% level. They were therefore chosen in preference to the global model, and are presented in detail in Sections 11.1.1B and C. However, the Type 2 model does not incorporate a diameter variable because of the limited diameter range in the original data. The original global model is therefore presented as a supplementary function for estimating costs of Type 2 boreholes over 0.8 m drilled diameter.

Attempts were made to improve on these models by producing separate sub-models for the various elements of a drilling contract, namely setting-up costs, drilling costs, casing costs, grouting costs, screen costs and pack costs. The original sub-costs were first extracted from the BoQs, and models were then developed from this data using the same range of explanatory variables as for the Type 1 and Type 2 models.

Of these sub-models, the one with the greatest standard error (i.e. the one with the greatest residual scatter) was the 'setting-up costs' model. Setting-up costs varied from 8 to 45% of the total construction cost of a contract and could not be satisfactorily explained by any of the variables considered. Discussion with contractors has shown that these costs are a function of a number of factors, including:-

(i) depth and diameter of borehole - this decides the size of drilling rig required;

(ii) rock type - this may determine

  (a) the type of drilling rig, i.e. percussion or the more expensive rotary;

  (b) whether temporary casing is required over great lengths; and

  (c) the frequency of renewal of drill bits;

(iii) distance from the contractor's office - this determines the transport costs;

(iv) the presence of a sufficient water supply for the drilling method being used (for example, the reverse rotary method requires an emergency standby supply of 1500 m^3/d, which may have to be bought from the Water Authority and transported by a temporary pipeline from the nearest suitable water main);

(v) ease of access to site - a temporary access road may have to be constructed to the site.

However, this information was not always available, nor could it easily be quantified. There is the further difficulty that this is the item in the BoQ where a contractor will tend to 'load' a contract, and as such it is frequently more a reflection of the state of the market, or a particular contractor's work load and preference, than a function of the contract itself.

The removal of the setting-up costs from the total construction costs enabled more accurate Types 1 and 2 models to be produced. However, the problem then remains of having to estimate the very variable setting-up component. For the purposes of the sub-model approach a model for setting-up costs as a function of depth, diameter and length of casing was adopted. However, the confidence limits on this model are very wide.

The sub-models for all the elements of a drilling contract are presented in Section 11.1.1E. They are presented in less detail as the standard errors of all except the screen costs model are greater than those for either the Type 1 or Type 2 model. Comparison of the residuals of the sub-models with those of the previous models shows that there is no statistical advantage in proceeding to the lower hierarchy of models. However, the greater detail of the sub-modelling approach allows for more flexibility in estimation of the total cost when coupled with the experience of the user.

The reader may find it helpful to refer at this point to Figure 11-1, which illustrates the complete hierarchy of borehole models discussed above. The models are presented under the following headings:-

B. The results - Type 1 global model.

C. The results - Type 2 global model.†

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† The supplementary Type 2 model is presented also under this heading.

D. Additional costs:-

(i) acidization;
(ii) test-pumping;
(iii) pump and accessories;
(iv) headworks.

E. Other cost functions:-

(i) setting-up costs;
(ii) drilling costs;
(iii) casing costs;
(iv) grout costs;
(v) screen costs;
(vi) pack costs.

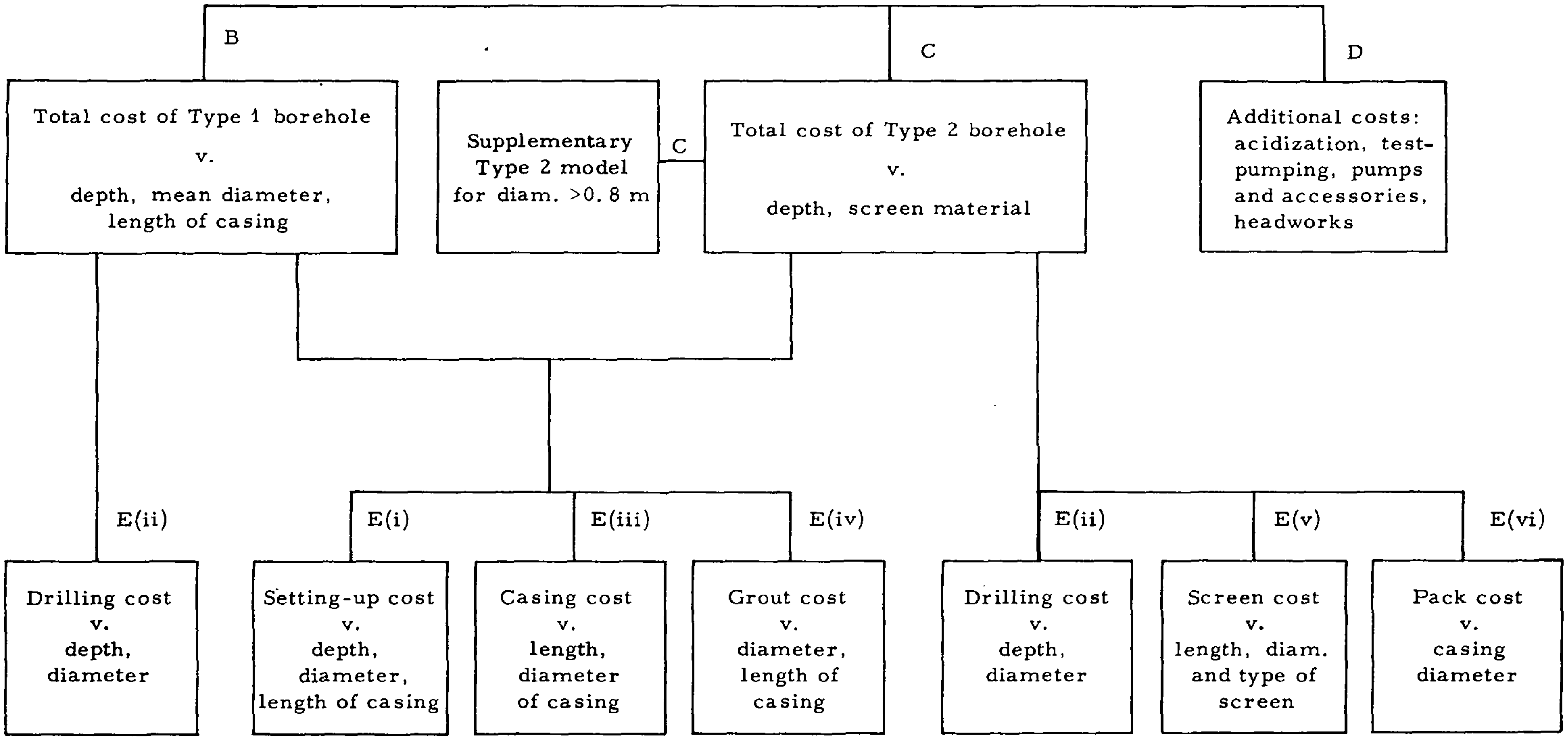


Figure 11-1. The single borehole models hierarchy

B. The results - Type 1 global model

(i) Data summary

Table 11-1. Type 1 borehole data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total construction cost (corrected to 1976 Q3)	COST	£'000	5.18	24.3	13.3	5.05
Borehole depth	DEP	m	51.8	241	126	46.1
Borehole diameter	DIAM	m	0.300	1.00	0.616	0.164
Casing length	CASLEN	m	7.62	82.3	32.5	20.2
Omnibus 6 (see Section 8.3.3)	Z6	-	13.3	307	132	72.0

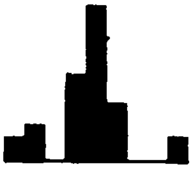
Note:
1. Number of cases: 30.
2. The Average Earnings Index was used for deflation.
3. COST is defined as the total cost of setting-up, drilling, casing, and grouting a borehole.

Mini-histograms for the main variables of interest:-

COST

LOG COST

DEP



DIAM

CASLEN

(ii) The recommended cost function

The recommended function for Type 1 boreholes is:-

$$\boxed{\text{COST} = 0.851 * \text{DEP}^{0.49} * \text{DIAM}^{0.64} * \text{CASLEN}^{0.21}}$$

11.1.1. Single boreholes

Statistical details of the function are as follows:-

Number of observations : 30
Multiple correlation coefficient (R) : 0.88
Coefficient of determination (R^2) : 77%
Standard error of residuals (in $\log_{10}$ model) : 0.086

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DEP	0.485	0.112	18.9	<0.1%
DIAM	0.645	0.135	22.9	<0.1%
CASLEN	0.212	0.069	9.44	<1.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.77	1.30
95%	0.67	1.50

The omnibus variable is defined as:-

$$Z6 = 0.437*DEP*DIAM^{1.33}*CASLEN^{0.44}.$$

Figures 11-2 and 11-3 show the five standard diagrams in support of the function.

(iii) The data

The Type 1 borehole data is listed in Table A-11.

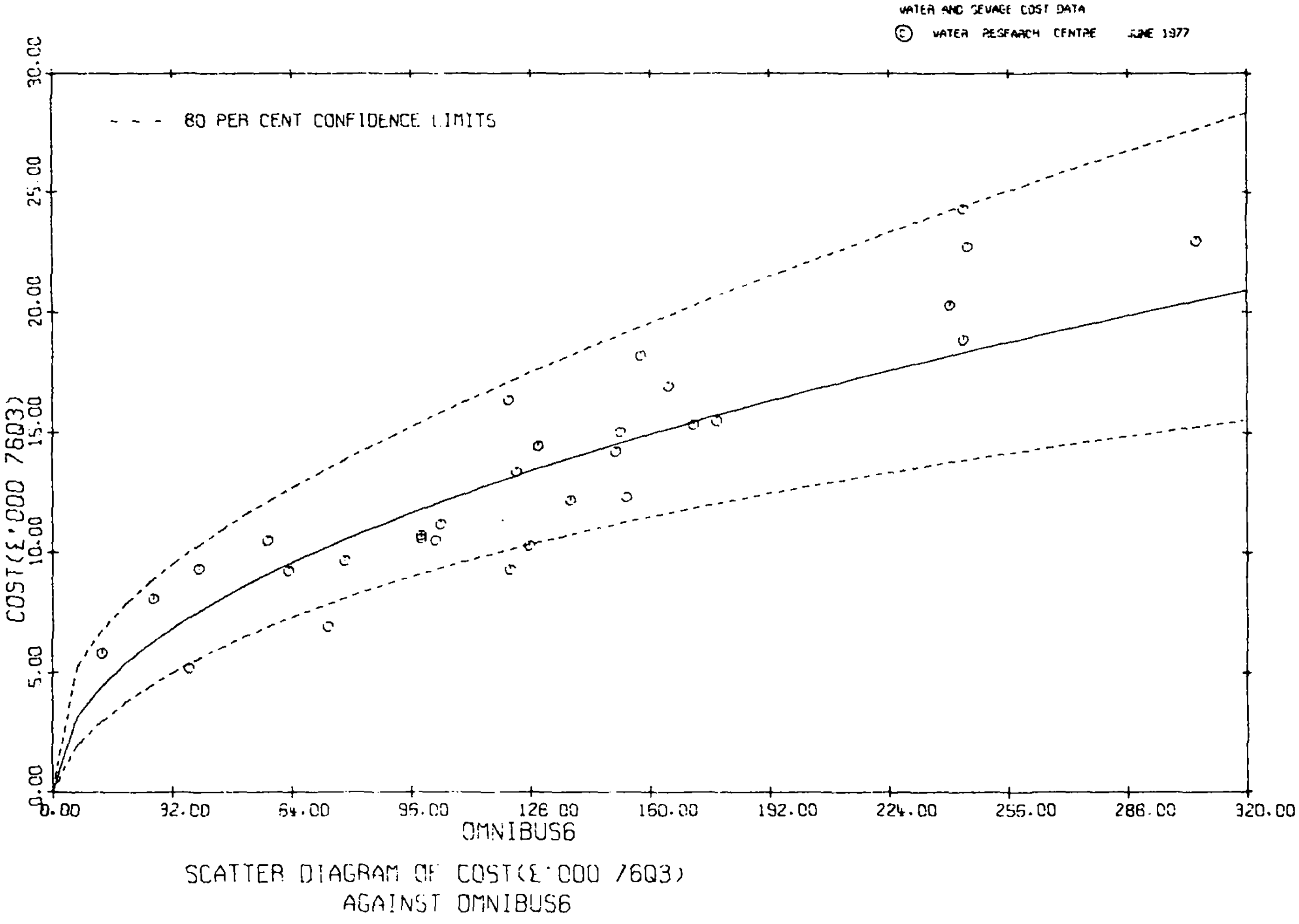
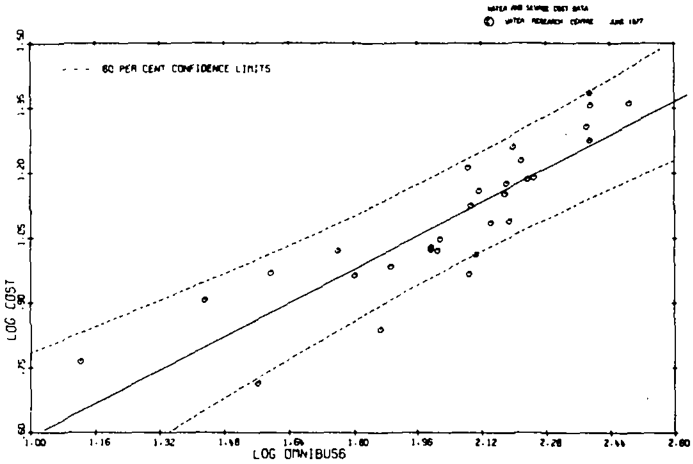


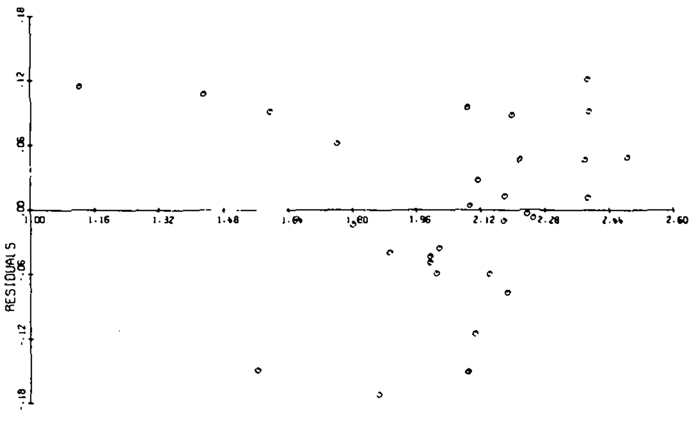
Figure 11-2. Type 1 boreholes

11.1.1. Single boreholes

Figure 11-3. Type 1 boreholes

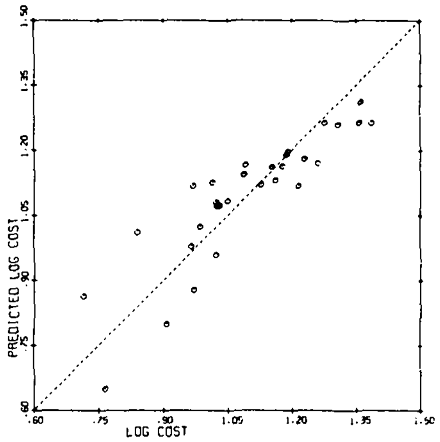


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS6



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS6

HISTOGRAM OF RESIDUALS
11-5



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - Type 2 global model

(i) Detailed modelling approach

The model developed from the 29 Type 2 boreholes data is of a simpler form, incorporating only two explanatory variables - depth and screen type. Diameter was inhibited from appearing in the model because of the limited range of diameter values in the sample. Table 11-2 indicates that Type 2 borehole diameters range from 0.46 to 0.91 m. The corresponding mini-histogram shows that the majority of diameters fall in a much narrower range - indeed, all but five cases lie between 0.57 and 0.80 m. This variation proved to be too small to allow the effect of diameter on cost to be estimated statistically. The recommended function is consequently valid only over the limited diameter range spanned by the data, and should be used with caution outside the range 0.5 to 0.8 m.

It had also been expected that screen length would have a significant effect on the costs of these boreholes, but this factor could not be isolated because of its high correlation with depth. However, screen type was found to be important.

As steel for casing and screen accounts for a large proportion of the costs of Type 2 boreholes, the Steel Output Index was used to update the costs for this model; this was shown to reflect the cost variations through time more accurately than the Average Earnings Index.

For estimating the cost of larger diameter Type 2 boreholes, an alternative cost function has been developed by pooling the Type 1 and Type 2 data and distinguishing between types by a '1-2' explanatory variable. This function is less reliable because it makes the assumption that the proportional effect of diameter on cost is the same for both borehole types. This assumption is thought to be reasonable for larger but not for smaller diameters. The alternative function may therefore be used for estimating Type 2 costs in the higher diameter range, but should not be used for diameters falling below the range covered by the main Type 2 model.

11.1.1. Single boreholes

(ii) Data summary

Table 11-2. Type 2 borehole data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total cost (corrected to 1976 Q3)	COST	£'000	16.7	45.4	26.9	7.01
Borehole depth	DEP	m	35.4	137	77.1	25.2
Screen type	SCRTYP	-	1	2	1.28	0.455
Casing length	CASLEN	m	7.62	76.8	28.9	20.4
Borehole diameter	DIAM	m	0.460	0.910	0.703	0.108
Omnibus 7 (see Section 8.3.3)	Z7	-	35.4	133	67.8	24.2

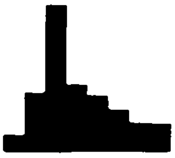
Note:

1. Number of cases: 29.
2. The Steel Output Index was used for deflation.
3. SCRTYP is 1 for a screen made of stainless steel or rubber-coated steel with a pre-formed pack, and
   2 for a mild steel slotted screen.
4. COST is defined as the total cost of setting-up, drilling, casing, grouting, screening and packing the borehole.
5. The diameter of Type 2 boreholes is taken as the drilled diameter, not the screen diameter.
6. This model is only strictly valid in the diameter range 0.5 to 0.8 m.

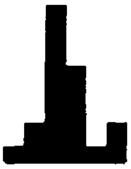
Mini-histograms for the main variables of interest:-

COST

LOG COST



DEP



DIAM

(iii) The recommended cost function

The recommended function for Type 2 boreholes of drilled diameter between 0.5 and 0.8 m is:-

$$\boxed{COST = 1.94*DEP^{0.62}*SCRTYP^{-0.44}}$$

For those boreholes with stainless steel or rubber-coated steel, the cost function simplifies to:-

$$\boxed{COST = 1.94*DEP^{0.62}}$$

Where the screen used is slotted mild steel casing the equation becomes:-

$$\boxed{COST = 1.43*DEP^{0.62}}$$

The statistical details of the cost function are as follows:-

Number of observations	:	29
Multiple correlation coefficient (R)	:	0.81
Coefficient of determination (R^2)	:	65%
Standard error of residuals (in $\log_{10}$) model	:	0.066

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DEP	0.625	0.097	41.2	≪0.1%
SCRTYP	-0.436	0.096	20.7	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.82	1.22
95%	0.73	1.37

11.1.1. Single boreholes

The omnibus variable is defined as:-

$$Z7 = DEP*SCRTYP^{-0.70}.$$

Figures 11-4 and 11-5 show the five standard diagrams in support of the function.

(iv) The data

The Type 2 borehole data is listed in Table A-12.

(v) Supplementary Type 2 function

The function to be used for estimating the cost of Type 2 boreholes with drilled diameter greater than 0.8 m is:-

$$\boxed{COST = 3.00*DEP^{0.42}*DIAM^{0.62}*CASLEN^{0.14}}$$

where COST is the construction cost (£'000 1976 Q3) deflated using the Average Earnings Index,

DEP is the borehole depth (m),

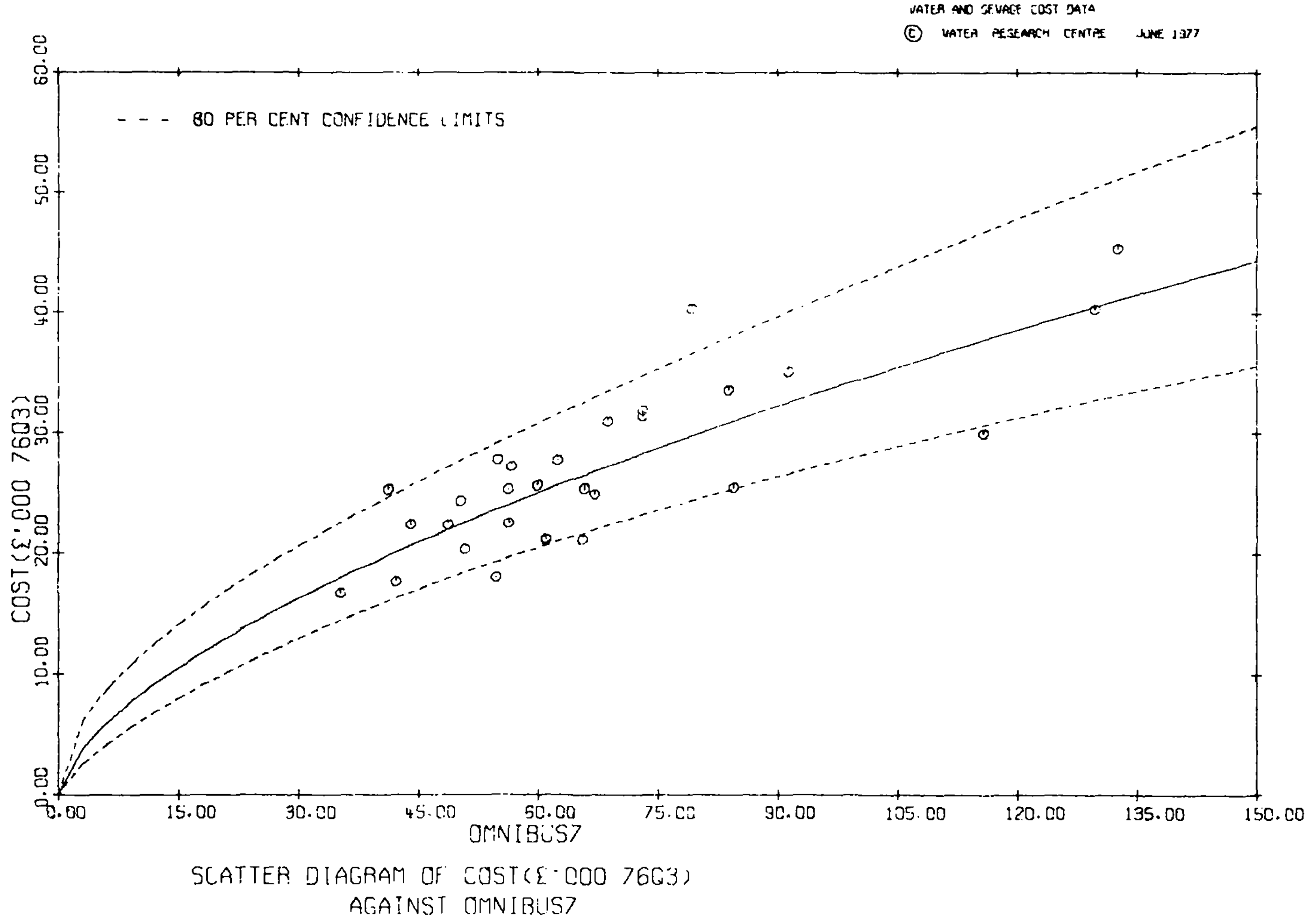
DIAM is the drilled diameter (m),

and CASLEN is the length of casing (m).

The function was developed using all the Type 1 and Type 2 borehole data summarized in Tables 11-1 and 11-2. Thus, borehole depth ranged between 35.4 and 241 m, casing length ranged between 7.62 and 82.3 m, and the maximum drilled diameter represented was 1.00 m. The statistical details of the function are as follows:-

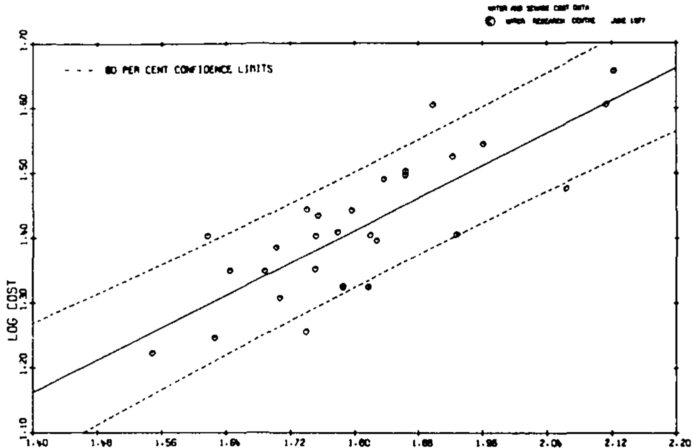
Number of observations	:	59
Multiple correlation coefficient (R)	:	0.90
80% confidence interval multipliers	:	0.78, 1.29
Standard error of residuals (in $\log_{10}$ model)	:	0.085

Figure 11-4. Type 2 boreholes

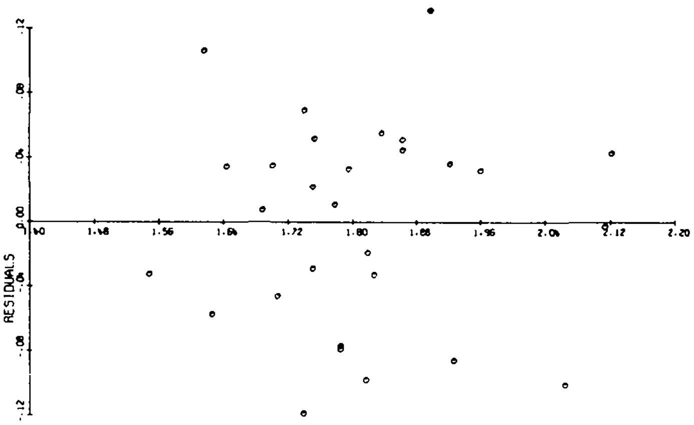


11.1.1. Single boreholes

Figure 11-5. Type 2 boreholes

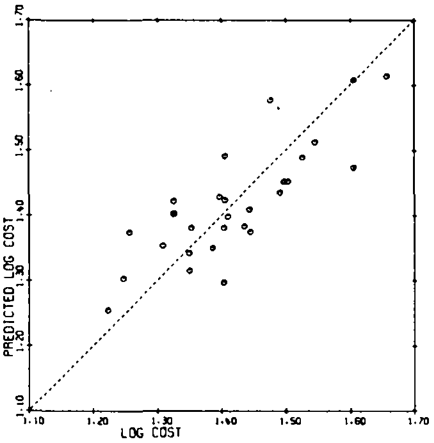


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS7



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS7

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

D. Additional costs

The additional costs associated with any supply borehole are as follows:-

(i) development (only acidization is considered here);
(ii) test-pumping;
(iii) installation of pumps and associated equipment;
(iv) construction of headworks chambers and small building to house starter and instrumentation.

All the costs given in the following discussion refer to 1976 Q3.

Cost functions have been developed on data extracted from the BoQs for acidization and test-pumping. The cost of installation of borehole pumps is considered in Section 10.4.1C. Three models are presented there, with cost as a function respectively of:-

(a) operating head and designed pump capacity;
(b) installed power of the installation; and
(c) installed power and the number of pumps being installed.

For pump installations with a capacity less than 200 m^3/h one of the last two models should be used.

A small sample of BoQs for headworks chambers and buildings was collected. Owing to the great variety in styles of construction it is only practicable to present here what is considered to be a reasonable mean cost for a standard construction. Users of this report will perhaps have a better idea of the costs of headworks designed to suit their own requirements.

The available functions for additional costs are discussed in (i) to (iv) below.

11.1.1. Single boreholes

(i) Acidization

The cost of acidization has been related to the amount of acid used as follows:-

$$\boxed{\text{ACIDIZATION COST (£)} = 91.0(\text{TONNES OF ACID})^{0.97}}$$

The Average Earnings Index was used for deflation.

The statistical details of the model are:-

Number of observations	:	29
Correlation coefficient (R)	:	0.88
80% confidence interval multipliers	:	0.76, 1.31
Standard error of residuals (in $\log_{10}$ model)	:	0.089

(ii) Test-pumping

A relationship has been established between costs of test-pumping and number of hours of the test, as follows:-

$$\boxed{\text{TEST PUMP COST (£)} = 137*\text{HOURS}^{0.66}}$$

Again, the Average Earnings Index was used for deflation.

The statistical details of the model are:-

Number of observations	:	53
Correlation coefficient (R)	:	0.86
80% confidence interval multipliers	:	0.58, 1.72
Standard error of residuals (in $\log_{10}$ model)	:	0.181

The average length of test-pumping for a supply borehole is two weeks (336 hours). An average cost for this length of test would be approximately £6000. The costs for test-pumping assume that the contractor supplies all the equipment and supervision necessary. However, the costs make no allowance for the great lengths of temporary pipeline which may be required in some sites, and do not allow for extra supervision which may be necessary if a multi-stage test is undertaken. As a guide to the cost of temporary pipelines, data was collected from 32 pumping tests in a limited area. The costs ranged from £1.70 to £5 per metre, shorter lengths having a greater unit cost.

(iii) Pump and accessories

It is not possible to relate the cost of a pump to the physical characteristics of a borehole, e.g. depth or diameter. Each pump is specifically chosen for each borehole, and the type of pump will depend on the yield of the borehole, the operating head, the duty required and several other factors. Borehole pump costs are considered in detail in Section 10.4.1C. For planning purposes where details of the yield of a borehole and the operating head are not known, an average cost of £8000 seems to be a reasonable estimate of the cost of installation of a pump.

(iv) Headworks

There was not sufficient data available to develop a model of cost against size of construction. The following costs are an estimate of the construction costs of a head chamber and small control building, and should only be used for broad planning purposes.

Cost of head chamber (approx. 40 m^3) = £1500 to £2500

Cost of control building (approx. 60 m^3) = £4500

11.1.1. Single boreholes

E. Other cost functions

The following sub-models for costs related to the various elements of a drilling contract were produced to allow greater detail in the modelling approach. However, in all cases except for screen costs the scatter of the residuals about the models is greater than in either of the borehole Type 1 and Type 2 models. These models will therefore only be of practical value when coupled with the experience of the engineer. Again, they all refer to 1976 Q3.

(i) Setting-up costs

The Average Earnings Index was used for deflation. The following model was obtained:-

$$\boxed{\text{SETTUPCOS (£)} = 28\,000*\text{DEP}^{-0.59}*\text{DIAM}^{1.09}*\text{CASLEN}^{0.25}}$$

Number of observations : 59

Multiple correlation coefficient (R) : 0.65

80% confidence interval multipliers : 0.56, 1.79

Standard error of residuals (in $\log_{10}$ model) : 0.195

(ii) Drilling costs

Two cost functions, one for each borehole type, were developed for the drilling costs. In each case the Average Earnings Index was used for deflation.

Type 1 borehole:

$$\boxed{\text{DRILCOS (£)} = 86*\text{DEP}^{0.93}*\text{DIAM}^{0.60}}$$

Number of observations : 30

Multiple correlation coefficient (R) : 0.83

80% confidence interval multipliers : 0.70, 1.43

Standard error of residuals (in $\log_{10}$ model) : 0.119

Type 2 borehole:

$$\boxed{\text{DRILCOS (£)} = 61*\text{DEP}^{1.03}}$$

Number of observations	:	29
Correlation coefficient (R)	:	0.78
80% confidence interval multipliers	:	0.71, 1.40
Standard error of residuals (in $\log_{10}$ model)	:	0.112

(iii) Casing costs

The model for casing costs incorporates both material and installation costs. There was no significant difference between the casing costs for Type 1 and Type 2 boreholes and so one cost function was developed from all the data, namely:-

$$\boxed{\text{CASCOS (£)} = 330*\text{CASLEN}^{0.83}*\text{CASDIAM}^{0.62}}$$

Number of observations	:	59
Multiple correlation coefficient (R)	:	0.85
80% confidence interval multipliers	:	0.65, 1.55
Standard error of residuals (in $\log_{10}$ model)	:	0.146

Note: 1. CASDIAM is the diameter of the casing, weighted for length (m).

2. The Steel Output Index was used for deflation.

(iv) Grout costs

Similarly, grout costs showed no significant dependence on borehole type, and the overall function is:-

$$\boxed{\text{GROUTCOS (£)} = 63*\text{DIAM}^{0.70}*\text{CASLEN}^{0.71}}$$

Number of observations	:	59
Multiple correlation coefficient (R)	:	0.81
80% confidence interval multipliers	:	0.64, 1.57
Standard error of residuals (in $\log_{10}$ model)	:	0.152

The Average Earnings Index was used for deflation.

(v) Screen costs

The screen costs model incorporates both material and installation costs. It is based on data from all the 29 Type 2 boreholes, and 11 chalk boreholes employing slotted mild steel casing. The equation is:-

$$\boxed{\text{SCREENCOS (£)} = 609*\text{SCRLEN}^{0.92}*\text{SCRDIAM}^{0.93}*\text{SCRTYP}^{-1.09}}$$

Number of observations	:	38
Multiple correlation coefficient (R)	:	0.95
80% confidence interval multipliers	:	0.74, 1.35
Standard error of residuals (in $\log_{10}$ model)	:	0.099

Note:
1. SCRTYP is 1 if screen is stainless steel or rubber-coated steel, and
   2 if screen is slotted mild steel.
2. SCRDIAM is the internal diameter of the screen, weighted for length (m).
3. SCRLEN is the length of the screen (m).
4. The Steel Output Index was used for deflation.

(vi) Pack costs

This model only applies to Type 2 boreholes:-

$$\boxed{\text{PACKCOS (£)} = 2060*\text{CASDIAM}^{1.84}}$$

Number of observations	:	28
Correlation coefficient (R)	:	0.62
80% confidence interval multipliers	:	0.57, 1.75
Standard error of residuals (in $\log_{10}$ model)	:	0.185

Note:
1. CASDIAM is the diameter of the casing, weighted for length (m).
2. The Average Earnings Index was used for deflation.

11.1.2. MULTIPLE BOREHOLES

A. The modelling approach

To meet the cost estimation requirements of the long-term planning of groundwater development schemes, 13 BoQs were collected which related specifically to multiple borehole contracts. As there has been no large-scale development of any of the unconsolidated aquifers, all these contracts are for Type 1 boreholes. Eight of these are for groundwater development schemes (four of them for one scheme), mainly for river regulation purposes.

Detailed costs are not all available for elements of the schemes other than the supply borehole construction, namely wellheads, pipelines, river outfalls, observation boreholes, instrumentation and telemetry. Sometimes these are not relevant in any case as the schemes may not be complete. With such an unavoidably sparse data sample it is meaningless to perform any statistical analysis on these additional costs. In order to estimate total costs for a groundwater development scheme assumptions must be made, based on experience, about the probable costs of these elements compared with the size of the scheme. Some rough guidelines are offered later in the section.

The construction details of each borehole in a contract were summarized as for the single borehole models, by depth, diameter and length of casing. The following variables were then assembled for each contract:-

(i) average depth drilled;
(ii) average diameter (obtained by weighting each individual borehole diameter by the depth drilled);
(iii) average length of casing;
(iv) number of boreholes.

The behaviour of the single borehole Type 1 model in predicting the costs for a multiple borehole contract was then examined, by using that model to predict the cost of each borehole in a contract and then summing these cost estimates. It was expected that this process would over-estimate the actual costs, as it took no account of the economies to be gained in the setting-up costs where a drilling rig has only to be moved short distances between boreholes. However, the predicted costs exceeded the actual construction costs by over 20% in only seven of the cases, and under-estimated in two cases.

11.1.2. Multiple boreholes

This approach was repeated using the sub-models described in Section 11.1.1E, and a comparison of the sub-costs for each contract for setting-up, drilling, casing and grouting with predicted costs for these elements is shown in Table 11-3. In only five of the contracts were the actual setting-up costs substantially less than the predicted costs. Furthermore, there was no obvious relationship between the sub-cost prediction errors and the number of boreholes in each contract.

Table 11-3. Comparison of actual sub-costs for multiple borehole contracts with predicted costs from the sub-models

Contract	Number of boreholes	Setting up: actual cost/ predicted cost	Drilling: actual cost/ predicted cost	Casing: actual cost/ predicted cost	Grouting: actual cost/ predicted cost
A	8	0.904	0.776	0.716 (includes grout cost)	
B	11	1.172	0.898	0.966 (includes grout cost)	
C	7	2.571	0.912	0.919 (includes grout cost)	
D	6	3.016	0.995	0.731 (includes grout cost)	
E	6	0.626	1.030	1.413	1.17
F	6	1.177	1.153	0.966	0.735
G	18	1.767	1.129	0.570	1.074
H	3	0.543	0.862	0.972	0.749
I	3	1.176	1.130	0.954	0.989
J	2	1.075	1.223	0.944	1.186
K	5	0.702	1.051	0.708	0.619
L	4	0.133	0.976	0.363 (includes grout cost)	
M	8	0.555	0.752	0.685	0.763

In an attempt to improve on the scatter indicated by Table 11-3, the 13 data points were used to develop a predictive model for multiple borehole construction costs. The variables included in the model were the average weighted diameter, the average length of casing used in the contract, and the number of boreholes in the contract. Average depth was very poorly correlated with total cost because of the limited range of depths drilled; nor could total depth drilled be included as this factor was highly correlated with the number of boreholes in the contract.

The multiple boreholes cost function is presented in part B following.

B. The results

(i) Data summary

Table 11-4. Multiple borehole data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost of scheme (corrected to 1976 Q3)	COST	£'000	17.3	150	72.0	41.3
Mean borehole diameter	DIAM	m	0.28	0.76	0.586	0.142
Mean borehole depth	DEP	m	81.4	164	117	24.8
Mean casing length per borehole	CASLEN	m	15.4	79.5	30.9	20.1
No. of boreholes	NOBHS	-	2	18	6.69	4.19
Omnibus 8 (see Section 8.3.3)	Z8	-	1.77	10.3	5.71	2.71

Note:
1. Number of cases: 13.
2. The Average Earnings Index was used for deflation.
3. COST is defined as the total cost of setting-up, drilling, casing and grouting the boreholes.
4. Mean diameter is obtained by weighting individual borehole diameters by their depths.
5. The recommended function should be used with caution for mean depths outside the range 80 to 165 m.

Mini-histograms for the main variables of interest:-

COST

LOG COST

DIAM

CASLEN

NOBHS

11.1.2. Multiple boreholes

(ii) The recommended cost function

Because of the limited sample, the recommended model for multiple borehole schemes is only applicable to Type 1 boreholes, i.e. boreholes in consolidated aquifers. However, repeated application of the single borehole Type 1 model was found to give a reasonably good estimate of total scheme cost for the 13 available cases, and so the single borehole Type 2 model could be used as a rough approximation for estimating the cost of multiple borehole schemes for Type 2 boreholes.

The recommended function for Type 1 multiple borehole schemes is:-

$$\boxed{\text{COST} = 2.08 * \text{DIAM}^{1.26} * \text{CASLEN}^{0.63} * \text{NOBHS}^{1.16}}$$

The statistical details of the function are as follows:-

Number of observations	:	13
Multiple correlation coefficient (R)	:	0.97
Coefficient of determination (R^2)	:	94%
Standard error of residuals (in $\log_{10}$ model)	:	0.080

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DIAM	1.26	0.199	39.8	≪0.1%
CASLEN	0.630	0.131	23.2	<0.1%
NOBHS	1.16	0.119	94.8	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.77	1.29
95%	0.65	1.54

The omnibus variable is defined as:-

$$Z8 = 0.278*NOBHS*DIAM^{1.08}*CASLEN^{0.54}.$$

Figure 11-6 illustrates the recommended function.

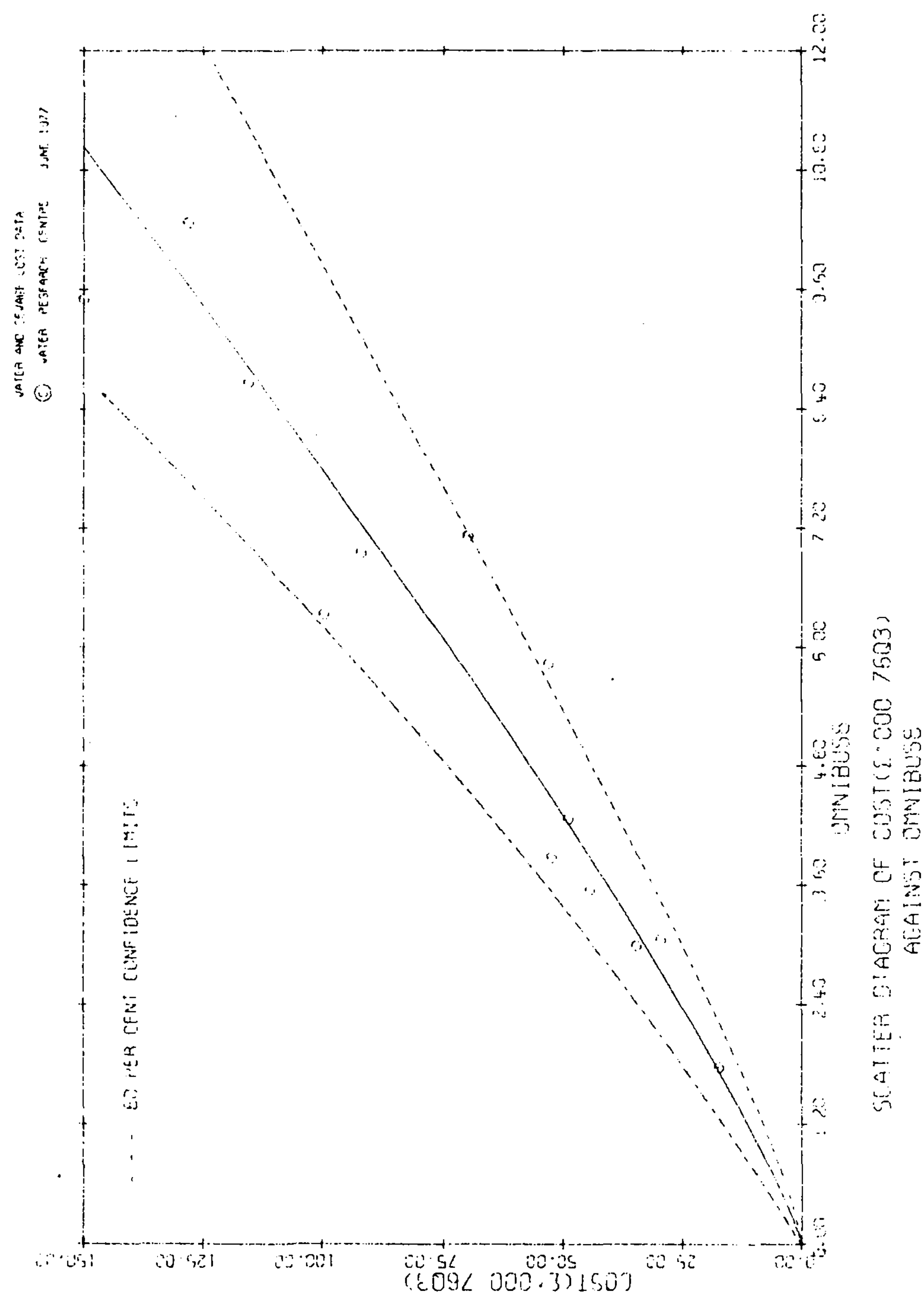
It will be noticed that the coefficient of NOBHS, the number of boreholes, is 1.16. This means that for a given mean diameter and mean casing length, the estimated cost for a ten borehole scheme (say) is 2.23 times that for a five borehole scheme. This runs counter to the common sense view that there should be a discernible economy of scale. However, despite a careful re-examination of the data sample (which, though small, represents a substantial proportion of all recent multiple borehole schemes), no way could be found of deriving a more acceptable function. It is inevitable, with the purely empirical approach taken throughout this study, that anomalies of this sort occasionally arise - though in this case the function is not in fact inconsistent with there being an economy of scale, because a 90% confidence interval about the 1.16 estimate is 0.95 to 1.37. In other words, it is quite conceivable that the true (but unknown) value of the coefficient is actually less than one.

(iii) <u>The data</u>

The multiple borehole data is listed in Table A-13.

11.1.2. Multiple boreholes

Figure 11-6. Multiple boreholes



C. Additional costs

The additional items to be added to the total construction cost are the same as those for single boreholes outlined in Section 11.1.1D. For planning purposes, average costs of these items can be taken and simply multiplied by the number of boreholes in the contract. Thus,

(i) Acidization costs (if necessary) = £2500*no. of boreholes.
(ii) Test-pumping costs (2 weeks per borehole) = £6000*no. of boreholes.
(iii) Pump and accessories = £8000*no. of boreholes.
(iv) Head chamber = £2000*no. of boreholes.

Test-pumping costs for a groundwater development scheme will include single tests for each abstraction borehole, and a group test-pumping to evaluate the full potential of the scheme. Although costs are available for the first of these, there was only very limited information on costs of group tests, so these are not included here.

D. Ancillary costs

The ancillary costs which make up the rest of the capital costs of a groundwater development scheme are as follows:-

(i) exploration boreholes, observation boreholes and compensation works;
(ii) pipelines;
(iii) treatment facilities (where necessary);
(iv) river outfalls;
(v) instrumentation and telemetry (if required);
(vi) access roads and easement charges;
(vii) design consultant costs (if required);
(viii) provision of electrical power lines and land acquisition.

All of these costs will be dependent on the size and type of the scheme, the distribution of the boreholes over the area, and the amount of technical information available before the scheme is started. They are discussed in (i) to (viii) below.

11.1.2. Multiple boreholes

(i) Exploration and observation boreholes and compensation works

Exploratory boreholes are customarily drilled at the start of a scheme to investigate the geology of the area, the aquifer properties and the probable yield of the aquifer, and possibly to establish whether hydraulic connections with surface water sources exist. Such holes would frequently be cored and would therefore be more expensive than standard observation boreholes, although they may later be used for that purpose, or reamed out for use as abstraction boreholes.

The number of exploratory boreholes drilled in any scheme will depend to a great extent on the amount of existing information in the area and the size of the area (although two or three such boreholes should provide sufficient information for most areas of the UK). The cost of these boreholes will depend on depth, diameter, length of core taken and length and type of casing. For planning purposes an average figure would be £5000 to £7000 per borehole. Acidization and test-pumping of exploratory boreholes would be additional items in this category, the same costs applying as for the single borehole model.

In addition to these boreholes a number of observation wells will be required. Opinions vary as to the number of observation wells required for groundwater development schemes. Existing schemes appear to have an average of three observation boreholes to every abstraction borehole, some of which may be existing boreholes. Future schemes may not require such a high ratio as this, as experience gained in developing present groundwater schemes should reduce this number to one or two observation boreholes per abstraction borehole. However, small groundwater schemes with only a few abstraction boreholes may require a proportionately larger number of observation boreholes than a large scheme, where much information can be gathered from the interaction of the abstraction boreholes.

An average cost for an observation borehole would be £1500 to £3000, although the Water Authorities should have more accurate figures from their own drilling contracts.

The cost of compensation works required in a scheme (e.g. deepening of private boreholes, augmentation of streamflows for fishery and amenity purposes) are impossible to predict without more detailed knowledge of the aquifer and the proposed development. However, experience to date suggests that a figure of 3 to 5% of the total cost of the scheme should be added for planning purposes.

(ii) Pipelines

The cost of pipelines is likely to be a very substantial part of the total cost of a scheme. Because this is highly dependent on the particular scheme, average figures are largely meaningless. In planning a scheme an estimate of the lengths and diameters of pipes required should be made, and this data applied to the model for water mains (see Section 10.2).

In the schemes studied, pipeline costs have been 80 to 300% of the total costs of the abstraction boreholes.

(iii) Treatment facilities

Treatment facilities would not be required on all types of groundwater scheme. Chlorination is normally sufficient treatment for groundwater. For costs of chlorination and construction of treatment facilities see Sections 12.4.1 and 14.1.

(iv) River outfalls

River outfalls will be required for groundwater schemes where river regulation is the main aim. The cost of such outfalls will be a minor part of the total scheme cost, and dependent on the design features. For planning purposes an average figure of £2000 per outfall would be reasonable.

(v) Instrumentation and telemetry

The amount of instrumentation required for a groundwater scheme will depend to a large extent on the type of scheme and the data requirements of the Water Authority concerned. The types of instrumentation that may be considered are:-

(a) water level recorders on observation boreholes;
(b) rainfall gauging stations;
(c) river gauging stations;
(d) river sampling stations, for both chemical and biological variations.

If only water level recorders are required then a budget price of £500 per recorder can be used.

If a full hydrometric network is incorporated into the scheme this will probably be of the order of 2 to 5% of the total cost of the scheme.

11.1.2. Multiple boreholes

Telemetry is usually incorporated into a groundwater scheme, if at all, after completion of all the construction work. These costs are difficult to predict without a clear idea of the scheme requirements. The lowest costs for a very simple system would be £1200 per telemetry station. However, on a full river regulation scheme where perhaps abstraction programmes are related to river flow and water levels in the aquifer, the costs are likely to be much greater than this. The type and availability of this data precludes any further estimates of costs.

(vi) Access roads and easement charges

These costs will be very minor in relation to the total cost of a scheme, generally less than 1%, and for planning purposes can be ignored.

(vii) Design consultant costs

No data was available for design costs and no attempt has been made to estimate a figure. However, unless Water Authorities do their own design work, an allowance should be made for this work.

(viii) Provision of electrical power and land acquisition

The cost of providing a link into the national grid system is small unless great lengths of electrical cable are required to connect the boreholes. No information was available for this item.

Land acquisition costs have not been considered in the study.

E. Yield of a scheme

In long-term planning the yield of any scheme is the fundamental factor of importance. However, there was little advantage in attempting to develop a simple relationship between cost and yield, as the variability of yield from different aquifers is so great. Furthermore, when considering yield, especially with river augmentation schemes, the net gain to the system is more important than simply the amount of water pumped from the boreholes. In areas where there is good connection between the surface water and the aquifer, pumping at about 4500 m^3/d from each of ten boreholes may only result in an increase in river flow of 20 000 m^3/d - a net gain of only 44%. Net gain is an important factor which must be taken into consideration for the realistic costing of a scheme.

Table 11-5 gives the distribution of yield from wells in the more important aquifers of England (7). In order to determine the number of boreholes required to produce the desired yield of a scheme it is recommended that, in the absence of more detailed data from the aquifer under consideration, the 50% probability yield of a well in that aquifer should be taken from Table 11-5. Thus:-

$$\text{No. of boreholes in scheme} = \left(\frac{\text{Desired yield of scheme}}{\text{50\% probability yield of one borehole}}\right) \ast \left(\frac{100}{\text{\% net gain}}\right)$$

Net gain depends on the type of scheme (i.e. river regulation or direct supply) and its estimation requires detailed knowledge of the hydrogeology of the area, and some field information which would be provided by pilot-scale experiments. In the absence of any other information a 50% net gain could perhaps be considered for river regulation schemes. Experience in the Permo-Triassic Sandstone has shown that a 70% net gain is realistic, whereas in the Chalk net gain may be lower than 50%. Pump testing of pilot boreholes should give a better estimate of the likely yield from a borehole, so that field estimates could then be substituted into the above equation.

Having determined the required number of boreholes the construction cost of these boreholes can be determined from the model presented in part B, using either average values of mean diameter and average casing length, or specific values if the data is available. The average values of diameter and length of casing per borehole are 0.59 and 31 m respectively in the data sample studied.

11.1.2. Multiple boreholes

Table 11-5. Distribution of yield from public supply boreholes and wells in the more important aquifers of England and Wales

Aquifer	Number of wells in sample	Yield (m^3/d) exceeded by:		
		25% of cases	50% of cases	75% of cases
Chalk (excluding Metropolitan area and Devonshire)	360	5700	3300	1900
Chalk (Metropolitan Water Board wells with headings)	33	9500	4700	2900
Permo-Triassic Sandstones	247	5200	2200	700
Magnesian Limestone	21	5900	3500	1100
Middle and Upper Jurassic (excluding Lincolnshire Limestone)	64	1400	500	170
Lincolnshire Limestone	17	6400	2500	1000
Spilsby Sandstone	17	1700	850	430
Lower Greensand	91	2800	1100	370
Hastings Beds	27	1800	850	380

Note: The data in this table was assembled from the returns made by statutory water undertakings under Section 6 of the Water Act (1945). Abortive wells are not included and the data is therefore biased towards successful sites.

F. Worked example

Suppose that a river regulation scheme has been envisaged using water from the Bunter Sandstone aquifer, to produce an increase in flow of the river of 45 000 m^3/d. The catchment area has a partial covering of superficial deposits and alluvium and a net gain of 65% has been established by pilot-scale experiments. No treatment of the water will be required, but two river outfalls will be needed. Any telemetry requirements are ignored.

From Table 11-5, 50% probability yield of Bunter Sandstone = 2200 m^3/d.

Therefore number of boreholes required in scheme $= \frac{45\ 000}{2\ 200} * \frac{100}{65}$

$= 32$ boreholes.

The maximum number of boreholes in a contract used to construct the multiple borehole model was 18, and so it would be invalid to use the model as it is for 32 boreholes. However, it is unlikely that only one contract would be let for such a number of boreholes, and it is reasonable to subdivide it into three contracts of, say, 10, 10 and 12 boreholes.

The diameter of each borehole is assumed to be 0.61 m (24 inches). The length of casing will vary with the depth of superficial deposits to be screened out in each borehole. It is assumed that there are ten boreholes close to the river where 30 m of casing is required per borehole, ten boreholes towards the edge of the flood plain of the river (approximately 0.75 km distant from the river) requiring 15 m of casing, and 12 boreholes 1.25 km distant from the river having no superficial deposits and requiring only 5m of casing.

Using the multiple borehole construction cost model the cost of the first ten boreholes will be:-

$$\text{COST} = 2.08*(0.61)^{1.26}*(30)^{0.63}*(10)^{1.16}$$

$$= 137.5, \text{ i.e. } £137\ 500.$$

Similarly, estimated cost of second ten boreholes = £88 800,

and estimated cost of remaining twelve boreholes = £54 900.

Thus estimated total construction cost of the 32 boreholes is £281 000.

11.1.2. Multiple boreholes

There would be no acidization costs on a borehole in Bunter Sandstone.

Two weeks' test-pumping of each of the 32 boreholes, at an average cost of £6000 per borehole, is £192 000.

The cost of installation of pumps and construction of headworks, at an average of £10 000 per borehole, is £320 000.

The total predicted cost of installation of the abstraction boreholes is therefore £793 000.

It is assumed that three exploratory boreholes are drilled at £5000 per borehole, and 48 observation wells at £2000 per borehole. These additional boreholes will therefore cost £111 000.

The prediction of the pipeline costs is difficult without a more detailed consideration of the configuration of the abstraction boreholes and the layout of the connecting pipes and their diameters. Assuming an interconnecting pipeline of length 15.5 km and mean average diameter of 430 mm, the predicted cost (from Section 10.2) is:-

$$\begin{aligned} \text{COST} &= 0.0702{*}(15\,500)^{0.73}(430)^{0.91{*}(430/1430)} \\ &= 423, \text{ i.e. } \underline{£423\,000}. \end{aligned}$$

The cost of two river outfalls, at an average cost of £2000 each, is £4000. Without instrumentation, the cost of the scheme is therefore £1 331 000. Assuming a further 3% for instrumentation the estimate of total cost becomes £1 371 000.

To summarize, the cost estimates are:-

		£ 1976 Q3
(i)	Construction of 32 boreholes	281 000
(ii)	Test-pumping	192 000
(iii)	Installation of pumps and headworks construction	320 000
(iv)	Construction of exploratory and observation boreholes	111 000
(v)	Cost of pipelines	423 000
(vi)	Two river outfalls	4 000
(vii)	Instrumentation	40 000
	Total cost	1 371 000

11.1.3. OPERATING COSTS

Data has been collected from various water undertakings on operating costs of pumping stations over the period 1972 to 1976. The major cost is in providing the power for abstracting water from boreholes. Subsidiary costs include maintenance of boreholes and equipment, labour costs and chemical costs. These are very variable and depend largely on the size of the pumping station and whether or not it is permanently manned.

The costs have not been subdivided between Types 1 and 2 boreholes as the pumping costs will be similar between the two types, being dependent on operating head and output of the pumps. Long-term maintenance costs of Type 2 boreholes would be expected to be higher than for Type 1 as sand may be drawn into the borehole, thus affecting pump performance, or the screen may become clogged. However, it has proved impossible to quantify these long-term costs. The operating costs data has been summarized in Table 11-6.

Table 11-6. Summary of borehole operating costs data

	Number of observations	Min.	Max.	Mean	St. dev.
Total operating costs (£ 1976 Q3/Ml/100 m lift)	41	7.10	28.92	14.05	6.87
Pumping costs (£ 1976 Q3/Ml/100 m lift)	53	1.92	22.15	8.47	4.08
Other costs, e.g. mechanical, labour, chemicals (£ 1976 Q3/Ml)	44	0.12	12.22	3.51	3.30

Note:
1. The Fuel and Light Retail Price Index was used to deflate operating and pumping costs.
2. The Average Earnings Index was used to deflate other costs.

11.2. DAMS AND RESERVOIRS

A. General modelling approach

Within this section, the following definitions have been assumed for a number of commonly used terms:-

(i)	Embankment:	a structure with material such as earth, gravel or crushed rock compacted in layers with a clay and/or concrete impervious core.
(ii)	Dam:	a structure used for cutting off a valley.
(iii)	Concrete dam:	a dam constructed from concrete.
(iv)	Earthbank dam:	an embankment used as a dam.
(v)	Reservoir:	a wholly man-made impervious structure containing a body of stored water (as compared with a lake created by damming a valley).
(vi)	Lagoon:	a reservoir constructed for settling sludge.
(vii)	Bund:	a continuous embankment used for creating a reservoir or lagoon (and therefore having a length to height ratio greater than might be found for a dam).

Data was gathered from four sources: tender and final account BoQs and associated documents, the original TP 60 (2) survey, technical journals, and the International Commission on Large Dams World Register (8). Initially the sample included only dams and reservoirs. Subsequently it was decided to extend the sample of reservoirs by including a number of sludge lagoons.

An examination of the more detailed costs available in BoQs showed that the embankment, together with any cut-off, formed typically about 60% of the total cost. The other items were generally relatively small, with none amounting to more than about 10% of the total cost; these are discussed further in part F. Furthermore, the manner in which these costs were broken down varied from contract to contract, making comparisons difficult.

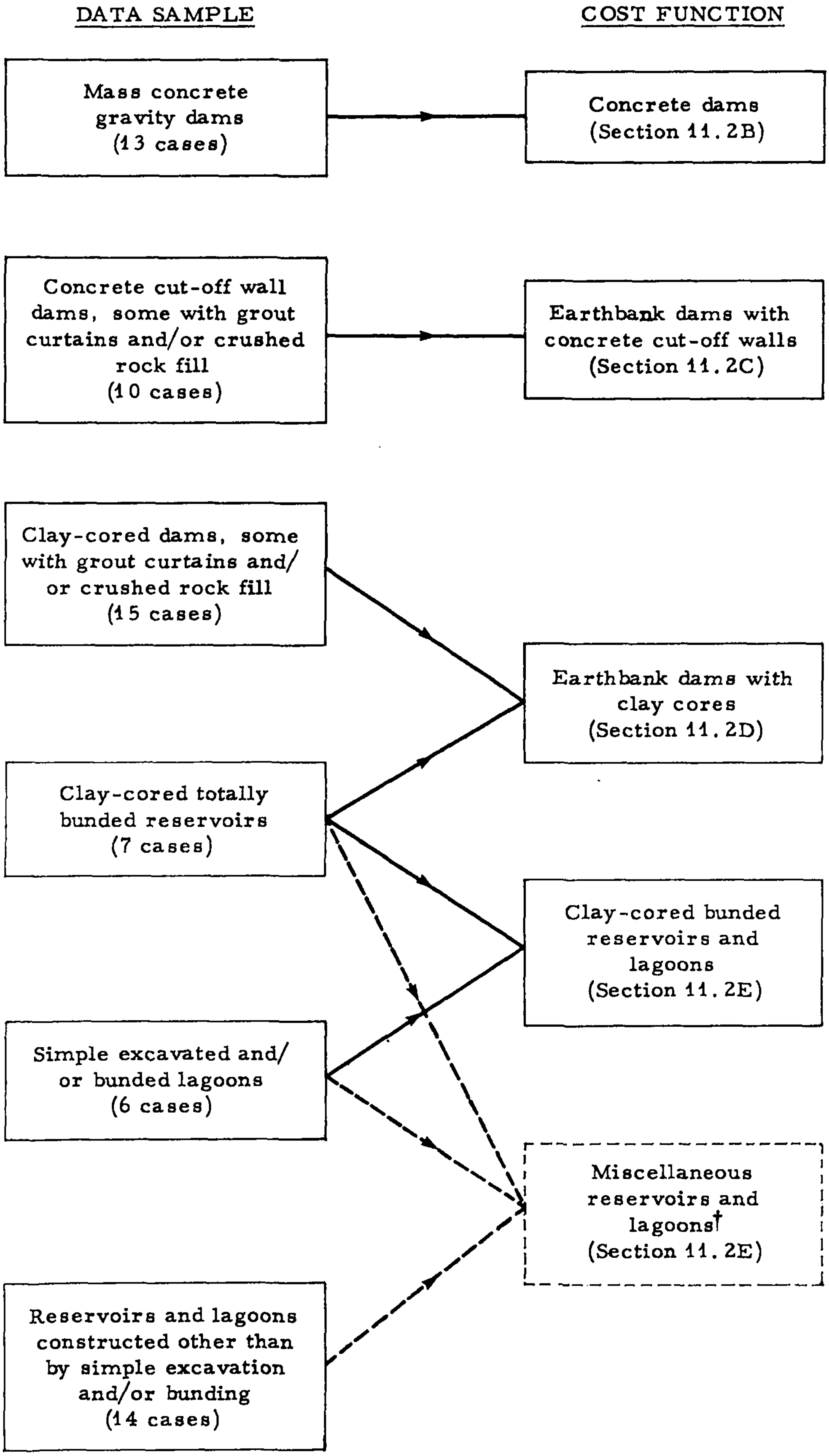
Preliminary modelling work using data from the detailed BoQs indicated that no significant advantage was to be gained from treating the cost of the embankment separately. Cost was therefore defined to include the cost of the embankment (or concrete dam), cut-off, adjacent or integral inlet and outlet works (but excluding river intakes and inlet aqueducts for pumped storage), integral pipe and tunnel works, minor road and river diversions and other minor ancillary works. Engineers' fees and design, legal and land costs are excluded. Where a dam or reservoir is to be put to use as part of a storage scheme, costs of other components such as river intakes and aqueducts will need to be estimated separately as outlined in part F.

The total data sample amounted to 65 cases covering a wide variety of dams and reservoirs. These have been grouped into six categories according to the method of construction, as shown in the left-hand portion of Figure 11-7. The categories evolved to a certain extent during the modelling work: with earthbank dams, for example, it was found necessary to distinguish clay-cored structures from those in which there was a major concrete cut-off which in some cases took the place of most or all of the clay core. However, some other factors expected to be important, such as whether crushed rock was used as fill or grouting was used to aid the cut-off, had no significant effect on cost.

In all, five cost functions were developed for different categories of dam and reservoir: these are listed in the right-hand portion of Figure 11-7. The figure also indicates the data sub-samples that were used in developing each function. In some cases, it was considered appropriate to use a set of data for more than one function. The seven cases of clay-cored totally bunded reservoirs, for example, were used both for the clay-cored earthbanks dams model and the clay-cored bunded reservoirs and lagoons model.

During development of the models the following explanatory variables were examined:-

(i) volume of water stored;
(ii) area of top water level;
(iii) volume of embankment (or concrete dam);
(iv) crest length;
(v) maximum dam height from original ground level;
(vi) maximum useful water depth (in reservoirs);
(vii) location factors of dam, such as latitude, height above sea level, site rainfall;
(viii) number of reservoir (or lagoon) compartments.



† This cost function is recommended only for reservoirs and lagoons constructed other than by simple excavation and/or bunding.

Figure 11-7. The data samples used in developing each reservoirs and dams cost function

Of these variables, cost was most strongly related to volume of embankment in all cases except for reservoirs and lagoons, where volume of water stored was the most significant explanatory variable and was therefore preferred. Two functions are available for clay-cored bunded reservoirs (see Figure 11-7), one based on each factor. No other explanatory variable was ever found more significant than either of these volume factors.

For most types of dams and reservoirs, the Construction Materials Index was found more satisfactory than the New Construction and DQSD Indices and so this was used throughout. Deflation was based on the tender date, as this was generally found more satisfactory than the mid-date of construction.

B. The results - concrete dams (mass concrete gravity)

(i) Detailed modelling approach

Cost was related to volume of concrete used for a sample of 13 mass concrete gravity dams. Although one of the dams contained a central section constructed as an arch dam, and two other dams were constructed with round-head buttresses, these three cases were found to be compatible with the remainder of the data. Information was also available for a buttressed dam; however, this case was clearly an outlier, with a cost of £8.83 million (1976 Q3) for a volume of concrete of 126 000 m^3.

(ii) Data summary

Table 11-7. Concrete dams data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost of scheme (corrected to 1976 Q3)	CONCOS	£ million	1.13	12.1	4.38	3.35
Volume of fill of dam	DAMVOL	'000 m^3	19	252	94.8	75.1

Note: 1. Number of cases: 13.

2. The Construction Materials Index was used for deflation.

Mini-histograms for the main variables of interest:-


CONCOS


LOG CONCOS


DAMVOL

(iii) The recommended cost function

The recommended function for mass concrete gravity dams is:-

$$\boxed{\text{CONCOS} = 0.0569*\text{VOL}^{0.95}}$$

The statistical details of the function are as follows:-

Number of observations : 13

Correlation coefficient (R) : 0.97

Coefficient of determination (R^2) : 95%

Standard error of residuals (in $\log_{10}$ model) : 0.082

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DAMVOL	0.951	0.067	203	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.77	1.29
95%	0.71	1.40

Figures 11-8 and 11-9 show the five standard diagrams in support of the function.

(iv) The data

The concrete dams data is listed in Table A-14.

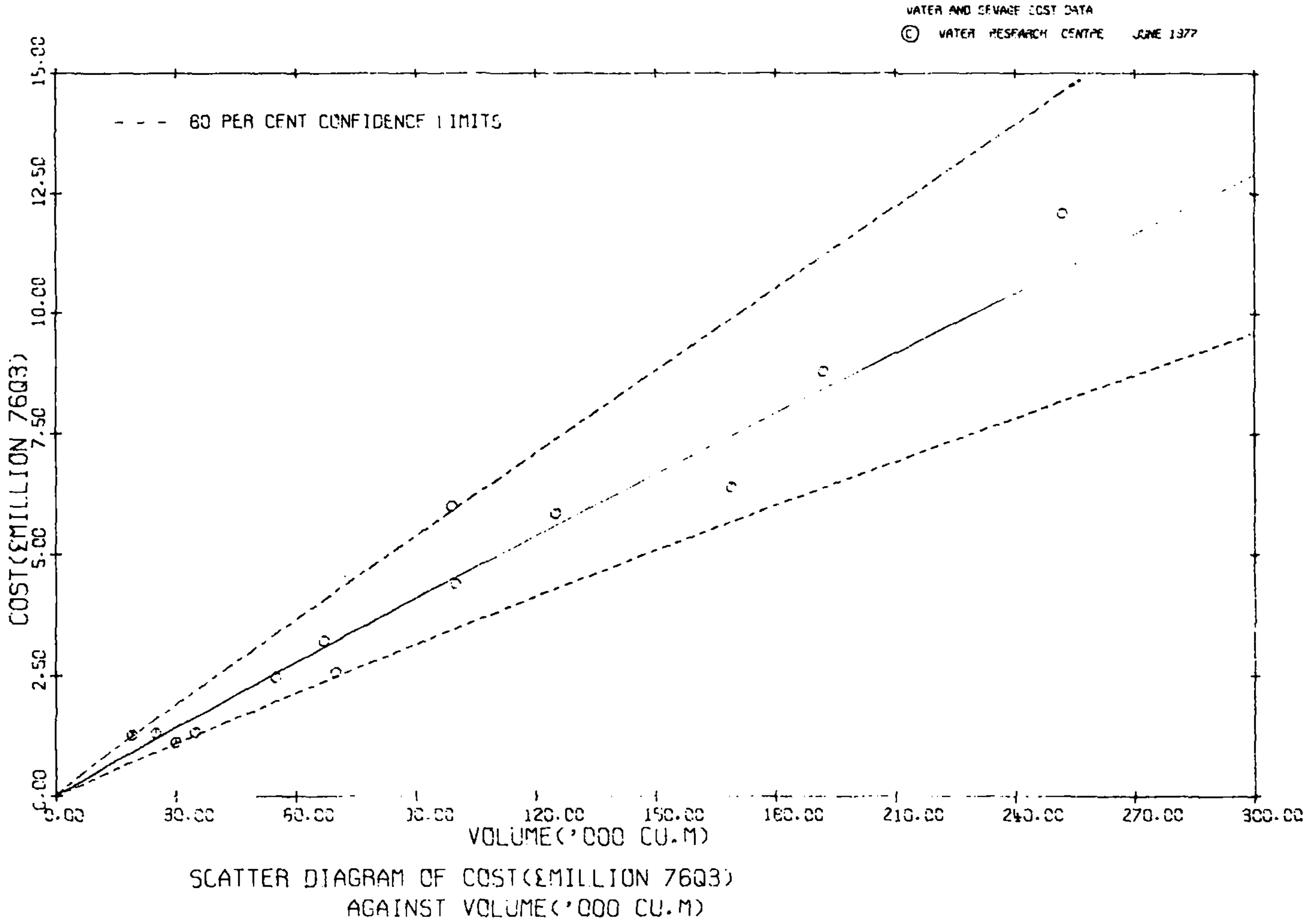
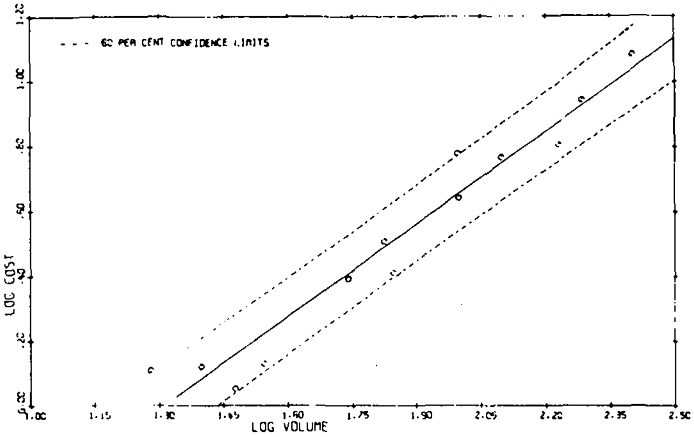


Figure 11–8. Concrete dams

11.2. Dams and reservoirs

Figure 11-9. Concrete dams



WATER AND SEWAGE COST DATA
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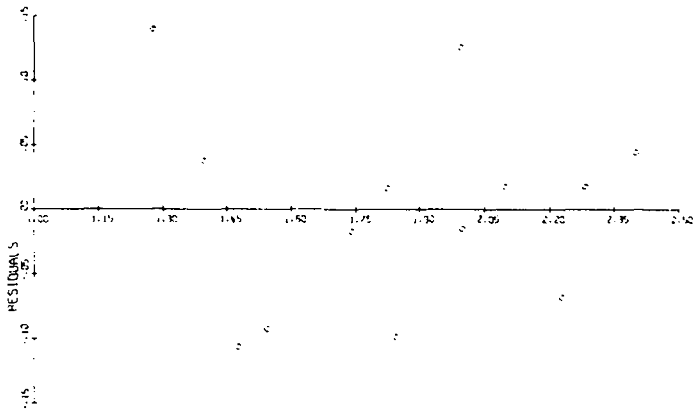
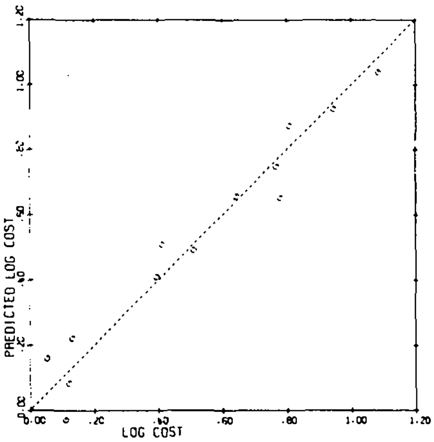
SCATTER DIAGRAM OF LOG COST
AGAINST LOG VOLUME



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG VOLUME

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - earthbank dams with concrete cut-off walls

(i) Detailed modelling approach

A preliminary study of the 32 cases of earthbank structures showed a significant cost difference between the ten dams with substantial concrete cut-off walls (in some cases completely taking the place of a clay core) and the remaining 22 clay-cored structures. Two separate cost functions were therefore developed: the concrete cut-off wall earthbank dams model is presented below, and the clay-cored earthbank dams model follows in part D.

Some of the ten concrete cut-off dams had grout curtains and/or crushed rock fill, but this had no apparent effect on cost. The recommended function therefore contains volume of embankment as the single explanatory variable. This includes all material placed and compacted as part of the embankment.

(ii) Data summary

Table 11–8. Earthbank dams with concrete cut-off walls data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost of scheme (corrected to 1976 Q3)	CONWALL-COS	£ million	2.61	18.9	7.46	5.72
Volume of fill of dam	DAMVOL	million m^3	0.116	3.00	0.863	0.944

Note: 1. Number of cases: 10.

2. The Construction Materials Index was used for deflation.

Mini-histograms for the main variables of interest:-

CONWALLCOS

LOG CONWALLCOS

DAMVOL

(iii) The recommended cost function

The recommended function for earthbank dams with concrete cut-off walls is:-

$$\boxed{\text{CONWALLCOS} = 8.97 * \text{DAMVOL}^{0.66}}$$

The statistical details of the function are as follows:-

Number of observations : 10
Correlation coefficient (R) : 0.98
Coefficient of determination (R^2) : 96%
Standard error of residuals (in $\log_{10}$ model) : 0.067

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DAMVOL	0.658	0.050	171	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.81	1.24
95%	0.70	1.42

Figure 11-10 illustrates the recommended function.

(iv) The data

The earthbank dams with concrete cut-off walls data is listed in Table A-15(a).

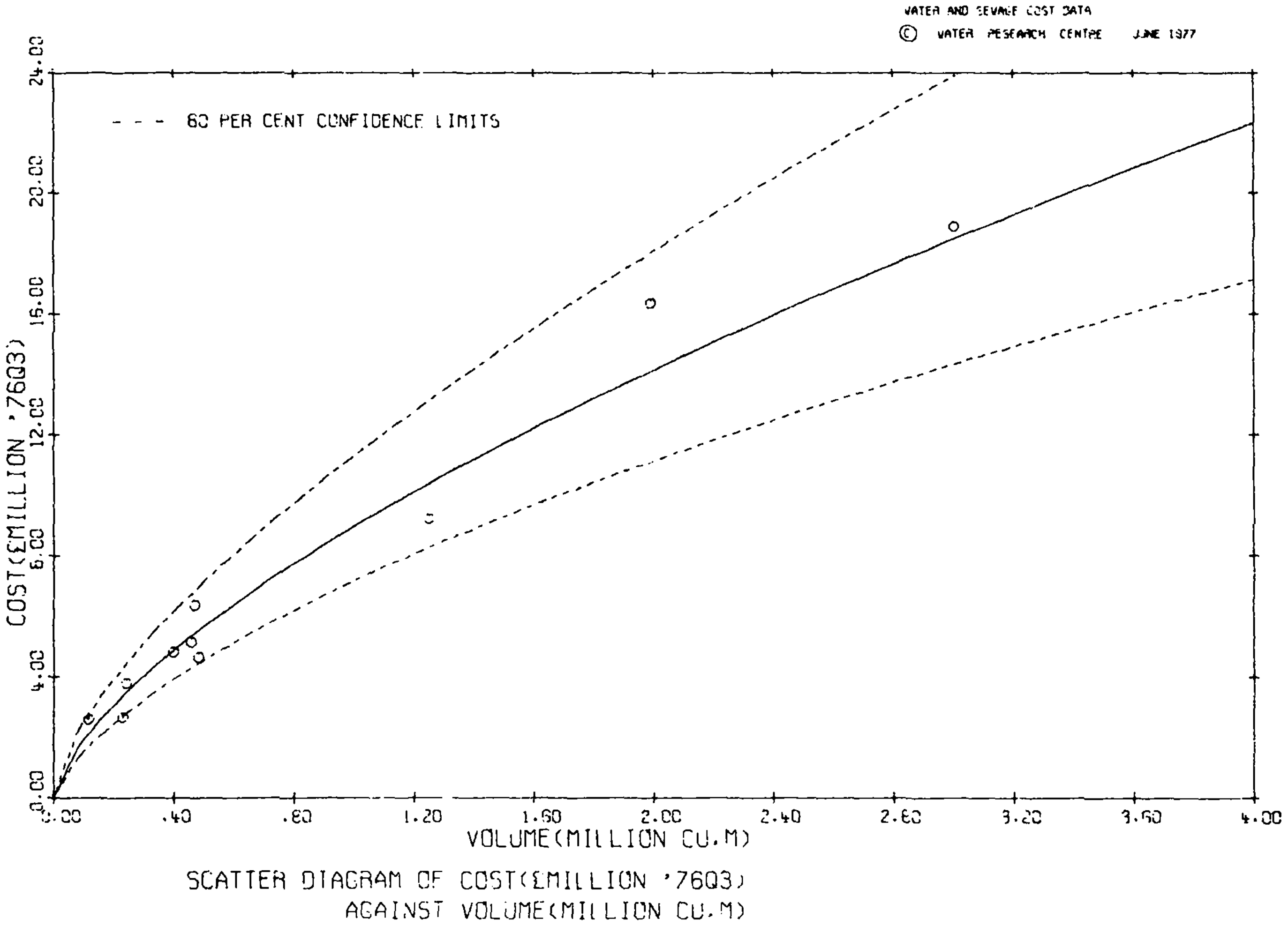


Figure 11–10. Earthbank dams with concrete cut-off walls

D. The results - earthbank dams with clay cores

(i) Detailed modelling approach

The 22 cases of clay-cored structures were subdivided into two categories: clay-cored dams, and clay-cored bunds. Some of the clay-cored dams contained grout curtains and/or some crushed rock fill, but these cases were found not to be significantly more expensive than the simple clay-cored dams. Consequently one recommended function is presented containing two explanatory variables: volume of embankment (including all material placed and compacted as part of the embankment), and a TYPE variable to differentiate between dams and bunds.

(ii) Data summary

Table 11-9. Earthbank dams with clay cores data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost of scheme (corrected to 1976 Q3)	CLAYCORECOS	£ million	1.07	11.9	6.69	3.64
Volume of fill of dam	DAMVOL	million m^3	0.195	7.65	2.29	1.98
Type of dam	TYPE	-	1	2	1.32	0.477
Omnibus 5 (see Section 8.3.3)	Z5	-	0.178	4.50	1.86	1.41

Note:
1. Number of cases: 22.
2. The Construction Materials Index was used for deflation.
3. TYPE is 2 for clay-cored bunds, and
   1 for other clay-cored dams.

Mini-histograms for the main variables of interest:-

CLAYCORECOS

LOG CLAYCORECOS

DAMVOL

TYPE

(iii) The recommended cost function

The recommended function for earthbank dams with clay cores is:-

$$\boxed{\text{CLAYCORECOS} = 4.53*\text{DAMVOL}^{0.73}*\text{TYPE}^{-0.58}}$$

The statistical details of the function are as follows:-

Number of observations	:	22
Multiple correlation coefficient (R)	:	0.98
Coefficient of determination (R^2)	:	96%
Standard error of residuals (in $\log_{10}$ model)	:	0.064

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DAMVOL	0.727	0.035	442	≪0.1%
TYPE	-0.584	0.099	34.8	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.82	1.22
95%	0.73	1.36

The omnibus variable is defined as:-

$$Z5 = \text{DAMVOL}*\text{TYPE}^{-0.80}.$$

Figures 11-11 and 11-12 present the five standard diagrams in support of the function.

(iv) The data

The earthbank dams with clay cores data is listed in Table A-15(b).

Figure 11–11. Earthbank dams with clay cores

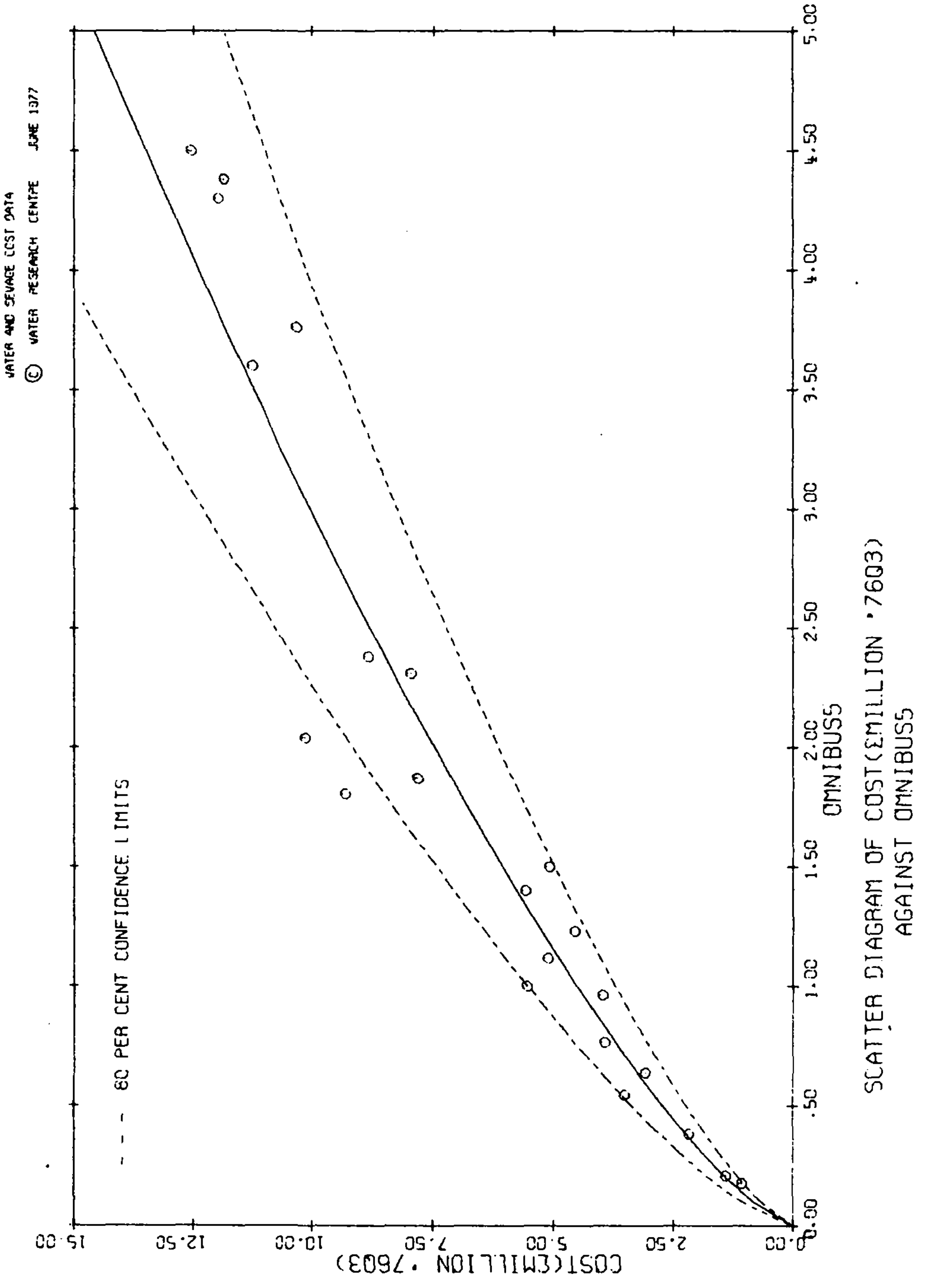
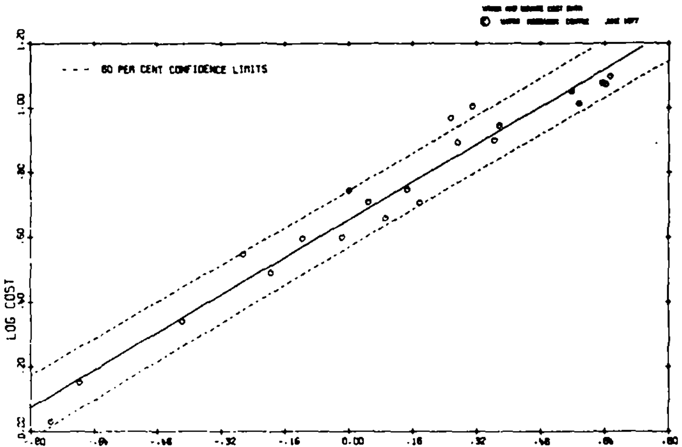
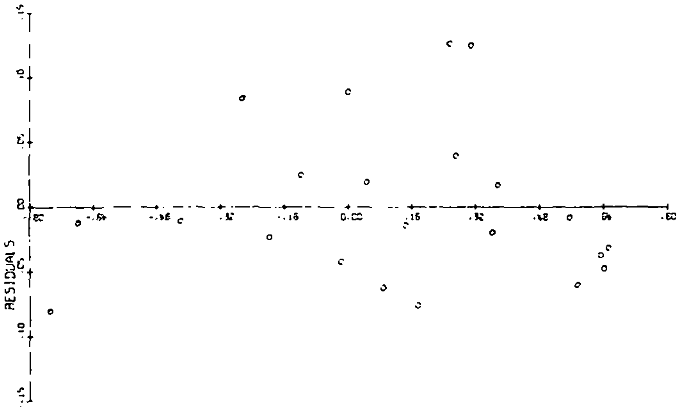


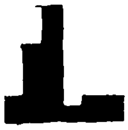
Figure 11–12. Earthbank dams with clay cores



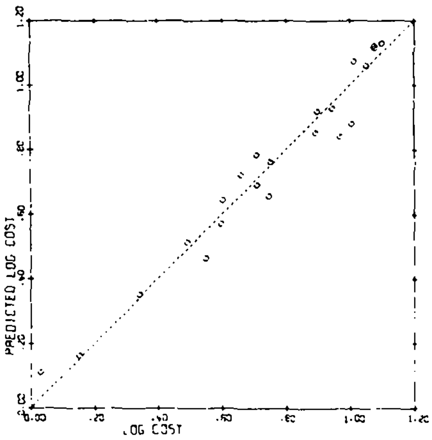
SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUSS



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUSS



HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

E. The results - reservoirs and lagoons

(i) Detailed modelling approach

The 27 data cases were found to split into two significantly different categories:-

I: Clay-cored totally bunded reservoirs and other simply excavated and/or bunded lagoons; and

II: Other reservoirs and lagoons (constructed other than by simple excavation and/or bunding, with special attention paid to creating an impervious structure).

Lagoons of an appropriate construction type were included in the category I sub-sample because the clay-cored bunded reservoirs which originally constituted the whole sub-sample did not span a sufficiently wide range. It was expected that it would then be necessary to distinguish between the reservoirs and the lagoons cases; however, the two groups were found to be so homogeneous that this was unnecessary.

Category II embraced a variety of construction methods, including open concrete tanks with sloping walls, concrete or steel-sheet cut-off walls, reinforced concrete floor lagoons, and a butyl-sheet-lined reservoir. No distinction could be made between these with the limited data available, although it was noted that the cost of concrete tanks was about 70% that of rectangular concrete covered service reservoirs (see Section 12.7.1). One other type of structure was observed: adapted quarries and spoil heaps. The costs for these are mainly due to landscaping and inlet and outlet works, and will therefore depend much more on the particular site than on storage volume.

Two cost functions are presented below. The first of these is the recommended function and is restricted to category I. The second function covers both categories of data, differentiating between each by means of a TYPE variable, but should only be used for estimating costs in category II, namely the more expensive miscellaneously constructed reservoirs and lagoons.

(ii) The data

Table 11-10 summarizes the data samples both for the clay-cored bunded reservoirs and lagoons and for the other reservoirs and lagoons of miscellaneous construction.

Table 11–10. Reservoirs and lagoons data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Clay-cored bunded reservoirs and lagoons (13 cases)						
Cost of scheme (corrected to 1976 Q3)	CLAYBUN-COS	£ million	0.0135	11.9	3.51	4.38
Volume stored	RESVOL	million m^3	0.00226	37.7	9.01	13.4
Miscellaneous reservoirs and lagoons (14 cases)						
Cost of scheme (corrected to 1976 Q3)	MISCOS	£ million	0.0128	3.91	1.18	1.24
Volume stored	RESVOL	million m^3	0.00053	2.79	0.399	0.747

Note: The Construction Materials Index was used for deflation.

Mini-histograms for the main variables of interest:-

CLAYBUNCOS

LOG CLAYBUNCOS

RESVOL

(iii) The recommended cost function

The recommended function for clay-cored bunded reservoirs and lagoons is:-

$$\boxed{CLAYBUNCOS = 1.05*RESVOL^{0.68}}$$

The statistical details of the function are as follows:-

Number of observations : 13

Correlation coefficient (R) : 0.998

Coefficient of determination (R^2) : 99.6%

Standard error of residuals (in $\log_{10}$ model) : 0.080

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
RESVOL	0.680	0.013	2800	$\ll 0.1\%$

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.78	1.29
95%	0.67	1.50

Figure 11-13 illustrates the recommended function.

(iv) Other cost functions

The data samples for the clay-cored bunded and the miscellaneously constructed reservoirs and lagoons were pooled so that a subsidiary function could be developed for estimating the cost of miscellaneous reservoirs and lagoons. The function is as follows:-

$$\boxed{MISCOS = 1.04*RESVOL^{0.67}*TYPE^{1.65}}$$

where TYPE is 1 for clay-core bunded reservoirs or lagoons, and
2 for other miscellaneous reservoirs or lagoons.

The statistical details of the function are as follows:

Number of observations	:	27
Correlation coefficient (R)	:	0.99
80% confidence interval multipliers	:	0.67, 1.49
Standard error of residuals (in $\log_{10}$ model)	:	0.132

For miscellaneous bunded reservoirs and lagoons, TYPE = 2 and the above function can be rewritten as:-

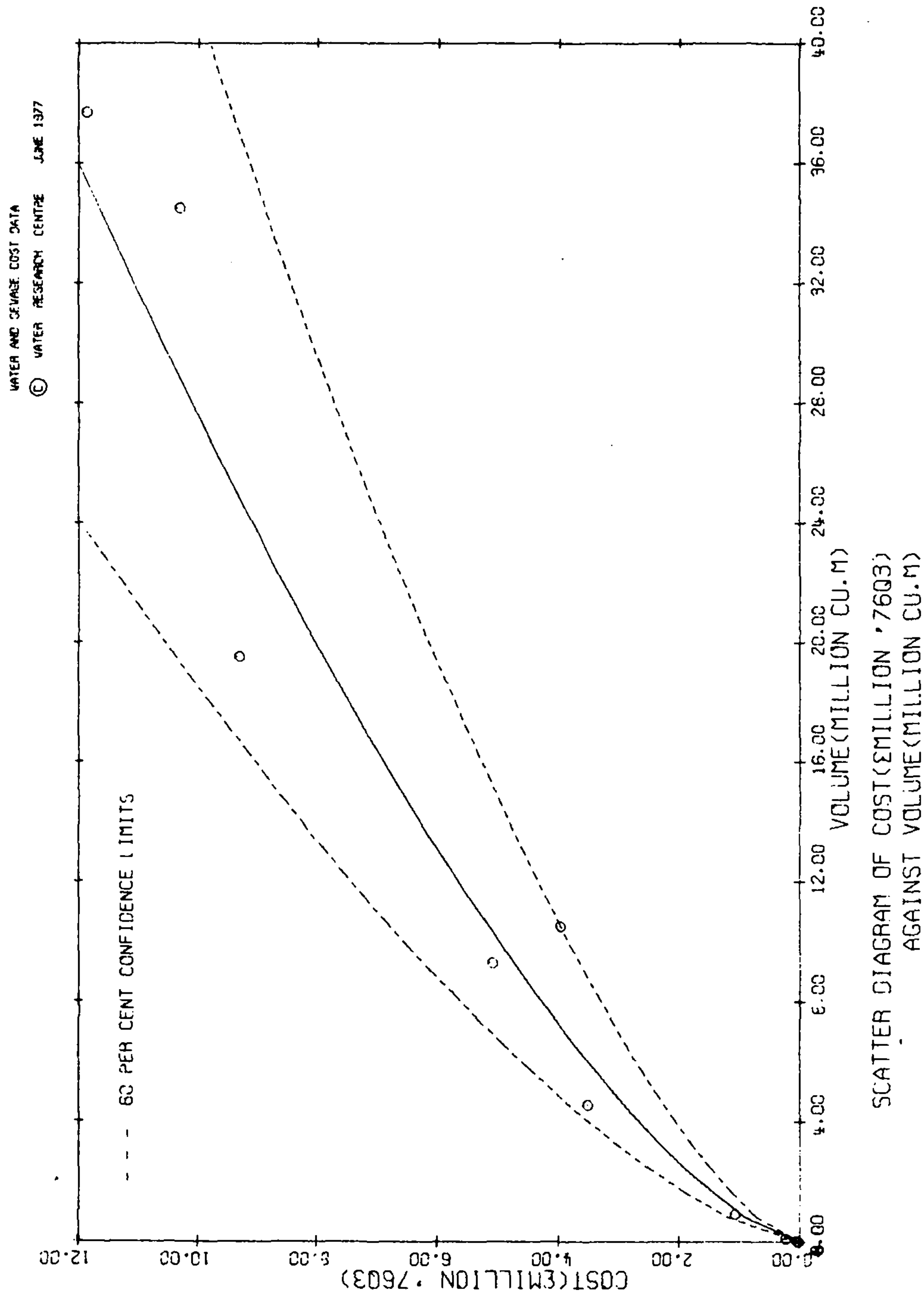
$$\boxed{\text{MISCOS} = 3.26*\text{RESVOL}^{0.67}}$$

For TYPE = 1, the recommended function presented earlier in (iii) is available and should be used in preference to the subsidiary function.

(v) The data

The clay-cored bunded reservoirs and lagoons data is listed in Table A-16.

Figure 11-13. Clay-cored bunded reservoirs and lagoons



F. Application and limitations of results

(i) Volume of embankment

The cost functions presented earlier in parts B, C and D all require volume of embankment as an explanatory variable. There is no quick and accurate method of estimating embankment volume, which is largely determined by the nature of the strata at the site and the properties of the material to be used as fill. Embankment volume is related to a combination of crest length and height for each dam type, and the crude relationships given below will allow preliminary approximate estimates to be made. However, it must be stressed that if embankment volume is obtained by these means, the confidence limits attached to the various cost functions will no longer apply.

I: Earthbank dams with concrete cut-off walls

$$\underset{(\text{million m}^3)}{\text{DAMVOL}} = 0.0123 * \underset{(\text{m})}{\text{HEIGHT}}^{1.33} * \underset{(\text{km})}{\text{LEN}}^{0.882}$$

Number of cases	:	10
Multiple correlation coefficient (R)	:	0.97
Standard error of residuals (in $\log_{10}$ model)	:	0.126

II: Earthbank dams with clay cores

$$\underset{(\text{million m}^3)}{\text{DAMVOL}} = 0.00749 * \underset{(\text{m})}{\text{HEIGHT}}^{1.53} * \underset{(\text{km})}{\text{LEN}}^{1.18}$$

Number of cases	:	22
Multiple correlation coefficient (R)	:	0.95
Standard error of residuals (in $\log_{10}$ model)	:	0.140

(ii) Volume of water stored

For reservoirs and lagoons, the storage volume will probably be known before the method of construction is confirmed. Volume stored is the only explanatory variable required by the two functions in part E (although there was some evidence that cost increased with the number of compartments).

In spite of the differences in configuration of reservoirs, there does appear to be a definite relationship between depth and volume stored: this is illustrated in

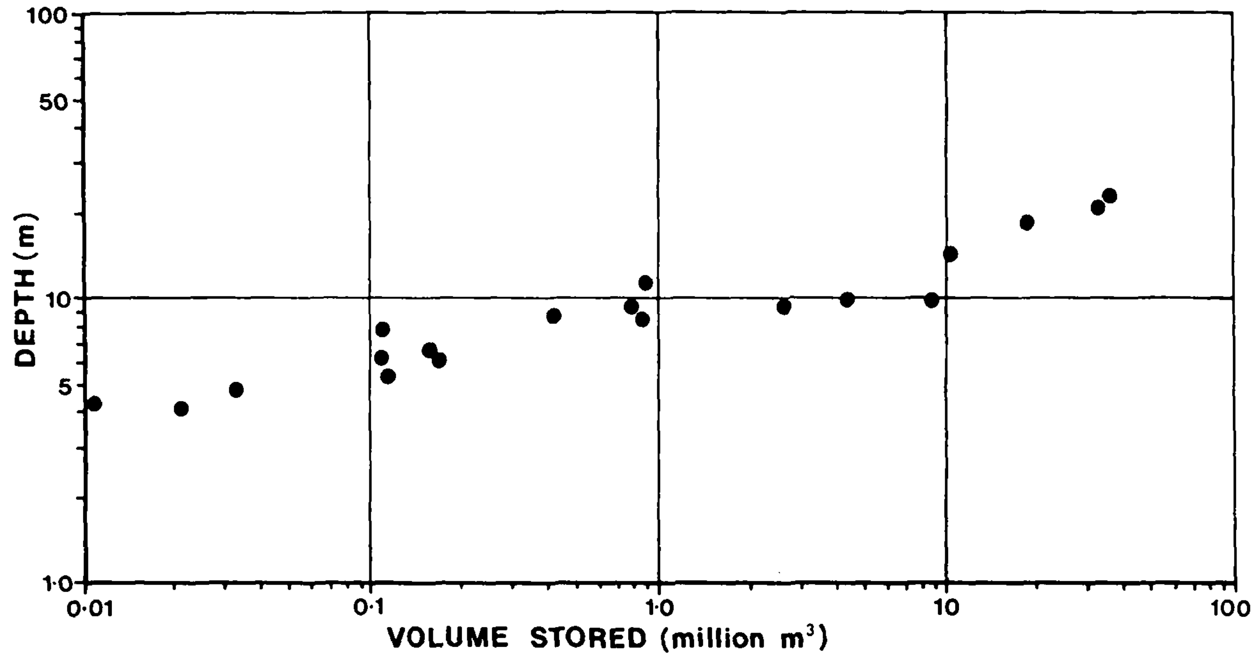


Figure 11–14. Scatter diagram of depth against volume stored for reservoirs and lagoons

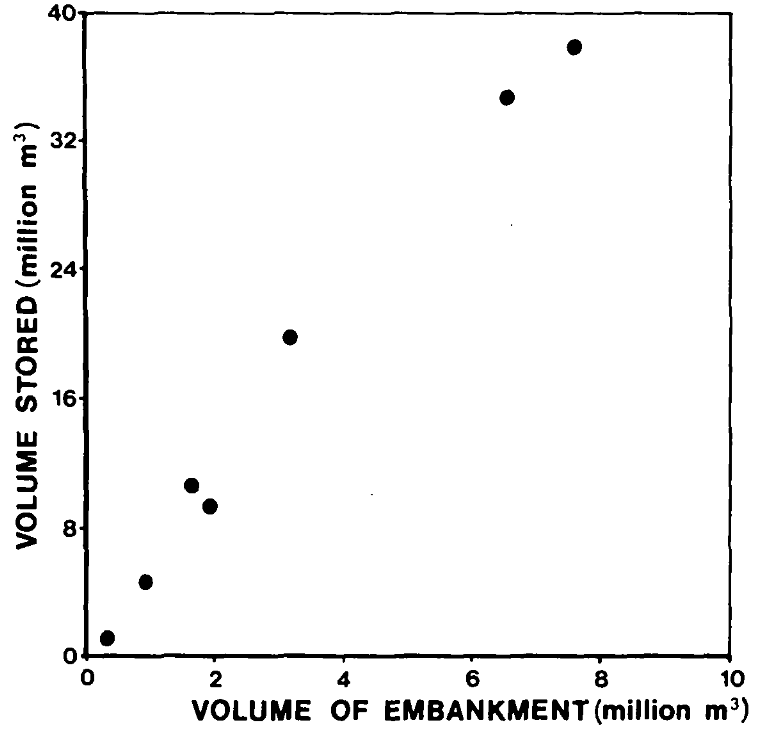


Figure 11–15. Scatter diagram of volume stored against volume of embankment for clay-cored bunded reservoirs

Figure 11-14. A more surprising relationship was found between volume stored and volume of embankment for the seven clay-cored bunded reservoirs. On basic theoretical grounds, volume stored would be expected to curve upwards when plotted against volume of embankment; however, Figure 11-15 offers no evidence at all of an economy of scale of this sort.

(iii) Embankment-associated works

For the reported functions, engineering and design, legal, compensation and land costs are excluded. Costs include the embankment and only those works that can be regarded as a fundamental (adjacent or integral) part of the dam or reservoir, such as the inlet and outlet works (e.g. valve towers and spillways), minor road and river diversions, and integral pipes and tunnels. Major items that could be the subject of another contract, such as river intakes and pumping stations for pumped storage, are excluded. However, in the case of a major pumphouse constructed as part of the embankment, a proportion of the pumphouse structure cost must be allocated to the embankment; the proportion identified in Section 10.4.2 for intakes is suggested.

A detailed breakdown of costs was available from 15 dam and reservoir BoQs, and is summarized in Table 11-11. This shows that the embankment and cut-off costs are typically about 60% of the total cost, whereas other items of construction work rarely exceed 10% of the total cost.

(iv) Unquantifiable factors

The cost of a dam or reservoir contract will be influenced by a number of major factors whose effects it is impossible to quantify. These include the difficulty of access, the prevailing weather conditions, the necessity for major diversions, and the ground conditions encountered. An assessment of such factors must depend largely on experience and local knowledge, such as whether it is necessary to import fill material or to provide substantial temporary drainage.

It should also be noted that in areas where land is expensive, the cost of land could for larger schemes be more than 10% of the total cost.

(v) Raw water storage schemes

In estimating the total cost of a raw water storage scheme, a number of additional costs must be estimated separately and added to the cost of the dam or reservoir (see (iii) above). These include the costs of river intakes, pumping stations and

Table 11–11. Breakdown of costs for 15 dam and reservoir contracts

Contract number	Component costs as percentages of total cost					
	General and daywork	Intakes, inlet and outlet works, and diversions	Embankment and cut-off	Catch-water	Spillways and overflows	Other items[†]
1	24.6	10.4	24.1	13.2	9.9	17.8
2	27.5	12.7	47.4			12.4
3	4.9	7.5	70.3		10.1	7.2
4	17.7	5.3	61.7		3.8	11.5
5	15.9	12.7	64.3			7.1
6	29.5	4.6	56.0		7.9	2.0
7	13.7	6.3	78.7			1.3
8	14.6	10.8	62.3		4.2	8.1
9	10.4	14.2	63.1	3.5	1.1	7.7
10	17.6	14.4	58.2			9.8
11	33.6	1.5	40.9			24.0
12	15.9	7.4	67.1			9.6
13	6.1	4.5	85.8			3.6
14	17.7	9.8	61.0			11.5
15	46.8[††]		27.1			26.1
Mean	19.7	8.7	57.9	8.4	6.2	10.6

[†] Includes roadworks, pipelines, instrumentation, site clearance, valves, valve towers, site investigation, landscaping, etc.

[††] Includes intakes, spillways and testing.

plant, raw water tunnels and mains which are not minor and adjacent or integral to the dam or reservoir, and other works such as major road and river diversions. Nine such schemes are summarized in Table 11-12, from which it can be seen that the overall cost of a pumped storage scheme is typically between 30 and 60% more than the cost of the dam or reservoir. However, this pattern can be severly distorted if substantial expenditure is required on pumping plant and buildings and aqueducts - a feature likely to become increasingly common. Consequently, each component cost should be estimated separately whenever local knowledge is available.

Table 11–12. Breakdown of costs for nine pumped raw water storage schemes

Scheme		Yield ('000 m^3/d)	Storage volume ('000 m^3)	Volume embankment (million m^3)	Major period of construction	Cost of embankment and associated work (£ million)	Cost in £ million (cost as proportion of embankment cost)			
							River intakes, pumping stations and plant	Raw water tunnels, mains and valves	Other works and costs	Total cost
Earthbank dam: pumped-cum-impounding	A	295	124	450	1972 - 1975	13.7	6.44 (0.47)	1.60 (0.12)	14.9 (1.09)	36.6 (2.67)
	B	22.7	5.05	1.50	1966 - 1969	1.68	0.28 (0.17)	0.13 (0.08)	0.34 (0.20)	2.43 (1.45)
	C	21.4	3.55	0.765	1967 - 1970	1.36	0.23 (0.17)	incl. -	0.21 (0.15)	1.80 (1.32)
	D	24.5	2.19	0.195	1968 - 1971	0.93	0.23 (0.25)	0.27 (0.29)	incl. -	1.43 (1.54)
Total earthbank bund: pumped storage	E	355	72.2	14.2	1965 - 1976	8.44	1.41 (0.17)	1.63 (0.19)	1.39 (0.16)	12.9 (1.53)
	F	146	0.910	0.311	1972 - 1976	0.33	1.58 (4.79)	0.85 (2.58)	0.02 (0.06)	2.78 (8.42)
	G	45.5	2.79	N.A.	1966 - 1972	1.33	0.43 (0.32)	0.27 (0.20)	0.12 (0.09)	2.15 (1.62)
	H	63.6	10.5	1.68	1966 - 1969	1.53	0.17 (0.11)	0.34 (0.22)	0.01 (0.01)	2.05 (1.34)
	J	29.5	4.55	0.95	1962 - 1966	1.19	0.17 (0.14)	0.08 (0.06)	0.02 (0.02)	1.46 (1.23)

12. WATER TREATMENT

12.1. TOTAL WATER TREATMENT WORKS COSTING

12.1.1. INTRODUCTION

The process stages required in a treatment works can broadly be related to the raw water quality. Five basic types of raw water have been defined, and these are discussed in Section 12.1.2.

In the cost functions for water treatment process units presented in Sections 12.2 to 12.7, capital costs have usually been related to simple, readily understood engineering variables such as 'plan area for filtration of gravity filters' or 'volume of sludge thickening tanks'. To estimate the total cost of a particular treatment works, therefore, it is necessary to assume suitable performance relationships in order to 'size' the various component units selected. Typical performance data is given in Section 12.1.3.

In addition to the process units, costs have to be estimated for other items, such as inter-process pipework and siteworks. For treatment works these costs have been allocated on a proportional basis to the costs of the process units. This is described in Section 12.1.4. (It is not necessary to consider costs related to conditions of contract, as these were spread proportionally over the process unit costs prior to developing the cost functions.)

An example which demonstrates how the total cost of a complete works is built up from estimates of its component parts is given in Section 12.1.5. It should be noted that the method is slightly different from that described in Chapter 13 for sewage treatment.

In the absence of detailed information on the raw water required to be treated and the processes to be included, the planner is likely to estimate the costs of works under average conditions. To avoid the need for a number of readers independently to repeat these standard calculations, the costs of works for a range of throughputs for each of the five raw water types have been estimated in the manner of the example in Section 12.1.5; these are presented in Section 12.1.6. In addition, confidence intervals have been derived for these estimates by the simulation method described in Section 8.4.2.

Finally, Section 12.1.7 provides an alternative means of estimating the total cost of a treatment works for use when the planner is not able to specify the component items in sufficient detail to use the results of Section 12.1.6. Complete treatment works models, relating total cost to throughput, have been developed for two categories of treatment:-

(a) single-stage clarification, using data relating to works built to treat raw water Type (iii), i.e. rockland/moorland;

(b) two-stage clarification, using data relating to works built to treat Types (iv) and (v), i.e. moorland and lowland.

It was not possible to discriminate between raw water Types (iv) and (v) from the available data, nor was there sufficient data to allow similar overall cost models to be developed for raw water Types (i) and (ii).

It must be emphasized that these 'whole works' models are too broadly based to provide more than a very rough indication of total cost; certainly they should not be used in preference to the more reliable estimates obtained from the 'component costs' approach.

12.1.2. WATER TREATMENT PROCESS STAGES

A. Classification of raw water

The extent and cost of treatment required to produce a potable water is dependent on the quality of the raw water. For planning purposes five basic raw water types can be identified according to the general nature of the source. Typical treatment needs for each type are summarized in Table 12-1 and discussed below.

Type (i): Groundwater

Although chlorination is the only standard form of treatment, other processes such as softening, iron removal or deacidification are commonly employed. Softening of large groundwater schemes is more likely to involve precipitation softening, with sedimentation and filtration, than ion exchange. For treatment of a simple kind, costing of all the components is straightforward. For more involved treatment such as precipitation softening, the approach used for costing coagulation-sedimentation-filtration treatment will need to be adopted.

Type (ii): Upland rock catchment

Normally, minimal treatment is required provided the water is aesthetically tolerable. The basic components are usually little more than the intake structure and plant and chlorination, together with necessary buildings. Cost estimation should therefore present no problem.

Type (iii): Upland rock and moorland catchment

The quantity of coagulant necessary to make the colour of the water aesthetically acceptable requires only one stage of clarification, by filtration. Thus this category differs from the moorland (iv) and lowland (v) categories in not requiring sedimentation. Other differences might include less chemical equipment and pumping plant, and therefore also fewer buildings. The smaller works are sometimes constructed with pressure rather than gravity filters to avoid breaking pressure. The use of filtration alone is usually limited to cases where the coagulant dose (aluminium or iron) does not exceed about 1.5 mg/l for most of the year.

Type (iv): Upland moorland catchment

The quantity of coagulant required for colour reduction makes two stages of separation necessary - sedimentation and filtration - and sludge disposal becomes more important.

Type (v): Lowland river

The turbidity and suspended solids of the water are usually greater than for upland water, and so sedimentation and filtration rates are higher. However, any capital savings that might be made from higher rate sedimentation and filtration can be outweighed by the need for greater provision of disinfection, pH adjustment for coagulation, activated carbon and low and high lift pumping.

Notes to Table 12-1 opposite.

(1) Microstraining is sometimes required in addition to coarse straining and (apart from water Type (ii)) chemical plant associated with coagulation.

(2) Including aeration.

(3) The selected combination of sludge processes is related to works size and location as well as water type.

(4) Flotation can be an alternative to sedimentation especially when settling rates are low.

(5) To avoid breaking head, pressure filtration is an alternative to gravity filtration.

(6) When the source is an impounding reservoir giving relatively constant quality water, upflow filtration is an alternative to sedimentation.

(7) Slow sand filtration can be an alternative to coagulation, preceded by rapid gravity filtration of settled or stored raw water.

(8) Slow sand filtration is an alternative to no treatment, especially when colour can sometimes be unacceptable. Ozonation can be an alternative, when coagulation is not always necessary, in conjunction with rapid gravity filtration or slow sand filtration, or both.

(9) Nitrate removal could become common.

12.1.2. Water treatment process stages

Table 12-1. Typical water treatment process stages

	Section	Raw water type				
		Ground-water (i)	Upland rock (ii)	Rock and moor-land (iii)	Moor-land (iv)	Low-land (v)
Basic treatment						
Preliminary works (1)	12.2		*	*	*	*(2)
Basic clarification:	12.3					
sedimentation	12.3.1				*	*
rapid gravity filtration	12.3.3			*	*	*
Disinfection	12.4	*	*	*	*	*
Sludge processes (3)	12.5			*	*	*
Water storage tanks	12.7			*	*	*
Other works items	12.8	*	*	*	*	*
Common alternative processes						
Flotation (4)	12.3.2				*	*
Pressure filtration	12.3.4			*(5)		
Upflow filtration	12.3.5				*(6)	
Slow sand filtration (7)	12.3.6		*(8)	*	*	*
Ozonation	12.4.2		*(8)			
Common additional processes						
Iron removal	12.6.1	*(2)				
Deacidification (CO_2)	12.6.1	*(2)				
Activated carbon	12.6.2	*		*	*	*
Softening	12.6.3	*				*
Hardening (pH adjustment)	12.6.3		*	*	*	
Nitrate removal (9)	12.6.4	*				*
Fluoridation	12.6.5	*	*	*	*	*

12.1.2. Water treatment process stages

B. General comments

The implications of raw water storage on treatment needs cannot readily be generalized. For a eutrophic water, algal-related problems might be enhanced. For a water which would otherwise be highly variable in turbidity and colour, storage can be advantageous in removing the extremes by mixing.

Treatment of surface waters based on slow sand filtration or ozonation or both deserves consideration. However, these processes have only been used a few times for wholly new treatment works in the last few decades. It has not therefore been possible to include them amongst the typical configurations for which costs are given in Section 12.1.6. Similar remarks apply to dissolved air flotation and upflow filtration.

Generally, water works sludges have no saleable value; the normal destination will therefore be an approved tip as a solid waste. The volume change from clarification effluent to solid sludge cake is large. The conversion is therefore usually done most economically in two stages: concentration and dewatering. For a particular sludge there will be an optimum combination of unit processes or a preferred sludge disposal strategy (see Section 12.1.3D).

12.1.3. PERFORMANCE DATA

A. Basic treatment

For estimating treatment works costs using the component approach, some idea is required of coagulant doses, clarification plant treatment rates and sludge production rates. Table 12-2 summarizes typical values of these for the five source types defined in 12.1.2.

Table 12-2. Typical coagulant doses, treatment rates and sludge quantities

	Raw water type				
	Groundwater (i)	Upland rock (ii)	Rock and moorland (iii)	Moorland (iv)	Lowland (v)
I. Coagulant dose (mg Al/l)	-	-	1.5	4.0	3.5
II. Sedimentation rate (m/h)	-	-	-	1.5	3.0
III. Filtration rate (m/h)	5 (iron removal)	-	4	5	6
IV. Sludge solids (kg/m^3)	0.005	-	0.015	0.025	0.045
V. Sludge volume as a proportion of total throughput	0.02	-	0.04	0.05	0.04
VI. Chlorination (mg Cl/l)	0.2	1.0	1.5	4.0	5.0

I. Coagulant dose

The choice of coagulant is best restricted to aluminium sulphate, ferric sulphate or chlorinated ferrous sulphate. Table 12-2 refers only to aluminium sulphate; typical iron doses are about twice as large, as the dosage is related to atomic weight. In the design of a new works, polyelectrolytes and other coagulation and flocculation aids are not normally considered; these are usually best reserved for uprating existing plant.

If the usual colour of the raw water is known (in $^{\circ}$Hazen), the typical values suggested in Table 12-2 may be replaced by an estimate of the required coagulant dose from the formula

$$\text{Dose in mg Al/l} = A + C*(^{\circ}\text{Hazen}).$$

The value of A ranges from about 1.0 for highly coloured, very soft upland waters to 2.0 for hard, highly reused lowland river water. The value of C is about 0.02 for highly coloured, very soft upland waters, about 0.05 for not very alkaline and not much reused lowland river water, and reaches about 0.2 for hard, highly reused lowland river water. The influence of turbidity is relatively unimportant unless it exceeds about 30 Ntu.

II. Sedimentation rate

The distribution of design sedimentation rates for treatment works constructed since 1960 is given in Table 12-3(a). The current trends in new works design and the uprating of existing plant makes the distribution conservative. The information cannot be used for estimating rates when precipitation softening is carried out.

III. Filtration rate

The distribution of design filtration rates for both gravity and pressure filters is given in Table 12-3(b). Again, these should be regarded as conservative. Table 12-3(c) shows the distribution of the ratio of filtration and sedimentation rates. Research experience favours a filtration-sedimentation rate ratio of about three.

IV. Dry sludge solids

The sludge solids production rate can be estimated from the following (9):-

- Weight of sludge solids production rate in mg/l (g/m^3)
  - = raw water suspended solids
  - + 0.07*($^{\circ}$Hazen colour removed)
  - + metal hydroxide precipitated from coagulation
  - + sum of other additives (e.g. carbon, polyelectrolyte) and sludge conditioners (e.g. lime).

Table 12-3. Sedimentation and filtration rates

(a) Sedimentation rates (46 cases)

m/h	< 1	1.5	2.0	2.5	3.0	> 3.5
%	28	22	15	11	13	10

(b) Filtration rates (63 cases)

m/h	< 3	4	5	6	7	> 8
%	11	35	29	13	8	4

(c) Ratio of filtration to sedimentation rates (43 cases)

ratio		1	2	3	4	5
%		12	28	37	16	7

V. Sludge volume

The sludge volume depends mainly upon the frequency of filter backwashing and the efficiency of excess floc removal and blanket level control in sedimentation. For example, for filters operating at 5 m/h washed daily for ten minutes with a 7 mm/sec wash rate, the washwater production will be about 3.5% of the filtered water. The sludge rate from floc blanket sedimentation might be more than 2.5% when water treatment is generally difficult, and less than 1.0% in easy situations and where excess floc removal involves some pre-concentration within the sedimentation tanks.

VI. Chlorination for disinfection

The typical doses of chlorine given in Table 12-2 assume the simplest common situations, as discussed below.

(i) Groundwater. For good groundwater the chlorine dose required is effectively the residual free chlorine concentration necessary for distribution.

(ii), (iii) Upland rock, rock and moorland. It has been the practice not to use superchlorination, i.e. excess chlorination followed by dechlorination, on water from well protected sources.

(iv), (v) Moorland, lowland. When these sources are eutrophic and relatively unprotected it is usually necessary to provide a higher chlorination capacity as a safety measure against sewage pollution, or to help remove algae and animals. The ability to apply chlorine doses of at least 10 mg/l is common. It is becoming relatively less important to relate chlorination capacity to the ammonia concentration in raw water: chlorine doses are tending to increase for other reasons, and ammonia concentrations are in any case reduced by the greater use of raw water storage.

Although affecting disinfection, the use of chlorine for colour bleaching to avoid coagulation treatment is regarded as a separate process, as is chlorine utilized for chlorinated ferrous sulphate as a coagulant.

B. Common alternative processes

Treatment rates of the common alternative processes are related less to raw water type and more to other site factors. Typical values are as follows:-

Flotation:	from 8 m/h for cold water of rapidly varying quality to 14 m/h for warm constant quality water.
Pressure filtration:	as for rapid gravity filtration.
Upflow filtration:	from 8 m/h for high concentration coagulated water to 15 m/h for low concentration coagulated or uncoagulated water.
Slow sand filtration:	from 0.1 m/h when no prefiltration to more than 0.2 m/h with efficient prefiltration.
Ozonation:	see Section 12.4.2.

C. Common additional processes

Performance data for additional processes is dependent on individual water qualities and generalizations are not possible. Some discussion of performance is included in the sections presenting the cost functions for these processes.

D. Sludge disposal

The objective of any new sludge processing works must be to remove sludge solids from the works or to dispose of them on site permanently at the rate at which they arise. For planning purposes, it is best assumed that sludge is processed for dumping as a solid waste and the separated water returned to the inlet works. This will require concentration by settlement or continuous thickening, or both, followed by dewatering on drying beds or in filter presses. Lagooning can also be considered, although it is not technically satisfactory in all cases.

Current studies indicate that, taking into account both capital and operating costs, direct thickening is typically less expensive than settlement followed by thickening, and that for solids loadings greater than about 1 000 kg dry solids a day, filter pressing is cheaper than using sludge drying beds. Lagooning is not much more expensive than using drying beds.

12.1.3. Performance data—water treatment

The estimated sludge processing costs presented in this report are for the production of a handleable solid to be loaded on to vehicles ready for transport to an approved tip. Transport and tipping charges have not been considered as these are largely dependent on the site.

Little information is available on how to scale sludge processing plant in relation to throughput. The following notes summarize current practice and may be used as a rough guide for planning.

(i) Settlement tanks

Although two tanks might be adequate, estimates should preferably be based on three tanks - one filling, one standing full, and one decanting and being made ready for filling. Typically after four hours of standing a tank can be decanted to yield a clear supernatant, so that three tanks must have a total capacity of at least 12 hours' flow. For small works the full daily volume should be catered for by the tanks.

(ii) Continuous thickeners

The simple rule adopted is to allow volume for one hour's total sludge flow plus 24*the average hourly thickened sludge flow. Thickener diameter should also allow for a maximum decanting upflow velocity equal to the floc blanket sedimentation rate. To allow for truly continuous operation some holding capacity is required prior to the thickener. Where thickening follows static settlement, the holding capacity should be about 16% of the total volume of the settling tanks. Without prior static settlement the holding capacity should be sufficient to hold the whole wash of one filter, and for average size filters is about 150 m^3. For small works where all the filters are washed immediately one after the other, the holding capacity should equal the total washwater volume. All the thickening volumes in the range can be accommodated in single tanks. For process security, duplicate thickeners are included.

(iii) Drying beds

With polyelectrolyte dosing and good operating conditions it is possible to dewater 50 kg sludge solids per year per m^2 of drying bed. However, the drying rate is not uniform through the year, and to allow for annual variations it is necessary to provide four months' storage.

12.1.3. Performance data - water treatment

(iv) Filter presses

Typical filter cakes are 25 mm thick with a solids content of 25% and bulk density of 1180 kg/m^3, corresponding to 3.7 kg dry solids per m^2 filtration area. Sludge conditioning can be adjusted to achieve a pressing cycle each working shift, or three pressings per day. In the absence of more suitable information, the frequency of pressing and the provision of pressing capacity can be based on the recommendations for sewage sludge pressing in Section 13.7.3, as shown in Table 12-4. Appropriate allowance should be made in the filtration area for the use of sludge conditioning chemicals.

(v) Lagoons

A lagoon might be sized so that after one year it is full of settled sludge at the same solids concentration as that produced by a continuous thickener. A second lagoon would then be brought into use and the first allowed to dewater and consolidate before it is emptied ready for reuse.

Table 12-4. Typical filtration areas for a range of values of sludge solids, output and pressing rate for water works sludge pressing (based on sewage sludge pressing relationships)

Sludge solids (kg/m³)	Output ('000 m³/d)	Filtration area ('000 m²) Maximum number of pressings per press per week 5	 10	 15
0.005	2	-	-	-
	5	-	-	-
	10	-	-	-
	20	-	-	-
	50	-	-	-
	100	0.224	-	-
0.015	2	-	-	-
	5	-	-	-
	10	-	-	-
	20	-	-	-
	50	0.336	-	-
	100	0.671	-	-
	200	1.34	0.671	-
	500	-	1.68	-
0.025	5	-	-	-
	10	-	-	-
	20	0.223	-	-
	50	0.559	-	-
	100	1.12	0.559	-
	200	-	1.12	-
	500	-	2.80	1.86
0.045	5	-	-	-
	10	0.201	-	-
	20	0.403	-	-
	50	1.01	0.504	-
	100	-	1.01	-
	200	-	2.01	1.34
	500	-	-	3.36

12.1.4. ESTIMATION OF WHOLE WORKS TOTAL COST

A. Summary of the method

This section describes a method of estimating the total capital cost of a water treatment works, using the individual component cost functions presented in Sections 12.2 to 12.7 and information elsewhere in the report.

The method proceeds in four stages, as summarized in Figure 12-1 below.

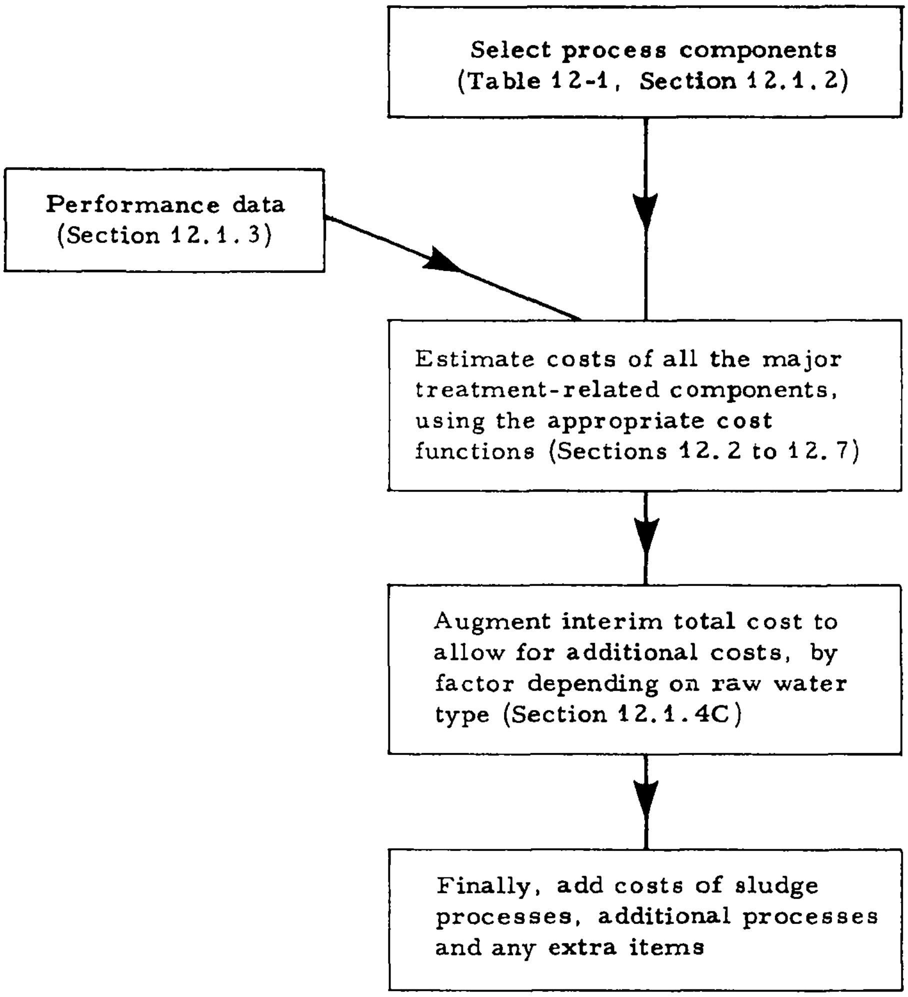


Figure 12-1. The four stages in estimating whole treatment works total cost

Firstly, Section 12.1.2 provides some basic guidelines for determining what components are required for the scheme under consideration. Using the typical performance data given in Section 12.1.3, cost estimates can then be made of all those components (except sludge processes) for which cost functions are available; these are totalled to form an 'interim' total cost. Next, allowance must be made for those components which cannot satisfactorily be modelled: these are mainly items related to the topography of the site or the extent of treatment chosen, such as siteworks and pipeworks, and are represented by a proportional factor depending on the raw water type. The numerical values taken by this factor are derived in part C following. Finally, costs associated with sludge (which it has been convenient to deal with separately, as explained in part D) and any extra items (see Section 12. 8. 3) should be added to obtain the final total cost estimate.

B. Costs relating to conditions of contract

There are some costs in contracts which relate mainly to the conditions of the contract. These include:-

general conditions of contract;
preliminaries;
contingencies, provisional sums;
guarantee and insurance bonds;
non-specific variations and additions;
lumps and supplementary sums, negotiated settlements;
dayworks;
installation, testing, commissioning, maintenance.

Mechanical engineering contracts include:-

handrailing, chequer plate, painting;
general piping and valves;
spares, laboratory equipment;
drawings, instruction manuals;
overhead charges and profit.

Unless otherwise stated, the costs used for developing the cost functions in Sections 12. 2 to 12. 7 (except for 12. 6) were adjusted proportionally to take account of these conditions of contract costs, which generally therefore need no further consideration. (It should be noted that this approach differs slightly from that taken in Chapter 13 for sewage treatment.)

Table 12-5 expresses the conditions of contract costs as a percentage of all other costs in the contract, for both civil engineering and plant contracts. There is no evidence from the data available that these percentage figures are related to the size of the treatment works.

Table 12-5. Costs relating to conditions of contract as a percentage of the sum of all other costs in contracts

Upland or lowland	Output ('000 m^3/d)	Conditions of contract costs	
		Civil engineering %	Process plant %
U	3.6		34.5
U	5.5	51.4	33.1
U	7.8	43.2	31.9
U	8.7	24.1	25.7
L	9.1	42.3	5.2
U	11.4	19.8	
U	13.6	30.8	
L	14.5	15.4	
U	15.0	29.5	19.8
U	18.2	34.3	
L	20.5	36.1	12.9
L	22.7	54.1	21.5
U	27.3	46.2	19.0
L	54.5	38.6	17.6
L	68.2	31.0	
U	72.7	31.4	40.0
L	109	27.0	60.6
L	145	52.6	19.3
U	159	49.2	38.3

12.1.4. Estimation of whole works total cost

C. Derivation of the 'additional costs' factor

(i) Sedimentation-filtration treatment

The costs of any one component in a water treatment works can be categorized under two headings: civil engineering and building work, and mechanical and electrical engineering work. These categories are usually covered by separate contracts. Table 12-6 shows the ratio of plant to civil engineering costs for 12 examples of complete sedimentation-filtration works (including extra items and sludge processes). The ratio appears to be unrelated either to output capacity or to the nature of the raw water.

Table 12-6. Ratio of plant to civil engineering costs for sedimentation-filtration treatment

Output ('000 m^3/d)	Raw water type	
	Upland	Lowland
5.5	0.56	
7.8	0.97	
8.7	0.87	
9.1		0.70
15.0	0.45	
20.5		0.41
27.3	0.55	
54.5		0.34
72.7	0.57	
109		0.69
145		0.97
159	0.26	
Mean	0.60	0.62
Grand mean	0.61	

The breakdown of costs within the civil engineering category has been determined from a sample of 18 sedimentation-filtration works; this is shown in Table 12-7. The table also shows the breakdown of process plant costs obtained from a sample of 14 cases. The categorizing of costs was not always easy because of the varied manner in which costs are assigned within contracts, and there was also considerable variation in some of the proportions from contract to contract. However, these fluctuations are to some extent smoothed out by the average figures given in Table 12-7.

Table 12-7. Average breakdown of costs for sedimentation-filtration treatment

Civil engineering and building			Process plant		
	%	Weighted %		%	Weighted %
Inlet works	2.1	(1.3)	Inlet equipment	2.4	(0.9)
* Buildings	23.7	(14.7)	* Chemical equipment	23.2	(8.8)
* Settling	14.1	(8.8)	* Clarification	6.7	(2.5)
* Filters	13.4	(8.3)	* Filtration	25.2	(9.7)
* Tanks	16.2	(10.1)	Instruments and control	12.0	(4.5)
* Sludge	2.8	(1.7)	* Sludge equipment	2.5	(0.9)
Siteworks	10.7	(6.6)	* Pumps, power and switchgear	28.0	(10.6)
Pipework	7.6	(4.7)			
Power	3.8	(2.4)			
Pumping	5.6	(3.5)			
	100.0	62.1		100.0	37.9

Note: Items marked * are those for which cost functions are available.

From Table 12-6, the average ratio of plant to civil engineering costs is 0.61. This means that civil engineering and plant costs amount respectively to 62.1% and 37.9% of the total cost, on average (because 37.9/62.1 = 0.61). The figures in Table 12-7 have been weighted in these proportions to provide an overall breakdown of total cost; this is given in brackets. Thus, for example, tanks amount on average to 16.2% of the civils costs, but only 10.1% of the total civils and plant costs.

The proportional factor introduced in part A can now be derived. Cost functions are available for all the items marked with an asterisk in Table 12-7. These amount to 76.1% of the total (using the weighted percentage figures). Thus the total cost of a works incorporating <u>all</u> the items listed in Table 12-7 would be estimated by multiplying the 'interim total' for the asterisked items by 100/76.1, or 1.31. However, if certain of the items in Table 12-7 are not to be included, the factor must be modified to

$$\frac{(100\% \ - \text{total } \% \text{ of items not included})}{(76.1\% \ - \text{total } \% \text{ of items not included})}.$$

This adjustment must be made for sludge costs, which are estimated separately (for reasons discussed later). The percentages associated with sludge are 1.7% (civils) and 0.9% (plant). The amended proportion therefore becomes (100 - 1.7 - 0.9)/(76.1 - 1.7 - 0.9) = 97.4/73.5 = 1.33, and this is the figure by which the interim total cost estimate for sedimentation-filtration should be multiplied to allow for the remaining items.

Finally, the costs of sludge and extra items should be added to obtain the whole works total cost.

(ii) <u>Other treatment configurations</u>

Insufficient data was available for the approach of Tables 12-6 and 12-7 to be taken for the treatment of groundwater, the treatment of upland rock catchment waters, treatment with filtration only, or even basic extensions. However, some simple generalizations can be made from the existing figures, as follows.

Treatment by rapid gravity filtration only differs from sedimentation-filtration in the absence of sedimentation. The multiplier can therefore be modified as described in (i) above by removing the settling and clarification proportions, to give (97.4 - 8.8 - 2.5)/(73.5 - 8.8 - 2.5) = 86.1/62.2 = 1.38.

For those upland treatment works with gravity filtration not involving major pumping plant, the multiplier is further modified to become

$$(86.1 - 10.6)/(62.2 - 10.6) = 75.5/51.6 = 1.46.$$

For pressure filtration, the 8.3% civil engineering figure for filters has been reallocated to the process plant costs to allow for steel rather than concrete filter shells. Thus, in the absence of better information,

$$\text{civils multiplier} = (1.3 + 14.7 + 10.1 + 6.6 + 4.7)/(14.7 + 10.1) = 1.51,$$
$$\text{plant multiplier} = (0.9 + 8.8 + 9.7 + 8.3 + 4.5)/(8.8 + 9.7 + 8.3) = 1.20,$$

and the combined civils and plant multiplier = 1.35.

Extensions can be treated in two ways. If an extension is basically a separate unit then it is best considered as a whole treatment works, although the building content might be less. When an extension is a true extension of the original unit, however, the cost of the extension to the component should first be estimated as if it were a separate unit and then adjusted for a proportion of the siteworks and pipeworks by multiplying by the factor $100/(100 - 6.6 - 4.7) = 100/88.7 = 1.13$. This should also be applied to additional and sludge processes.

The various multipliers derived above are assembled for ease of reference in Table 12-8.

Table 12-8. Additional cost multipliers for different types of treatment works

Description of works	Multiplier		
	Civils	Plant	Combined
Full sedimentation-filtration	1.42	1.19	1.33
Rapid gravity filtration with pumping	1.56	1.19	1.38
Rapid gravity filtration without major pumping	1.56	1.29	1.46
Pressure filtration	1.51	1.20	1.35
Extension to existing works	-	-	1.13

Note: All the above cases exclude sludge processes.

12.1.4. Estimation of whole works total cost

D. Sludge processing

Table 12-7 indicates that the capital cost of sludge processing has in the past been substantially less than the cost of either sedimentation or filtration. Current studies suggest that this will no longer be so; with the adoption of a satisfactory sludge disposal policy, the capital cost of sludge processing might be more than half the capital cost of either sedimentation or filtration. Guidelines on the sizing and selection of sludge processes have been given in Section 12.1.3.

12.1.5. WORKED EXAMPLE

This section presents a worked example to illustrate the method of estimating total cost outlined in Section 12.1.4. The example has been selected arbitrarily and should not be regarded as 'typical'. It concerns a works of 50 000 m^3/d output treating upland moorland water of Type (iv) (see Table 12.1), for which the components are as shown in Figure 12-2 below.

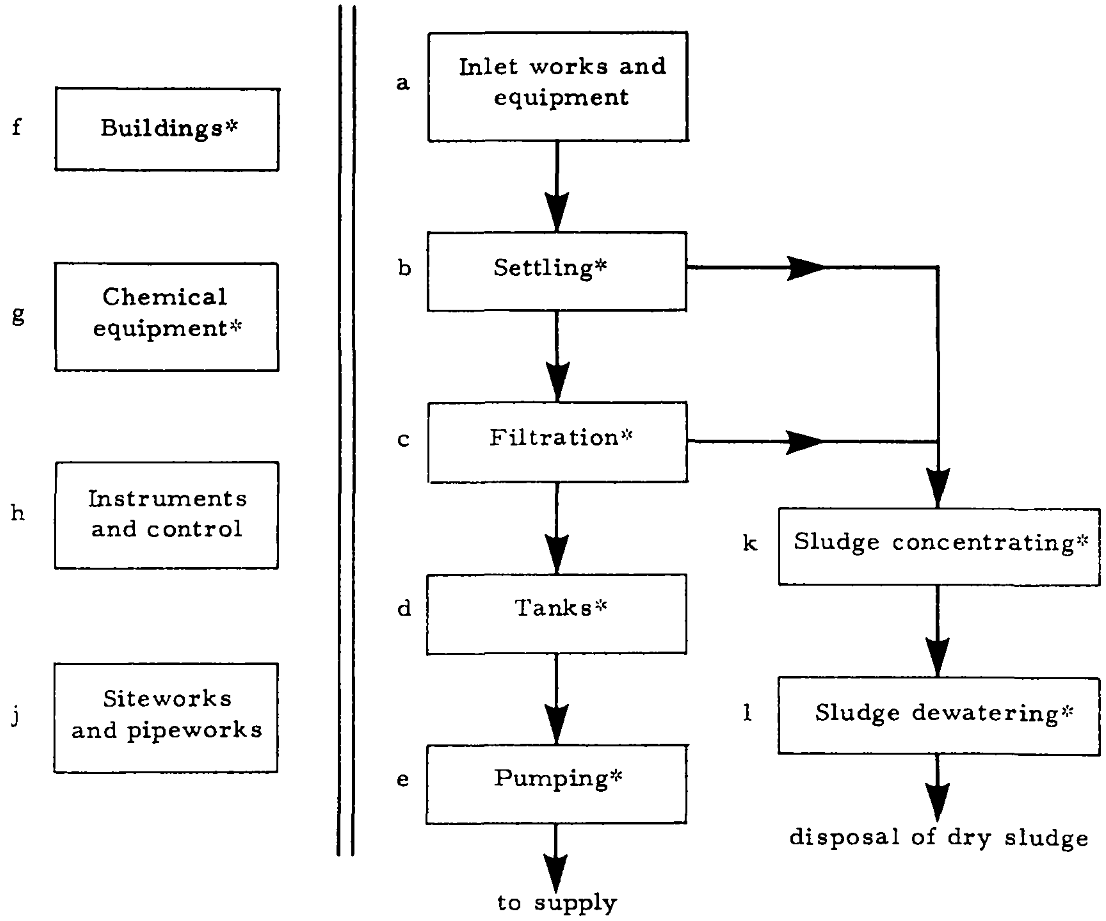


Figure 12-2. Process components in water treatment worked example

For the components marked with an asterisk, all or most of the cost can be estimated from quoted cost functions. The cost of the remaining items is accounted for by using multipliers developed in Section 12.1.4.

For convenience, costs have been rounded to the nearest £'000.

12.1.5. Worked example—water treatment

(a) Inlet works and equipment

No detailed information is available for estimating the cost of this component separately. Allowance is therefore made for it in the final multiplier.

(b) Settling

Assumption: sedimentation rate = 1.5 m/h.

$$\text{Therefore sedimentation area required} = \frac{50\,000}{1.5*24} = 1390 \text{ m}^2.$$

For this size proprietary tanks are cheaper than hopper tanks.
Thus from Section 12.3.1, total civil engineering and plant cost is:-

$$\text{COST} = 0.389*(1.39)^{0.76}, \text{ i.e. } \underline{£500\,000}.$$

(c) Filtration

Assumption: filtration rate = 5 m/h.

$$\text{Therefore filtration area required} = \frac{50\,000}{5*24} = 417 \text{ m}^2.$$

Gravity filters will be used. Thus from Section 12.3.3B(iii),

$$\text{CIVCOS} = 0.388(0.417)^{0.81}, \text{ i.e. } \underline{£191\,000}$$

and

$$\text{PLANTCOS} = 0.437(0.417)^{0.68}, \text{ i.e. } \underline{£241\,000}.$$

(d) Tanks

For both the contact and the filtered water tanks the small rectangular concrete covered tank cost function given in Section 12.7.1C has been used.

Assumption for filtered water tank: two hour storage period.

$$\text{Therefore storage volume required} = \frac{50\,000*2}{24} = 4170 \text{ m}^3.$$

$$\text{Thus COST} = 69.1(4.17)^{0.48}, \text{ i.e. } \underline{£137\,000}.$$

Assumption for contact tank: 30 minute storage.

$$\text{Therefore storage volume required} = \frac{50\,000*0.5}{24} = 1\,040\ \text{m}^3.$$

Thus $\text{COST} = 69.1(1.04)^{0.48}$, i.e. £70 000.

(e) Pumping

The cost of pumping plant can be estimated from throughput alone using the function presented in Section 10.4.1(iv).

Assumption for pumping plant: 50% standby capacity.

$$\text{Therefore pumping capacity required} = \frac{1.5*50\,000}{24} = 3125\ \text{m}^3/\text{h}.$$

Thus $\text{WATCOS} = 0.160(3125)^{0.77}$, i.e. £79 000.

(f) Buildings

The cost of buildings required to house chemical plant, control rooms, pumping plant, basic laboratory, mess rooms, etc., can for normal circumstances be based on a single estimate related to total floor area required. This must first be estimated from throughput using the function given in Section 12.2.3A as follows:-

$$\text{CHEMAREA} = 31.6(50)^{0.85} = 879\ \text{m}^2.$$

Thus from Section 14.1,

$$\text{WATCOS} = 248(0.879)^{0.94},\ \text{i.e.}\ \underline{£220\,000}.$$

(g) Chemical equipment

Cost of chemical equipment is related to throughput, with the score for CHEM defining the complexity of chemical treatment and the value of TYPE representing the standard of equipment supplied.

12.1.5. Worked example—water treatment

Assumptions: CHEM = 7,
TYPE = 2.

Thus from Section 12. 2. 3C,

$$\text{COST} = 2.23(50)^{0.46}(7)^{1.17}(2)^{1.30}, \text{ i.e. } \underline{£324\ 000}.$$

(h) Instruments and control, and
(j) Siteworks and pipeworks

No detailed information is available for estimating the cost of these components separately. Allowance is therefore made for them in the final multipliers.

(k) Sludge concentrating

Concentrating is assumed to be carried out in a continuous thickener. The thickened sludge is then stored prior to dewatering.

Assumptions:
1. Sludge solids: 0. 025 kg/m^3 of throughput.
2. Thickening for 24 h at mean concentration of 0. 025 m^3/kg (4%).
3. Sludge volume: 0. 05% of throughput.
4. Clarification for 1 h.
5. Holding capacity of 150 m^3 included for convenience as part of the thickener volume.

As the necessary thickener volume can be provided by one tank, two tanks are to be constructed.

$$\text{Thus thickener volume} = 2*\left(\frac{0.025}{40} + \frac{0.05}{24}\right)*50\ 000 + 150\ m^3$$
$$= 421\ m^3$$

and so, from Section 12. 5. 1C, thickener tank cost is:-

$$\text{PYRCOS} = 55.4(0.421)^{0.56}, \text{ i.e. } \underline{£34\ 000}.$$

Assumption: thickened sludge stored for three days.

$$\text{Therefore storage volume} = \frac{50\ 000*0.025*3}{40} = 93.8\ m^3.$$

Thus storage tank cost is:-

$$\text{PYRCOS} = 55.4(0.0938)^{0.56}, \text{ i.e. } \underline{\pounds 15\ 000}.$$

(1) Sludge dewatering

Separate estimates can be made for the filter press plant cost and the building cost; both are based on the plate area required.

Assumptions:
1. Sludge solids: 0.025 kg/m^3 of throughput.
2. Quality of cake is 3.68 kg dry solids per m^2 filtration area.
3. Pressing five days per week with 15% downtime.

$$\text{Therefore filter press area required} = 0.025 * \frac{50\ 000}{3.68} * \frac{7}{5} * \frac{1}{0.85} = 559 \text{ m}^2.$$

Thus, from Sections 12.5.2 and 13.7.3,

$$\text{MECCOS} = 282 * 0.559^{0.87}, \text{ i.e. } \underline{\pounds 170\ 000}$$

and

$$\text{CIVCOS} = 159 * 0.559^{0.74}, \text{ i.e. } \underline{\pounds 103\ 000}.$$

(The cost function given in Section 13.7.3 for the civil costs has been reduced by 10% for the water sludge treatment application.)

(m) Total costs

These cost estimates can now be collected and allowances made for the remaining items, as follows:-

	£'000 (1976 Q3)	
Civil engineering:		
settling	500	
filtration	191	
tanks	137	
	70	
building	220	
Total	1118	
(Multiplier 1.42) Adjusted total		1588
Plant:		
filtration	241	
pumping	79	
chemical	324	
Total	644	
(Multiplier 1.19) Adjusted total		766
Sludge treatment:		
thickening	34	
storage	15	
press	170	
building	103	
Total	322	
(Assume multiplier 1.0) Adjusted total		322
Grand adjusted total		2676

Thus overall total capital cost = £2 676 000.

12.1.6. TOTAL COST ESTIMATES FOR TYPICAL CONFIGURATIONS

A. The general approach

The worked example given in Section 12.1.5 shows that it can be a lengthy process to gather together and evaluate all the relationships relevant to a particular treatment works. Also, although an approximate method of calculating a confidence interval about a total cost estimate is described in Section 8.4.1, this is an even more laborious undertaking which has little practical appeal. For these reasons a computer program was developed with the following aims:-

(i) to estimate total cost, in the manner of the worked example, for a number of typical flowrates and raw water types;

(ii) to repeat the calculations a large number of times for each particular configuration, simulating the random forecasting errors associated with each component cost estimate and thereby building up a distribution of 'possible' total costs from which a confidence interval could be determined.

This procedure was followed for three of the five raw water types considered in Section 12.1.2, namely:-

Type (iii): Rock and moorland;
Type (iv): Moorland;
Type (v): Lowland.

Costs have not been estimated for raw water Type (i). However, groundwater treatment is likely to be comparable to one of the examples of surface water treatment and so those cost estimates could be used. For raw water Type (ii), upland rock water, there is essentially no treatment works as the chlorination plant and floor area will normally be part of the intake structure and plant. However, typical costs for this situation (which will also generally apply to intakes for other surface waters) have been prepared, and these are given in part D.

B. The assumptions

Tables 12-9 (following) and 12-4 (Section 12.1.3D) summarize the performance relationships and other assumptions required to 'size' the component units and to obtain the final adjusted total costs. The estimate given of floor area for buildings housing pressure filters and the requirement for storing water to backwash pressure filters are only subjective assessments which have not been discussed elsewhere in the report.

It has been assumed that there is negligible loss or recycling due to sludge production and negligible spillage or addition due to chemical dosing; thus for simplicity, input is equivalent to output. The dimensioning of all components was related to normal throughput, without allowances being made for extensions to any components. Normal throughput was used rather than a maximum or overload value that might be required for short periods only. However, the costs from which the functions have been derived can be assumed to include an allowance for extra hydraulic capacity to meet usual maximum or overload throughputs.

Total cost includes the costs of all component items as defined in the preceding sections dealing with the basic configurations of treatment works for different raw water types. Cost also includes all costs relating to conditions of contract (see Section 12.1.4B). The quoted costs make no allowance for additional processes and extra items. However, some distinction has been made between 'sludge process' costs, 'civil engineering and building' costs and 'mechanical and electrical engineering' costs so that multipliers derived from Table 12-7 (and summarized in Table 12-8) could be used. Costs of sludge treatment were calculated separately so that they could, if desired, be replaced by other costs based on more specific local assumptions.

12.1.6. Total cost estimates for typical configurations

Table 12-9. Performance data and relationships for water treatment works

Treatment component	Design variable	Raw water type			
		(iii) Rock and moorland		(iv) Moorland	(v) Lowland
		Pressure filtration	Gravity filtration		
WATER					
Buildings	Floor area (plus additional component for pressure filtration)	AREA + either 4*vert. filter area or 3*horiz. filter area	AREA = 0.0316*(OUTPUT)$^{0.854}$		
Settling	Area	AREA = OUTPUT/(SED. RATE*24)			
	Sedimentation rate	none	none	1.5 m/h	3.0 m/h
Filters	Area	AREA = OUTPUT/(FILT. RATE*24)			
	Filtration rate	4 m/h	4 m/h	5 m/h	6 m/h
Contact tank plus either Filtered water tank or Backwash water tank	Volume for 0.5 h contact time	none	VOL = OUTPUT*0.5/24		
	Volume for 2 h storage time	none	VOL = OUTPUT*2/24		
	Volume to wash >25 filters 7-25 filters <7 filters	none 5*area of 2 filters 5*total filter area	none	none	none
Pumping plant	Capacity	none	CAP = OUTPUT*1.5		
Chemical plant	CHEM score Type OUTPUT	4 2	4 2	7 2	9 2
Adjustment factor (excluding sludge)	Civils cost Plant cost Combined cost	1.51 1.20 1.35	1.56 1.19 1.38	1.42 1.19 1.33	1.42 1.19 1.33
SLUDGE		Transition from drying to pressing at 1000 kg/d dry solids			
General	Sludge solids	0.015	0.015	0.025	0.045
	Sludge volume proportion	0.04	0.04	0.05	0.04
Continuous thickeners	Volume	VOL = 0.15 + OUTPUT*2(SLUDGE SOLIDS*0.025 + SLUDGE VOL/24)			
Thick sludge storage for pressing	Volume for 3 days' retention period	VOL = 3*OUTPUT*SLUDGE SOLIDS*0.025			
Thick sludge storage for drying	Volume for 120 days' retention period	VOL = 120*OUTPUT*SLUDGE SOLIDS*0.025			
Sludge drying	Area	AREA = OUTPUT*SLUDGE SOLIDS*365/50			
Sludge press and building	Area	See Table 12-81			

Note: The following units are used:-

AREA	-	'000 m^2
OUTPUT	-	'000 m^3/d
SED., FILT. RATE	-	m/h
VOL	-	'000 m^3
CAP	-	'000 m^3/d
SLUDGE SOLIDS	-	kg/m^3

12.1.6. Total cost estimates for typical configurations

C. The results - chemical treatment costs

Tables 12-10 to 12-13 present the estimated capital costs of chemical treatment over a range of throughputs for certain combinations of raw waters and treatment processes, as follows:-

Table 12-10:	Type (iii) (rock and moorland), pressure filtration;
Table 12-11:	Type (iii) (rock and moorland), gravity filtration;
Table 12-12:	Type (iv) (moorland), sedimentation-filtration;
Table 12-13:	Type (v) (lowland), sedimentation-filtration.

The tables show the combinations of components assumed for each throughput. In cases where there was no clear-cut choice of process units, alternative combinations were included; these are indicated by (a) and (b) in the throughput column. For example, at 10 000 m^3/d in Table 12-10 both vertical and horizontal pressure filters have been costed as alternatives in the treatment of rock and moorland raw water.

Every cost estimate is the mean of 1000 'worked examples', all containing different random errors in each cost component. It was found, as with sewage treatment, that log cost could be closely approximated by a Normal distribution (see Figure 13-2). This means that the standard deviation of each log cost distribution can be used to form multiplicative 80 and 95% confidence intervals similar to those quoted for the individual cost functions throughout Part III. These are shown at the foot of each table of results. For sludge costs the confidence limits depend on whether drying or pressing was assumed. In all other cases the limits are approximately independent of throughput or process alternatives.

Table 12-10. Costs for rock and moorland raw water, Type (iii), pressure filtration treatment

Throughput ('000 m^3/d)	Filtration processes	Other water treatment processes	Sludge drying or pressing	Other sludge processes	£'000 1976 Q3 Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost	Grand total cost
2	Vertical filters	Chemical building, chemical plant, backwash tanks	Sludge drying	Continuous thickening and sludge storage	94.6	92.0	187	46.4	233
5					159	180	339	68.4	408
10(a)					274	307	581	96.5	678
10(b)	Horizontal filters				287	230	517	96.5	614
20					440	335	774	140	915
50(a)					931	550	1480	241	1720
50(b)			Sludge pressing		931	550	1480	222	1700
100					1630	801	2430	374	2800

			Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost: Drying	Sludge cost: Pressing	Grand total cost
Confidence levels	80%	Upper	1.73	1.15	1.39	1.35	1.20	1.33
		Lower	0.58	0.87	0.72	0.74	0.83	0.75
	95%	Upper	2.32	1.24	1.65	1.59	1.32	1.56
		Lower	0.43	0.81	0.61	0.63	0.76	0.64

Table 12-11. Costs for rock and moorland raw water, Type (iii), gravity filtration treatment

Throughput ('000 m^3/d)	Filtration processes	Other water treatment processes	Sludge drying or pressing	Other sludge processes	£'000 1976 Q3 Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost	Grand total cost
2	Gravity	Chemical building, chemical equipment, pumping plant and water storage	Sludge drying	Continuous thickening and sludge storage	122	90.3	212	46.4	259
5					218	154	372	68.4	441
10					343	233	576	96.5	673
20					547	355	902	140	1040
50(a)					1030	627	1660	241	1900
50(b)			Sludge pressing		1030	627	1660	222	1880
100					1780	968	2750	374	3120
200					2990	1510	4490	395	4890
500					6080	2730	8800	801	9610

			Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost Drying	Sludge cost Pressing	Grand total cost
Confidence levels	80%	Upper	1.37	1.29	1.25	1.34	1.19	1.23
		Lower	0.73	0.78	0.80	0.74	0.84	0.81
	95%	Upper	1.62	1.47	1.41	1.58	1.32	1.37
		Lower	0.62	0.68	0.71	0.63	0.76	0.72

Table 12-12. Costs for moorland raw water, Type (iv), sedimentation-filtration treatment

Throughput ('000 m^3/d)	Sedimentation processes	Filtration processes	Other water treatment processes	Sludge drying or pressing	Other sludge processes	£'000 1976 Q3				
						Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost	Grand total cost
5	Hopper tanks	Gravity	Chemical building, chemical plant, pumping plant and water storage	Sludge drying	Continuous thickening and sludge storage	290	208	498	87.2	585
10						493	305	798	126	924
20(a)						853	450	1 300	187	1 490
20(b)	Proprietary tanks					827	450	1 280	187	1 460
50(a)						1 600	762	2 360	327	2 690
50(b)				Sludge pressing		1 600	762	2 360	322	2 680
100						2 730	1 140	3 870	340	4 210
200						4 600	1 730	6 330	578	6 910
500						9 280	3 030	12 300	887	13 200

						Dry-ing	Press-ing	
Confidence levels	80%	Upper	1.27	1.27	1.19	1.33	1.20	1.17
		Lower	0.79	0.79	0.84	0.75	0.83	0.85
	95%	Upper	1.44	1.44	1.31	1.56	1.32	1.28
		Lower	0.70	0.70	0.76	0.64	0.76	0.78

Table 12-13. Costs for lowland raw water, Type (v), sedimentation-filtration treatment

Throughput ('000 m^3/d)	Sedimentation processes	Filtration processes	Other water treatment processes	Sludge drying or pressing	Other sludge processes	£'000 1976 Q3 Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost	Grand total cost
5	Hopper tanks	Gravity	Chemical building, chemical plant, pumping plant and water storage	Sludge drying	Continuous thickening and sludge storage	236	246	481	118	599
10						388	355	743	174	917
20(a)						650	517	1 170	263	1 430
20(b)				Sludge pressing		650	517	1 170	244	1 410
50(a)						1 320	857	2 180	311	2 490
50(b)	Proprietary tanks					1 270	857	2 130	311	2 440
100						2 170	1 270	3 440	529	3 970
200						3 640	1 890	5 530	682	6 220
500						7 350	3 240	10 600	1 400	12 000

			Civil engineering cost	Mechanical engineering cost	Total cost (excluding sludge)	Sludge cost Drying	Sludge cost Pressing	Grand total cost
Confidence levels	80%	Upper Lower	1.28 0.78	1.26 0.79	1.20 0.84	1.34 0.75	1.20 0.83	1.17 0.85
	95%	Upper Lower	1.47 0.68	1.43 0.70	1.32 0.76	1.56 0.64	1.33 0.75	1.28 0.78

D. Pumping stations and intakes

Estimates for costs of intakes have been developed in a more simple manner than the method necessary in part C preceding. The total cost of a pumping station/intake is assumed to be the sum of the following components:-

(i) the cost of the equivalent pumping station, based on the required throughput (see Section 14.1);

(ii) the cost of the pumping plant, also based on throughput and assuming 50% standby (see Section 10.4.1);

(iii) the cost of the intake structure;

(iv) the cost of the intake plant.

It is assumed from Section 10.4.2 that the cost of the intake structure is directly proportional to the cost of the pumping station structure. A figure of 30% has been taken; this allows for short aqueducts only connecting intake and pumphouse. For intake plant in Section 12.2.2 it was not possible similarly to establish a proportional relationship between the costs of screening plant and pumping plant. Instead, an assessment was made of the likely unit cost of all intake plant, allowing for coarse and fine screening and associated penstocks.

Estimates of these four component costs have been calculated in the manner described for a range of throughputs, and are presented in Table 12-14. The table also shows the assumed unit costs for intake plant.

Overall confidence limits cannot be determined because confidence limits for intake plant costs are not known. However, the 80% confidence limit multipliers for both the pumping station and the pumping plant costs are about 0.5 (lower) and 2.0 (upper).

12.1.6. Total cost estimates for typical configurations

Table 12-14. Costs for pumping stations and intakes

Throughput ('000 m^3/d)	Costs (£'000 1976 Q3)					
	Pumping station building	Pumping plant	Pumping station total cost	Intake structure	Intake plant	Intake total cost
2	6.92	6.59	13.5	2.08	(2.0)† 4.0	19.6
5	14.3	13.3	27.6	4.28	(1.9) 9.5	41.4
10	24.7	22.8	47.4	7.40	(1.5) 15.0	69.8
20	42.6	38.8	81.4	12.8	(1.3) 26.0	120
50	88.0	78.6	167	26.4	(0.75) 37.5	230
100	152	134	286	45.6	(0.5) 50.0	382
200	263	228	491	78.9	(0.35) 70.0	640
500	542	463	1 000	163	(0.28) 140	1310

† Values in brackets are unit costs (£/m^3/d) for intake plant, estimated from Section 12.2.2.

12.1.7. TOTAL COST ESTIMATES BASED ON CONSTRUCTED WORKS

A. The modelling approach

Data on the costs of entire water treatment works was obtained from collected BoQs, from the TP 60 (2) data sheets and from information published in technical journals. An initial study of the data showed that it was necessary to exclude costs of items not primarily related to treatment, like raw water storage and staff housing (see Section 12. 8. 3), and to consider only the costs associated with the treatment processes.

Two main factors were expected to affect treatment cost: throughput, and the basic type of treatment (i. e. whether pressure filtration, rapid gravity filtration or sedimentation-filtration). In addition, it was thought that cost might be influenced by the ease of treatment, as represented by filtration rate, and by the extent of additional treatment processes. The latter factor was introduced by means of the variable SCORE, formed by counting one for each of the processes which was present out of the following:-

filtration (pressure or gravity);
sedimentation;
microstraining;
slow sand filtration;
activated carbon filtration;
softening (precipitation, ion exchange).

SCORE can be regarded as a measure of the complexity of treatment. For the 55 cases considered SCORE took the value 1, 2 or 3.

The data was divided into three categories according to basic treatment, namely:-

(i) pressure filtration (9 cases);
(ii) gravity filtration (11 cases);
(iii) sedimentation-filtration (35 cases).

Separate models were built for each category; models were also built for (i) and (ii) combined, for (ii) and (iii) combined, and for the entire data set. For pressure filtration, no significant variable was found. In all the other cases, throughput and SCORE were both significant. Filtration rate, however, was never significant.

Four indices were examined: the New Construction Index, the Construction Materials Index, the DQSD Index and the Basic Weekly Wage Rate Index. (It was necessary to forfeit the pre-1963 data when using two of the indices.) The general conclusion was that the New Construction Index could be used for all the recommended functions.

The individual models for gravity filtration and sedimentation-filtration are presented fully. The overall model provides a substantially worse fit than either of these and so has not been quoted. Although no pressure filtration function could be derived, a model was developed using the combined pressure and gravity filtration data, and this is given as a subsidiary function. However, this should be used with caution. Costs of pressure filtration treatment works can vary for reasons not associated with gravity filtration, such as whether the pressure filters are horizontal or vertical, or to what extent the filters are housed. In many ways, indeed, treatment works based on pressure filtration are technically more different from works based on gravity filtration than the latter are different from works based on sedimentation-filtration.

B. The results

(i) Data summary

Table 12-15 summarizes the data separately for pressure filtration (9 cases), gravity filtration (11 cases) and sedimentation with filtration (35 cases).

Table 12-15. Whole treatment works data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Pressure filtration (9 cases)						
Total cost (corrected to 1976 Q3)	PRESSCOS	£'000	104	588	345	176
Treatment works throughput	THRUPUT	'000 m^3/d	4.54	18.2	8.31	4.80
Treatment description factor	SCORE	-	1	2	1.22	0.441
Filtration rate	RATE	m/h	2.9	8.4	4.88	1.57
Gravity filtration (11 cases)						
Total cost (corrected to 1976 Q3)	GRAVCOS	£'000	333	10 700	3710	3610
Treatment works throughput	THRUPUT	'000 m^3/d	7.73	636	155	214
Treatment description factor	SCORE	-	1	3	1.64	0.674
Filtration rate	RATE	m/h	2.5	8.1	4.90	1.68
Sedimentation-filtration (35 cases)						
Total cost (corrected to 1976 Q3)	SEDFIL-COS	£'000	355	8450	2200	1510
Treatment works throughput	THRUPUT	'000 m^3/d	3.64	109	40.8	27.9
Treatment description factor	SCORE	-	2	3	2.29	0.458
Filtration rate	RATE	m/h	2.5	10.6	5.06	1.72

Note:
1. The New Construction Index was used to deflate costs.
2. Details of how to evaluate SCORE are given in part A.

12.1.7. Total cost estimates based on constructed works

(ii) Whole treatment works function - gravity filtration

The following function was developed from the gravity filtration works data:-

$$\boxed{\text{GRAVCOS} = 108*\text{THRUPUT}^{0.69}*\text{SCORE}^{0.54}}$$

The statistical details of the function are as follows:-

Number of observations	:	11
Multiple correlation coefficient (R)	:	0.98
80% confidence interval multipliers	:	0.69, 1.45
Standard error of residuals (in $\log_{10}$ model)	:	0.115

(iii) Whole treatment works function - sedimentation with filtration

The following function was developed from the sedimentation with filtration works data:-

$$\boxed{\text{SEDFILCOS} = 68.2*\text{THRUPUT}^{0.69}*\text{SCORE}^{1.07}}$$

The statistical details of the function are as follows:-

Number of observations	:	35
Multiple correlation coefficient (R)	:	0.88
80% confidence interval multipliers	:	0.61, 1.64
Standard error of residuals (in $\log_{10}$ model)	:	0.163

(iv) Subsidiary function - pressure filtration

No significant explanatory variable was found for the cost of whole treatment works using just the pressure filtration cases. However, when the pressure filtration sample was combined with the gravity filtration sample the function detailed below was obtained. This function may therefore be used with caution for pressure filtration, but should not be used in preference to the function given in (ii) above for gravity filtration works alone.

$$\boxed{\text{PRESSCOS} = 64.8*\text{THRUPUT}^{0.76}*\text{SCORE}^{0.81}}$$

The statistical details of the function are as follows:-

Number of observations : 20
Multiple correlation coefficient (R) : 0.97
80% confidence interval multipliers : 0.61, 1.65
Standard error of residuals (in $\log_{10}$ model) : 0.163

12.1.7. Total cost estimates based on constructed works

C. Comparison between the whole works models and summations of the component cost models

Two independent estimates of total works capital cost have been made for pressure filtration works, for gravity filtration works and for sedimentation-filtration works. Firstly, the whole works estimates of total cost were evaluated for a number of flowrates using each in turn of the three functions presented in B above; these estimates are tabulated in Tables 12-16, 12-17 and 12-18 following. Secondly, the corresponding cost estimates calculated by summing the estimates from the appropriate individual component cost models were obtained from Tables 12-10 to 12-13; these also are given in the following tables.

In view of the wide scatter associated with the three whole works cost functions, there is a very good measure of agreement between the independent pairs of estimates. This should be regarded as a confirmation of the 'component costs' approach, rather than an invitation to use the above whole works models for anything more than a preliminary rough guide.

Table 12-16. Comparison of estimates for pressure filtration works

Throughput ('000 m^3/d)	Whole pressure filtration works model estimate (£'000 1976 Q3)		Sum of component cost estimates (from Table 12-9) (£'000 1976 Q3)
	Value of SCORE		
	1	2	
2	110	192	233
5	220	386	408
10	373	654	614
20	631	1110	915
50	1270	2220	1700
100	2150	3760	2800

12.1.7. Total cost estimates based on constructed works

Table 12-17. Comparison of estimates for gravity filtration works

Throughput ('000 m^3/d)	Whole gravity filtration works model estimate (£'000 1976 Q3)		Sum of component cost estimates (from Table 12-10) (£'000 1976 Q3)
	Value of SCORE		
	1	2	
2	174	253	259
5	328	477	441
10	529	769	673
20	853	1 240	1 040
50	1 610	2 330	1 880
100	2 590	3 770	3 120
200	4 180	6 080	4 890
500	7 870	11 400	9 610

Table 12-18. Comparison of estimates for sedimentation-filtration works

Throughput ('000 m^3/d)	Whole sedimentation-filtration works model estimate (£'000 1976 Q3)		Sum of component cost estimates (£'000 1976 Q3)	
	Value of SCORE		Moorland raw water (from Table 12-11)	Lowland raw water (from Table 12-12)
	2	3		
5	435	671	585	599
10	701	1 080	924	917
20	1 130	1 750	1 460	1 410
50	2 130	3 290	2 680	2 440
100	3 430	5 300	4 210	3 970
200	5 540	8 550	6 910	6 220
500	10 400	16 100	13 200	12 000

12.2. PRELIMINARY WORKS

12.2.1. INLET STRUCTURES

Items in civil engineering BoQs regarded as inlet structures include:-

(i) grit settling, intake and screen chambers;
(ii) flowmeter, flume and valve chambers;
(iii) channels, inlet and distribution chambers and towers;
(iv) flash mixers, detention tanks;
(v) aerators.

The proportions of total cost relating to inlet structures are given in Table 12-19 for 18 civil engineering BoQs. They appear not to be related to the size of the treatment works. In half the cases, a cost of inlet structures could not be isolated. This`was probably because the costs had been included in the costs of other components such as settling pipeworks and siteworks, especially as inlet structures can embrace a large variety of works.

Further information on costs of grit settling is given in Section 13.2, and on intake and screen chambers in Section 10.4.2. If it is anticipated that detention tanks will be much larger than the sizes of mixing and distribution chambers normally encountered, reference should be made to the section dealing with the appropriate design of tank. Further information on aeration is given in Section 12.6.1.

If the costs of any of these items are untypically high, they should be treated as extra items (see Section 12.8.3).

12.2.1. Inlet structures

Table 12-19. Inlet structures civil engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of civil engineering costs
U	5.5	0
U	7.8	3.5
U	8.7	1.5
L	9.1	1.6
U	11.4	0
U	13.6	0
L	14.5	0
U	15.0	0
U	18.2	0
L	20.5	3.6
L	22.7	0
U	27.3	5.1
L	54.5	0
L	68.2	3.3
U	72.7	2.9
L	109	0
L	145	5.4
U	159	10.1

12.2.2. INTAKE AND INLET PLANT

A. General

This section is concerned with mechanical plant encountered in raw water intakes (Section 10.4.2) and in water treatment inlet structures (Section 12.2.1). Part B provides an indication of inlet equipment costs in relation to the total water treatment works plant costs; part C discusses a sample of costs of raw water straining and screening plant.

B. Total inlet equipment costs

Items in mechanical engineering BoQs regarded as inlet equipment include:-

(i) grit removal equipment;
(ii) intake screens, microstrainers;
(iii) aerator equipment;
(iv) flash mixers, primary tanks and collecting chamber equipment.

The proportions of total cost relating to inlet equipment in 14 mechanical engineering BoQs are given in Table 12-20. The proportions appear not to be related to the size of treatment works, and are relatively less variable than the corresponding proportional costs of inlet structures (see Section 12.2.1).

Further information is given on grit removal in Section 13.2 and on aeration in Section 12.6.1. Intake screens and microstrainers are discussed in part C below. If the costs of any of these items are untypically high, they should be treated as extra items (see Section 12.8.3).

C. Intake screens and microstrainers

Screening equipment includes:-

(i) coarse or trash bar screens, usually manually cleaned;
(ii) fine bar screens, usually mechanically raked;
(iii) band screens;
(iv) rotary screens (cup or drum);
(v) micro screens (microstrainers).

12.2.2. Intake and inlet plant

Table 12-20. Inlet equipment mechanical engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of civil engineering costs
U	3.6	0
U	5.5	0
U	7.8	1.8
U	8.7	3.1
L	9.1	0
U	15.0	0
L	20.5	4.2
L	22.7	1.1
U	27.3	5.5
L	54.5	2.4
U	72.7	3.7
L	109	5.6
L	145	2.2
U	159	4.1

Insufficient data was collected for a cost function to be developed for water screening plant. A cost function is given in Section 13.2C for mechanically raked screens installed for sewage treatment. However, the examples obtained suggest that water treatment costs are less than those for sewage treatment.

The available data is summarized in Table 12-21. The examples are generally for supply and install, with any necessary washing and trash removal equipment. Costs have been expressed in two ways: as cost per total screen area, and cost per rated throughput. The cost/area figures vary considerably according to the screen dimensions. The cost/throughput figures are less satisfactory because the area of screen installed might be for variable rather than constant water level operation. However, there does appear to be a cost benefit associated with increasing size.

It is not clear why a major change in cost occurs for bar screens. For one example of cup screens the equivalent double entry screen would have cost about 5% less. All the examples of micro screens (microstrainers) were of the same size, although smaller and larger units are manufactured. Excepting the two expensive examples of cup screens, the costs per unit area of band, cup and micro screens are fairly similar.

Without being able to relate performance of screens to installed sizes, the following costs per unit throughput are suggested:-

	£ per m^3/d
Bar screens:	0.20
Band screens:	0.23
Cup screens:	0.61

12.2.2. Intake and inlet plant

Table 12-21. Costs of screening plant

No. of screens	Dimensions (m)	Cost (£'000 1976 Q3)	Area/screen (m^2)	Throughput/ screen ('000 m^3/d)	Cost/screen area (£/m^2)	Cost/ throughput (£/m^3/d)
	Bar screens					
4	3.74 × 2.8	15.6	10.5	327[†]	370	0.048
1	1.4 × 1.0 (hand raked)	0.60	1.4	1.43	390	0.42
1	3.7 × 1.0	17.3	3.70	81.8	4690	0.21
1	2.7 × 1.0	14.4	2.70	11.4	5340	1.26
	Band screens					
3	11.0 × 1.0	69.6	22.0	107	1050	0.22
6	10.4 × 1.0	178.8	20.8	90.9	1430	0.33
2	6.9 × 1.9	78.0	26.6	166	1470	0.23
2	6.0 × 0.9	39.8	11.0	159	1810	0.13
	Cup screens (single entry).					
1	5.0 diam. × 1.5	24.1	23.6	81.8	1020	0.29
2	6.7 diam. × 1.5	72.8	32.0	57	1140	0.64
1	4.0 diam. × 1.0	17.3	12.6	11.4	1380	1.52
1	4.9 diam. × 0.9	20.8	14.0	136	1480	0.15
2	7.0 diam. × 1.1	93.7	23.5	164	1990	0.29
2	6.7 diam. × 1.2	141.6	27.7	90	2760	0.79
6	2.3 diam. × 0.46	60.9	3.32	-	3060	-
	Micro screens					
2	3 diam. × 3	30.8	28.3	40.9	540	0.38
			(supply only, excluding auxiliaries)			
2	3 diam. × 3	61.1	28.3	15.9	1080	1.92
1	3 diam. × 3	34.5	28.3	-	1220	-
1	3 diam. × 3	39.6	28.3	18.2	1400	2.18
2	3 diam. × 3	82.8	28.3	13.6	1460	3.04
2	3 diam. × 3	83.6	28.3	11.3	1480	3.70
1	3 diam. × 3	43.6	28.3	18.2	1540	2.40

[†] This figure refers to total throughput.

12.2.3. CHEMICAL PLANT AND CONTROL EQUIPMENT

A. General

Items in mechanical engineering BoQs regarded as chemical plant include:-

(i) coagulation equipment;
(ii) acid, lime and other pH adjustment equipment;
(iii) activated silica and polyelectrolyte equipment;
(iv) activated carbon equipment;
(v) potassium permanganate, copper sulphate, etc., equipment;
(vi) chlorination and dechlorination equipment;
(vii) fluoridation equipment.

Items in mechanical engineering BoQs regarded as control equipment include:-

(i) inlet control, flowmeters and weir plates;
(ii) motive water pumps, valve operating power systems, compressed air and hydraulic systems;
(iii) instruments, panels, transmitters, telemetry equipment.

The proportions of total cost relating to chemical plant and control equipment are given in Table 12-22 for 14 mechanical engineering BoQs.

12.2.3. Chemical plant and control equipment

Table 12-22. Chemical plant and control equipment mechanical engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of total mechanical engineering costs	
		Chemical plant	Control equipment
U	3.6	34.6	23.3
U	5.5	19.0	15.7
U	7.8	22.1	20.1
U	8.7	38.8	11.8
L	9.1	14.7	18.3
U	15.0	14.6	8.6
L	20.5	25.7	23.3
L	22.7	9.6	3.0
U	27.3	8.6	8.7
L	54.5	34.9	12.6
U	72.7	16.9	10.1
L	109	42.1	2.4
L	145	11.6	0
U	159	33.5	10.7

In Section 14.1 a cost function is given for water treatment and pumphouse buildings based on floor area. A cost function is also given relating cost of pumphouses to throughput, but a similar function could not be obtained for water treatment works buildings. A relationship was therefore derived between treatment plant building floor area and treatment works initial throughput. The use of final throughput as an explanatory variable (i.e. throughput after second stage, uprating or extensions) was statistically less satisfactory; it seems as though intended future capacity is usually planned for and accommodated without difficulty in the area provided for the initial capacity. The estimate of area allows for all normal chemical storage and dosing plant requirements (but excluding silos and other large bulk storage tanks), chlorination plant, a moderate amount of low lift pumping, treatment works laboratory, control and switch rooms, mess rooms and toilets.

The relationship which was obtained is as follows:-

$$\text{CHEMAREA} = 31.6*\text{INTTHR}^{0.85},$$

where CHEMAREA is the total floor area (m^2),
and INTTHR is the initial works throughput ('000 m^3/d).

Correlation coefficient (R)	:	0.98
Standard error of residuals (in $\log_{10}$ model)	:	0.098

B. The modelling approach - chemical plant

The total cost of chemical plant as defined in part A was related to treatment plant output, the chemicals involved and raw water type. The total number of chemicals was found to be an unsatisfactory explanatory variable, because some chemicals are used in greater quantities than others and their associated equipment is often more sophisticated. A variable CHEM was therefore defined which gave a score to each chemical according to the complexity of chemical treatment and associated chemical plant. Table 12-23 gives the details of this approach, which is illustrated by a worked example.

Table 12-23. Formation of the variable CHEM

Chemical	Extent of equipment additional to dosing	Score towards CHEM
Coagulant	Diluted stock	1
Acid	Diluted stock	1
Carbon dioxide	Simple storage	1
Lime, ground chalk	Feeder or slurry equipment	1[†]
Caustic soda	Diluted stock; for precipitation softening	1 1 extra
Soda ash	Stock solution; silos, bulk storage tanks (when not constructed with foundations of chemical house)	1 1 each
Polyelectrolyte	Stock solution	1
Activated silica	Stock solution, activation	1
Potassium permanganate	Stock and feeder	1
Copper sulphate	Stock and feeder	1
Chlorine	For each stage of dosing; bulk storage for large installations	1 each[†] 1 extra
Sulphur dioxide	Simple storage	1
Ammonia	Simple storage	1
Powdered activated carbon	Feeder or slurry equipment	1
Fluoridation	Stock solution	1
Other chemicals scored on same basis.		

[†] No extra score required for multiple stage dosing if only simple additional dosing or control equipment needed.

Example: treatment of upland source.

		CHEM score
Coagulant:	alum purchased as solution requiring storage	2
Lime:	required for pH adjustment for coagulation and for distribution, silo storage	2
Polyelectrolyte:	no special requirements	1
Disinfection:	breakpoint chlorination and dechlorination	2
		7

Although there was insufficient data to distinguish between the five raw water types, two categories could usefully be defined: Type 1 and Type 2.

Type 1: This covers the cheaper cases; it includes treatment of upland raw water Types (iii) (filtration only) and (iv) (sedimentation and filtration), and relates to plant constructed before 1972.

Type 2: This covers more costly cases; it describes treatment of upland raw water Type (iv) and lowland raw water Type (v), and relates to plant constructed since 1968.

There appears to be a trend towards providing chemical plant to a higher standard of construction (and operation) and allowing for a greater chemical dosing capacity. It is therefore recommended that Type 1 is assumed only when estimating costs for treatment of a well protected raw water source where extremes of treatment will not be necessary. The reported cost function must not be used for estimating the cost of plant for the use of any one chemical; it should only be used on a composite overall basis.

Costs given are based on tender prices with no allowance made for the type of contract. The Engineering and Allied Industries Index was used for deflation.

C. The results - chemical plant

(i) Data summary

Table 12-24. Chemical plant data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	9.02	1050	212	249
Treatment plant output	OUTPUT	'000 m^3/d	4.55	145	46.2	42.3
Chemical treatment variable	CHEM	-	2	12	5.77	2.70
Type of chemical plant	TYPE	-	1	2	1.58	0.504
Omnibus 16 (see Section 8.3.3)	Z16	-	0.477	22.9	5.91	5.59

Note: 1. Number of cases: 26.

2. The Engineering and Allied Industries Index was used for deflation.

3. TYPE is 1 for Type 1 chemical plant, and
2 for Type 2 chemical plant.

Mini-histograms for the main variables of interest:-


COST


LOG COST


OUTPUT


CHEM


TYPE

(ii) The recommended cost function

The recommended function for chemical plant is:-

$$\boxed{\text{COST} = 2.23*\text{OUTPUT}^{0.46}*\text{CHEM}^{1.17}*\text{TYPE}^{1.30}}$$

The statistical details of the function are as follows:-

Number of observations	:	26
Multiple correlation coefficient (R)	:	0.98
Coefficient of determination (R^2)	:	97%
Standard error of residuals (in $\log_{10}$ model)	:	0.099

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
OUTPUT	0.460	0.044	109	≪0.1%
CHEM	1.17	0.113	107	≪0.1%
TYPE	1.30	0.138	89.2	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.74	1.35
95%	0.62	1.60

The omnibus variable is defined as:-

$$\text{Z16} = 0.132*\text{CHEM}*\text{OUTPUT}^{0.39}*\text{TYPE}^{1.11}.$$

Figures 12-3 and 12-4 show the five standard diagrams in support of the function.

(iii) The data

The chemical plant data is listed in Table A-17.

12.2.3. Chemical plant and control equipment

Figure 12-3. Chemical plant

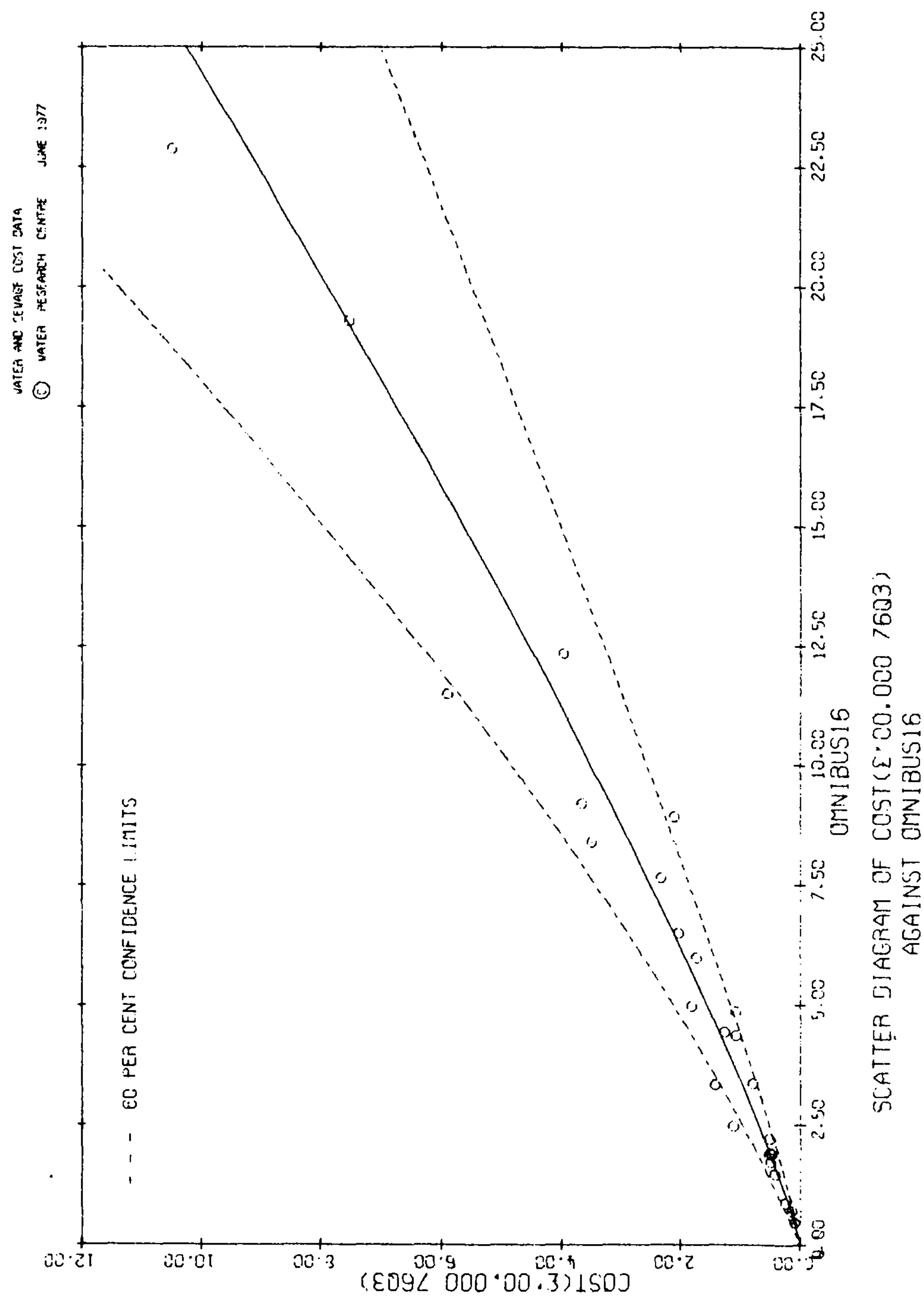
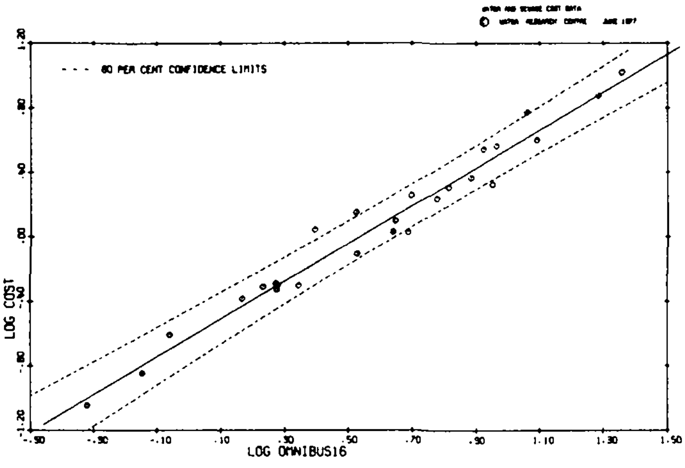
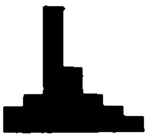


Figure 12-4. Chemical plant

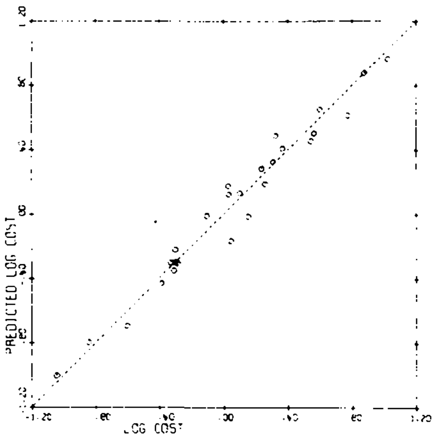


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS16

SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS16



HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

12.3. BASIC CLARIFICATION PROCESSES

Table 12-2 in Section 12.1.3 gives typical treatment rates for floc blanket sedimentation and rapid gravity and pressure filtration in relation to the water to be treated. Table 12-7 in Section 12.1.4 shows that the typical clarification unit processes of sedimentation and filtration amount to between about 10 and 30% of the total capital cost of a treatment works.

Items in civil engineering BoQs regarded as settling include:-

(i) clarifiers, softeners, floc blanket tanks, etc;
(ii) Pulsators, Accentriflocs, Precipitators, etc.

Items in civil engineering BoQs regarded as filters include:-

(i) filters;
(ii) filter control building, filter machinery block.

Items in mechanical engineering BoQs regarded as clarification equipment, and therefore part of settling, include:-

(i) settling tank and clarifier equipment;
(ii) clarifier sludge bleed systems;
(iii) vacuum pumps for Pulsators.

Items in mechanical engineering BoQs regarded as filtration equipment include:-

(i) filters and media;
(ii) underdrains, air scour system, air blowers;
(iii) backwash system;
(iv) filter controllers.

The proportions of total cost relating to these items are given in Table 12-25 and illustrated in Figure 12-5, for samples of 18 civils BoQs and 14 mechanical BoQs. The proportions appear not to be related to the size of treatment works. It is notable that the civil engineering costs for sedimentation and filtration are on average about the same, whereas their mechanical costs differ substantially.

Table 12-25. Sedimentation and filtration costs as percentages of total engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of total civil engineering costs	
		Settling	Filters
U	5.5	16.2	30.0
U	7.8	19.6	7.5
U	8.7	12.2	7.1
L	9.1	11.4	6.8
U	11.4	9.5	25.9
U	13.6	13.9	7.1
L	14.5	24.4	12.1
U	15.0	13.7	12.9
U	18.2	7.6	3.1
L	20.5	12.4	16.7
L	22.7	18.4	49.2
U	27.3	20.0	11.0
L	54.5	14.8	8.8
L	68.2	21.1	4.8
U	72.7	4.8	2.4
L	109	14.4	7.3
L	145	9.3	13.2
U	159	10.0	15.5
		% of total mechanical engineering costs	
		Clarification	Filtration
U	3.6	5.4	28.1
U	5.5	14.5	43.3
U	7.8	8.4	47.5
U	8.7	4.6	22.3
L	9.1	4.4	21.0
U	15.0	3.4	19.8
L	20.5	13.0	22.5
L	22.7	8.4	24.2
U	27.3	8.1	25.7
L	54.5	3.0	18.6
U	72.7	4.6	9.9
L	109	6.5	22.6
L	145	4.9	24.7
U	159	12.6	24.5

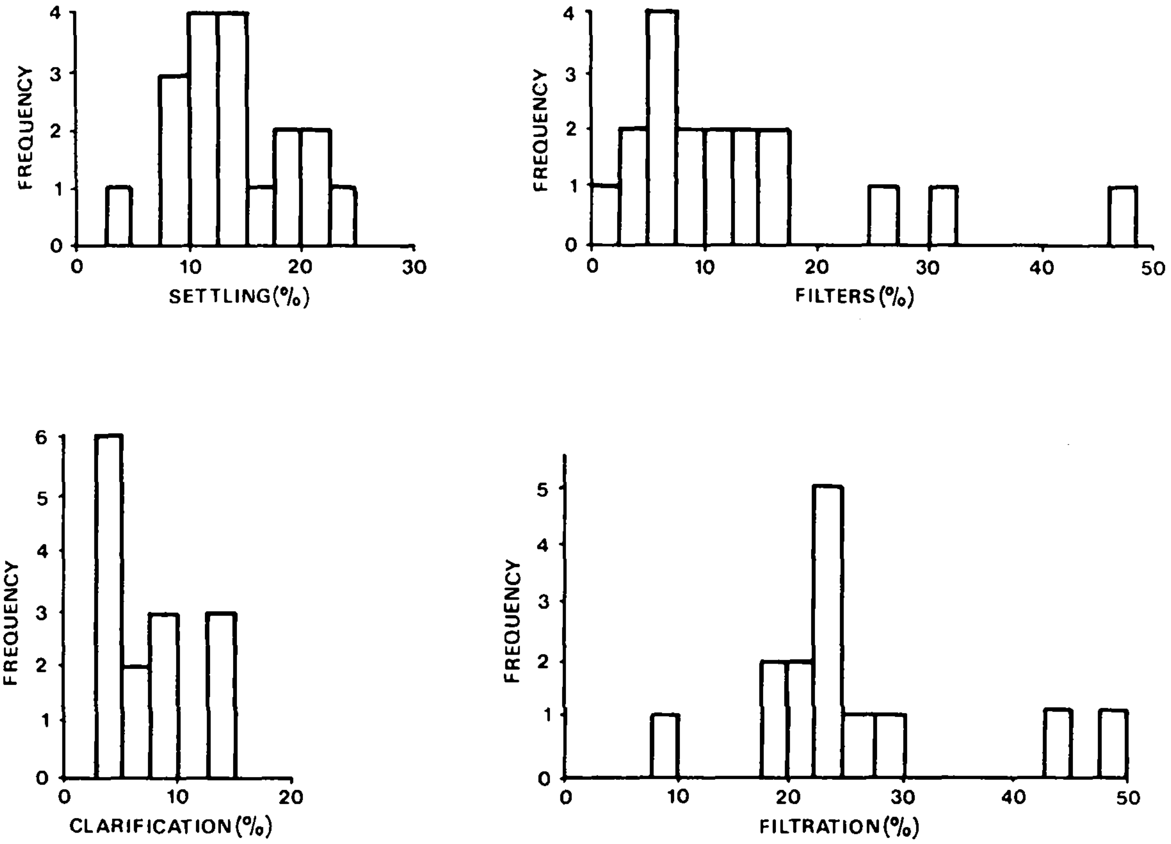


Figure 12-5. Sedimentation and filtration costs as percentages of total engineering costs

Percentages of total civil engineering costs
Percentages of total mechanical engineering costs

12.3.1. SEDIMENTATION

A. General

Sedimentation is concerned with the settling of coagulated or uncoagulated particles. Contemporary practice in the UK follows three main designs:-

(i) Upflow floc blanket tanks. These are widely used for settling coagulated water and are well represented by a range of designs, many of which are 'proprietary' (i.e. associated with specific plant contractors), such as Accentriflocs, Precipitators and Pulsators. They include pyramidal (square hopper-bottomed), annular flat-bottomed and rectangular flat-bottomed designs. Cost functions have been developed for the most common of these.

(ii) Horizontal flow rectangular tanks. These are rarely constructed, and then usually only for settling uncoagulated water subject to high suspended solids, or coagulated water when very high coagulant doses are necessary. The latter would, in addition, require flocculation prior to settling. No cost function is presented as no appropriate raw data was collected, but reference should be made to Section 13.3.2 - costs of rectangular storm aeration tanks.

(iii) Radial flow circular tanks. These are perhaps a little more common than horizontal flow rectangular tanks. They are most likely to be constructed where extremes of raw water quality, chemical treatment and throughputs are anticipated. No appropriate raw data was collected, but reference should be made to Section 13.3.1.

12.3.1. Sedimentation

B. The modelling approach

Data was collected for upflow floc blanket tanks from tender BoQs and other contract information. The sample of data available allowed pyramidal tanks (many of the smaller of which were constructed as thickeners) to be examined as a separate case. The samples of data for three common proprietary designs (Accentriflocs, Precipitators and Pulsators) were too small for individual analyses to be worthwhile; the data was therefore examined as a group.

The contract for mechanical equipment was usually separate from the contract for civil engineering work and made at an earlier date. Civil and equipment costs were therefore first modelled separately in both cases. Where these could be paired because they referred to the same physical set of tanks, they were combined to give samples on which total cost functions were based.

The DQSD, Construction Materials, New Construction and Basic Weekly Wage Rate Indices were examined for correcting civils costs; the New Construction Index was found to be most suitable. For deflating plant costs the New Construction Index was again chosen in preference to the DQSD, Engineering and Allied Industries and Basic Weekly Wage Rate Indices. Total cost was taken as the sum of the corrected civil and plant tender costs at their dates of tender. No adjustment was made for the type of contract as most of the sample originated from before the period of rapid inflation. Costs exclude any relatively expensive special constructional requirements such as untypical excavation or foundations.

For pyramidal tanks it was thought that both the individual tank size and the arrangement of the tanks in the contract could influence cost. Tank side length, number of tanks and total numbers of free and of common tank sides were therefore used as explanatory variables in addition to total plan area. However, total plan area was the only significant variable in all three models.

The combined data for the other types of upflow floc blanket tanks was used to relate civil cost, plant cost and total cost to total tank plan area. The number of tanks did not significantly influence cost. The total civil and mechanical cost function provided a better fit than either of the individual models, which have therefore not been presented in detail.

C. The results - pyramidal tanks

(i) Data summary

Table 12-26. Pyramidal tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total civil and mechanical cost (corrected to 1976 Q3)	COST	£'000	53.3	629	295	208
Total area of tanks in facility	AREA	'000 m^2	0.141	1.83	0.614	0.519

Note: 1. Number of cases: 14.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST

LOG COST

AREA

(ii) The recommended cost function

The recommended function for pyramidal tanks is:-

$$\boxed{COST = 471*AREA^{0.96}}$$

The statistical details of the function are as follows:-

Number of observations : 14

Correlation coefficient (R) : 0.92

Coefficient of determination (R^2) : 85%

Standard error of residuals (in $\log_{10}$ model) : 0.149

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.959	0.116	68.6	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.62	1.59
95%	0.47	2.11

Figure 12-6 illustrates the recommended function.

(iii) Other cost functions

The separate cost functions for civil and mechanical costs are:-

$$\boxed{\text{CIVCOS} = 371 * \text{AREA}^{0.97}}$$

The statistical details of the function are as follows:-

Number of observations	:	23
Correlation coefficient (R)	:	0.93
80% confidence interval multipliers	:	0.63, 1.58
Standard error of residuals (in $\log_{10}$ model)	:	0.151

and

$$\boxed{\text{MECCOS} = 66.2 * \text{AREA}^{0.73}}$$

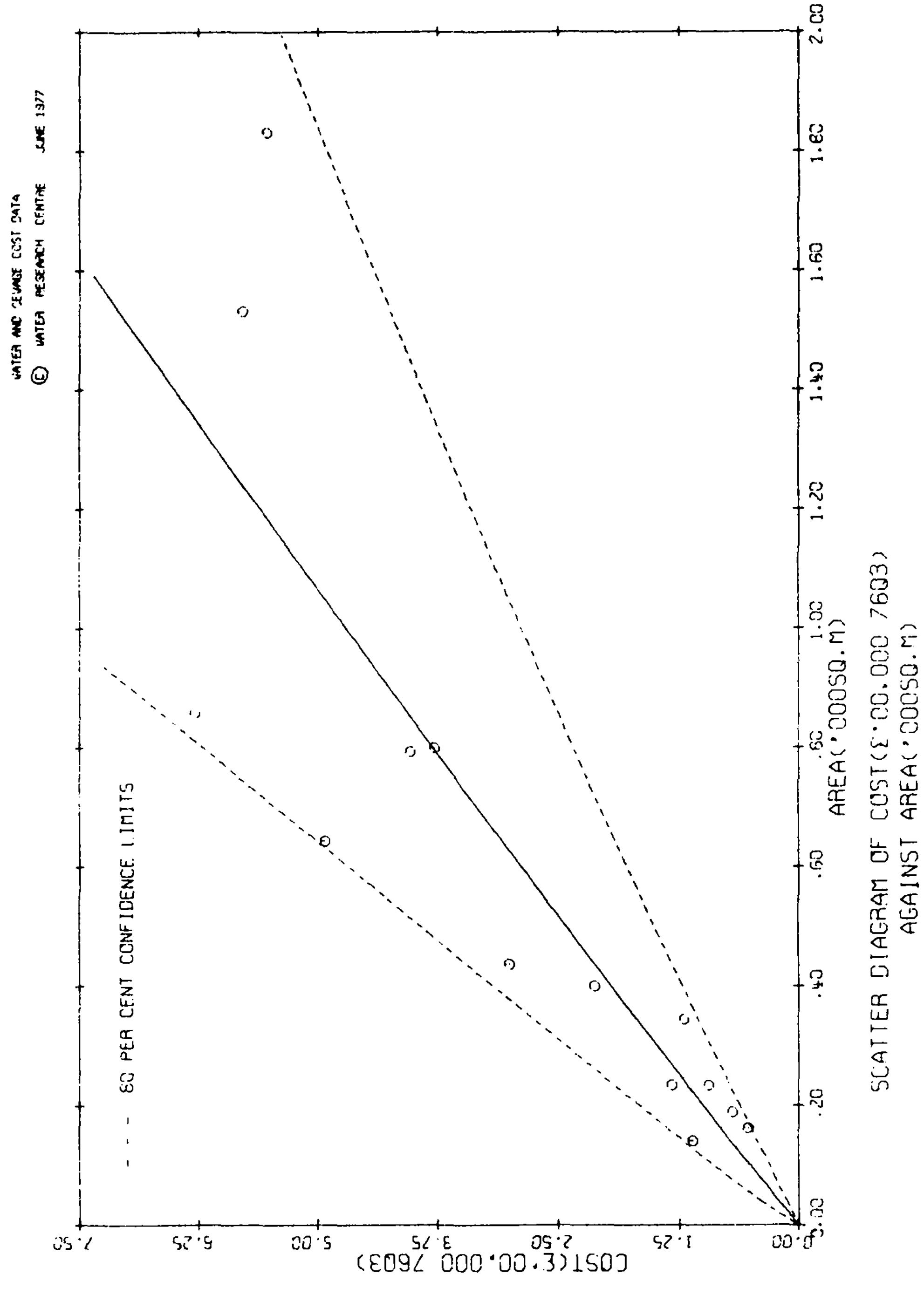
The statistical details of the function are as follows:-

Number of observations	:	19
Correlation coefficient (R)	:	0.84
80% confidence interval multipliers	:	0.58, 1.72
Standard error of residuals (in $\log_{10}$ model)	:	0.177

(iv) The data

The pyramidal tanks data is listed in Table A-18.

Figure 12-6. Pyramidal tanks



D. The results - proprietary tanks

(i) Data summary

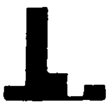
Table 12-27. Proprietary tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total civil and mechanical cost (corrected to 1976 Q3)	COST	£ million	0.068	1.12	0.373	0.292
Total area of tanks in facility	AREA	'000 m^2	0.091	3.48	0.995	0.968

Note: 1. Number of cases: 11.

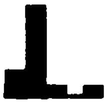
2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-



COST

LOG COST



AREA

(ii) The recommended cost function

The recommended function for proprietary tanks is:-

$$\boxed{\text{COST} = 0.389 * \text{AREA}^{0.76}}$$

The statistical details of the function are as follows:-

Number of observations : 11

Correlation coefficient (R) : 0.96

Coefficient of determination (R^2) : 93%

Standard error of residuals (in $\log_{10}$ model) : 0.092

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.757	0.071	115	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

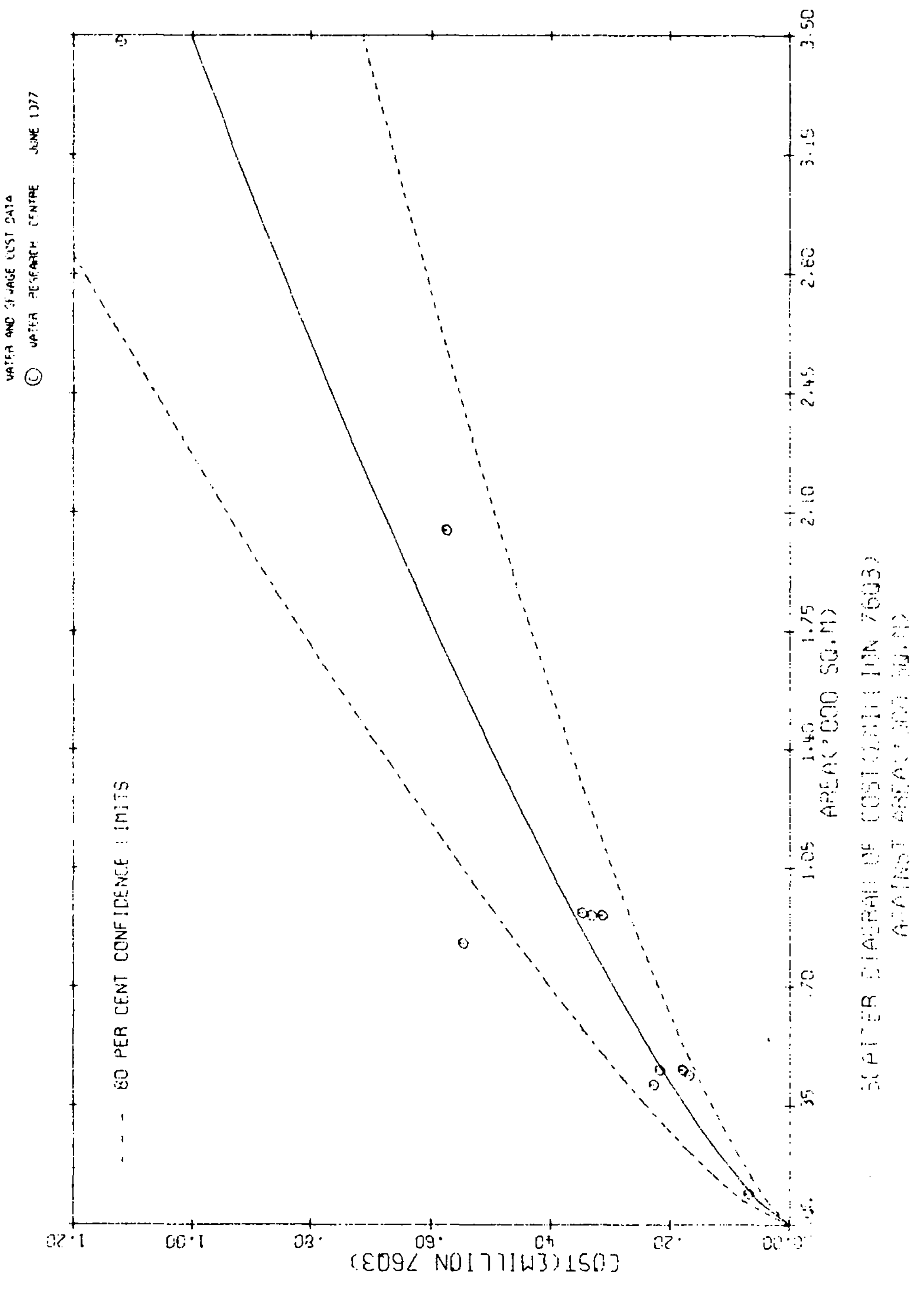
Confidence level	Lower	Upper
80%	0.75	1.34
95%	0.62	1.61

Figure 12-7 illustrates the recommended function.

(iii) The data

The proprietary tanks data is listed in Table A-19.

Figure 12-7. Proprietary tanks



12.3.2. FLOTATION

A. General

Dissolved air flotation for water clarification as an alternative to sedimentation is a recent innovation. Consequently only a small number of successful plant bids have been made to date incorporating flotation; these have mainly been for relatively small treatment works. Further, the technology of flotation is still at an early stage of development, and will remain so for several years whilst constructional and operational experience is gained.

An appreciation of costs can be helped by considering also flotation units constructed for thickening surplus activated sludge. However, there are distinct differences between the two applications. For water clarification, flocculation before flotation itself is a necessity; for activated sludge thickening, the dissolved air-recycle rate can be an order of magnitude greater.

In comparing flotation and sedimentation, account should be taken both of any technical benefits and of the relative operating costs (10).

For areas greater than about 200 m^2 the main structures tend to be constructed in concrete, whereas smaller units are constructed in steel. For the former the costs will be about equal for plant and civil engineering.

B. The modelling approach

Data was collected from BoQs and associated contract documents, both for successful tenders and for tenders not accepted but otherwise highly competitive. Some budget prices were also collected. Unfortunately, because of general practice and the design of some flotation units, the cost of flotation alone was not always explicit. However, using other information collected in the study, it was possible to adjust the costs of flotation so that they represented the costs due to flotation alone. Such adjusted costs were found to be in close agreement with the cases that did not need such adjustment. The costs were deflated using the New Construction Index as this had been found most suitable for both civil engineering and plant costs of rapid gravity filtration. Costs do not include any substantial buildings which might be needed to enclose the whole flotation plant or to shield the surface of the flotation tank from adverse weather. Costs are given as total capital cost at date of tender, with no allowance made for the type of contract.

12.3.2. Flotation

For the water clarification data, cost was related to the area available for flotation excluding flocculation. For one case, the corrected cost was found to be double that predicted by the function (see Figure 12-8); a possible reason for this is its location.

It was not possible to develop a similar cost function for activated sludge thickeners because area varied insufficiently over the available sample. The data is listed in Table 12-28 together with corresponding estimates made using the flotation for water clarification model. These range from 11 to 43% below the activated sludge thickener costs.

Table 12-28. Activated sludge thickener data listing

Total cost (£'000 1976 Q3)	Total area available for flotation (m^2)	Estimated cost using water clarification function (£'000 1976 Q3)
83.9	14.0	47.7
70.8	23.3	62.2
101.2	23.3	62.2
79.2	28.0	68.4
110.6	28.0	68.4
104.2	48.5	91.1

It should be noted that flotation can be arranged to take place above a filter bed, with some possible saving in cost. The cost of small flotation-filtration steel package plant is similar to the cost of steel activated sludge thickening package plant.

C. The results - flotation for water clarification

(i) Data summary

Table 12-29. Water clarification data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total capital cost of flotation for water clarification (corrected to 1976 Q3)	COST	£'000	55.4	739	228	202
Total area available for flotation	AREA	m^2	17.0	1670	347	484

Note: 1. Number of cases: 11.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST

LOG COST

AREA

(ii) The recommended cost function

The recommended function for flotation for water clarification is:-

$$\boxed{COST = 12.1 * AREA^{0.52}}$$

The statistical details of the function are as follows:-

Number of observations : 11

Correlation coefficient (R) : 0.92

Coefficient of determination (R^2) : 85%

Standard error of residuals (in $\log_{10}$ model) : 0.141

12.3.2. Flotation

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.522	0.074	49.6	$\ll 0.1\%$

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.64	1.57
95%	0.48	2.08

Figure 12-8 illustrates the recommended function.

(iii) <u>The data</u>

The flotation for water clarification data is listed in Table A-20.

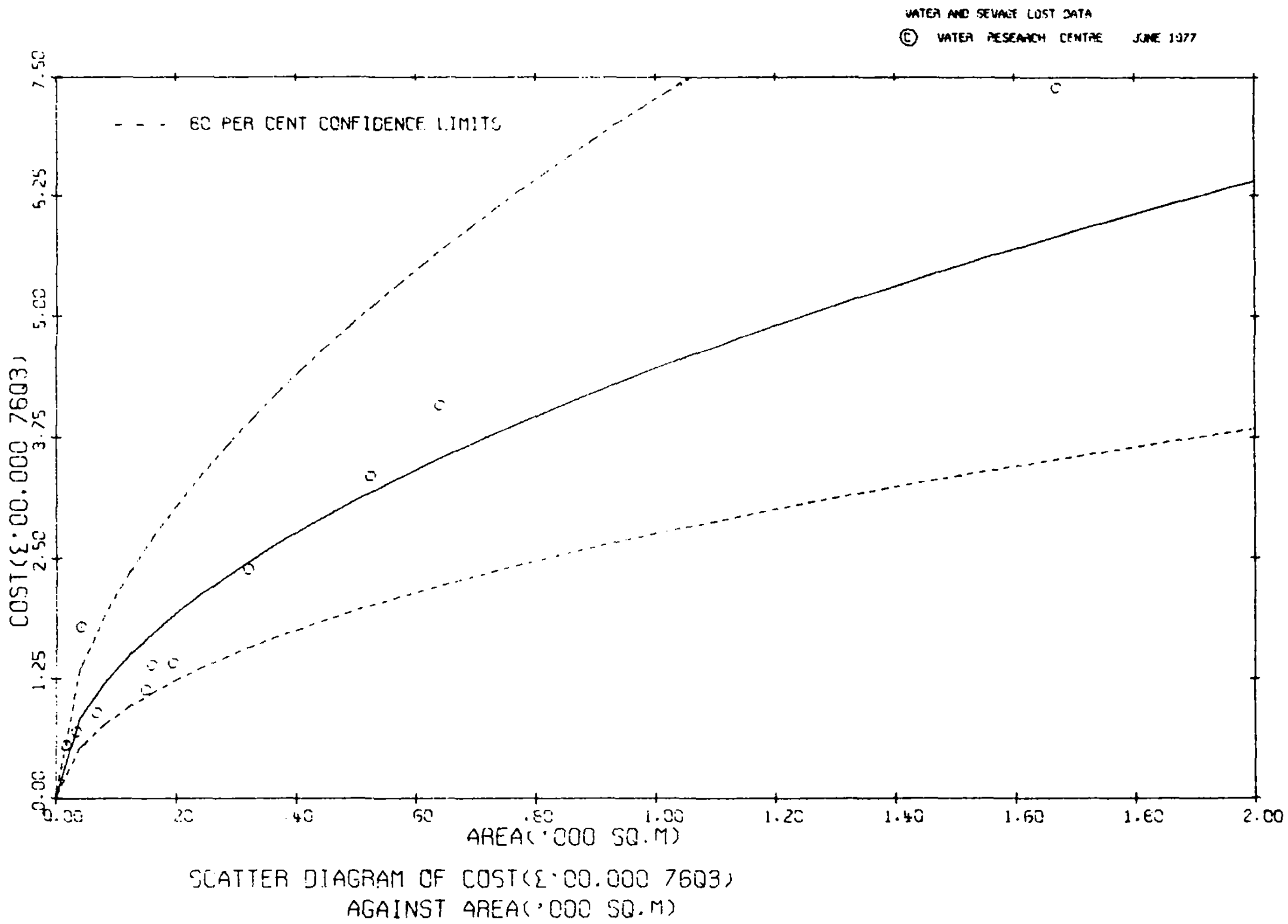


Figure 12-8. Flotation for water clarification

12.3.3. RAPID GRAVITY FILTRATION

A. The modelling approach

There are wide variations in the design and operation of rapid gravity filters, proprietary and otherwise. These are mostly associated with filter bed structure, including underdrain design and media type and size, method of filtration rate control, and the method of backwashing the filter media. Within conventional practice in the UK none of these factors seems to exert an obvious influence on cost of filters; at present they are important only when considering filtration performance and therefore the required filtration area and other process options.

The raw data was collected from tender BoQs and other associated documents. The civil engineering and plant costs were first examined separately. This was partly because the data was available in this form, owing to the common practice of plant contracts being let separately before the civil engineering contract, and partly because the two samples did not always refer to the same treatment works schemes.

The civil engineering costs include the cost of the filter shells, filter control gallery or building, pipeworks and other items normally found in the filter bill. Sometimes the filter control gallery was part of another larger building and the cost of the gallery had to be assessed from the appropriate bills. Sometimes filter pumping plant was installed in a common pumphouse; in these situations no allowance was made for the appropriate share of the building cost. The civil engineering cost does not include storage of water used for backwashing or the treatment of backwash effluent.

The plant costs include the provision and installation of filtration rate and other monitoring and control equipment, filter backwash equipment, and the provision of filter floor and media. The installation of the last item is often carried out by the civil engineering contractor under the supervision of the plant contractor. Its cost is therefore included as civil engineering.

Costs were taken at the date of tender. No allowance was made for type of contract because the samples relate mostly to pre-1973 contracts. Civil engineering costs were corrected using the New Construction Index in preference to the DQSD, Construction Materials and Basic Weekly Wage Rate Indices. Plant costs also were deflated by the New Construction Index, in preference to the DQSD, Engineering and Allied Industries and Basic Weekly Wage Rate Indices.

12.3.3. Rapid gravity filtration

Cost functions were developed for civil engineering and plant costs separately. A total costs sample was formed by combining those civil engineering and plant costs which referred to the same schemes, and this was used to construct a total cost function. Total plan area available for filtration and the numbers and dimensions of the individual filters were used as explanatory variables. Only total area appears in the recommended total cost function, but individual filter width or filter length is an additional significant factor in some of the subsidiary models.

12.3.3. Rapid gravity filtration

B. The results

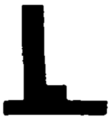
(i) Data summary

Table 12-30. Rapid gravity filters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£ million	0.102	1.39	0.519	0.387
Total area available for filtration	AREA	'000 m^2	0.097	1.78	0.469	0.491
Filter width	WIDTH	m	3.00	12.0	6.09	2.25
Filter length	LEN	m	5.40	15.3	8.79	2.50

Note:
1. Number of cases: 13.
2. The New Construction Index was used for deflation.
3. For filters which are not square, LEN is defined as the longer side length.

Mini-histograms for the main variables of interest:-



COST

LOG COST

AREA

(ii) The recommended cost function

The recommended total cost function for rapid gravity filters is:-

$$\boxed{COST = 0.967*AREA^{0.74}}$$

The statistical details of the function are as follows:-

Number of observations : 13
Correlation coefficient (R) : 0.92
Coefficient of determination (R^2) : 85%
Standard error of residuals (in $\log_{10}$ model) : 0.129

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.743	0.096	60.5	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.67	1.50
95%	0.52	1.92

Figure 12-9 illustrates the recommended function.

(iii) Other cost functions

A refinement of the recommended cost function which takes some account of the layout of the filtration plant is:-

$$\boxed{\mathrm{COST} = 10.3*\mathrm{AREA}^{1.14}*\mathrm{WIDTH}^{-1.09}}$$

The statistical details of the function are as follows:-

Number of observations : 13

Multiple correlation coefficient (R) : 0.96

80% confidence interval multipliers : 0.73, 1.38

Standard error of residuals (in $\log_{10}$ model) : 0.101

The civil engineering cost function exhibits a greater scale benefit from increasing individual filter size than that in the previous model. The function is:-

$$\boxed{\mathrm{CIVCOS} = 6.32*\mathrm{AREA}^{1.18}*\mathrm{WIDTH}^{-1.35}}$$

where CIVCOS is the civil engineering cost in units of £million (1976 Q3).

12.3.3. Rapid gravity filtration

The statistical details of the function are as follows:-

Number of observations	:	22
Multiple correlation coefficient (R)	:	0.93
80% confidence interval multipliers	:	0.58, 1.72
Standard error of residuals (in $\log_{10}$ model)	:	0.177

If the variable WIDTH is not available, an alternative model is:-

$$\boxed{\text{CIVCOS} = 0.388 * \text{AREA}^{0.81}}$$

For this model,

Number of observations	:	22
Correlation coefficient (R)	:	0.89
80% confidence interval multipliers	:	0.52, 1.92
Standard error of residuals (in $\log_{10}$ model)	:	0.213

The plant cost function differs from the earlier models in that the layout effect is best represented by the length of individual filters. The function is:-

$$\boxed{\text{PLANTCOS} = 5.83 * \text{AREA}^{0.92} * \text{LEN}^{-1.06}}$$

where PLANTCOS is the plant cost in units of £million (1976 Q3).

The statistical details of the function are as follows:-

Number of observations	:	21
Multiple correlation coefficient (R)	:	0.96
80% confidence interval multipliers	:	0.75, 1.33
Standard error of residuals (in $\log_{10}$ model)	:	0.094

If the variable LEN is not available, an alternative model is:-

$$\boxed{\text{PLANTCOS} = 0.437 * \text{AREA}^{0.68}}$$

For this model,

Number of observations	:	21
Correlation coefficient (R)	:	0.93
80% confidence interval multipliers	:	0.68, 1.48
Standard error of residuals (in $\log_{10}$ model)	:	0.127

(iv) The data

The rapid gravity filter total cost data is listed in Table A-21.

12.3.3. Rapid gravity filtration

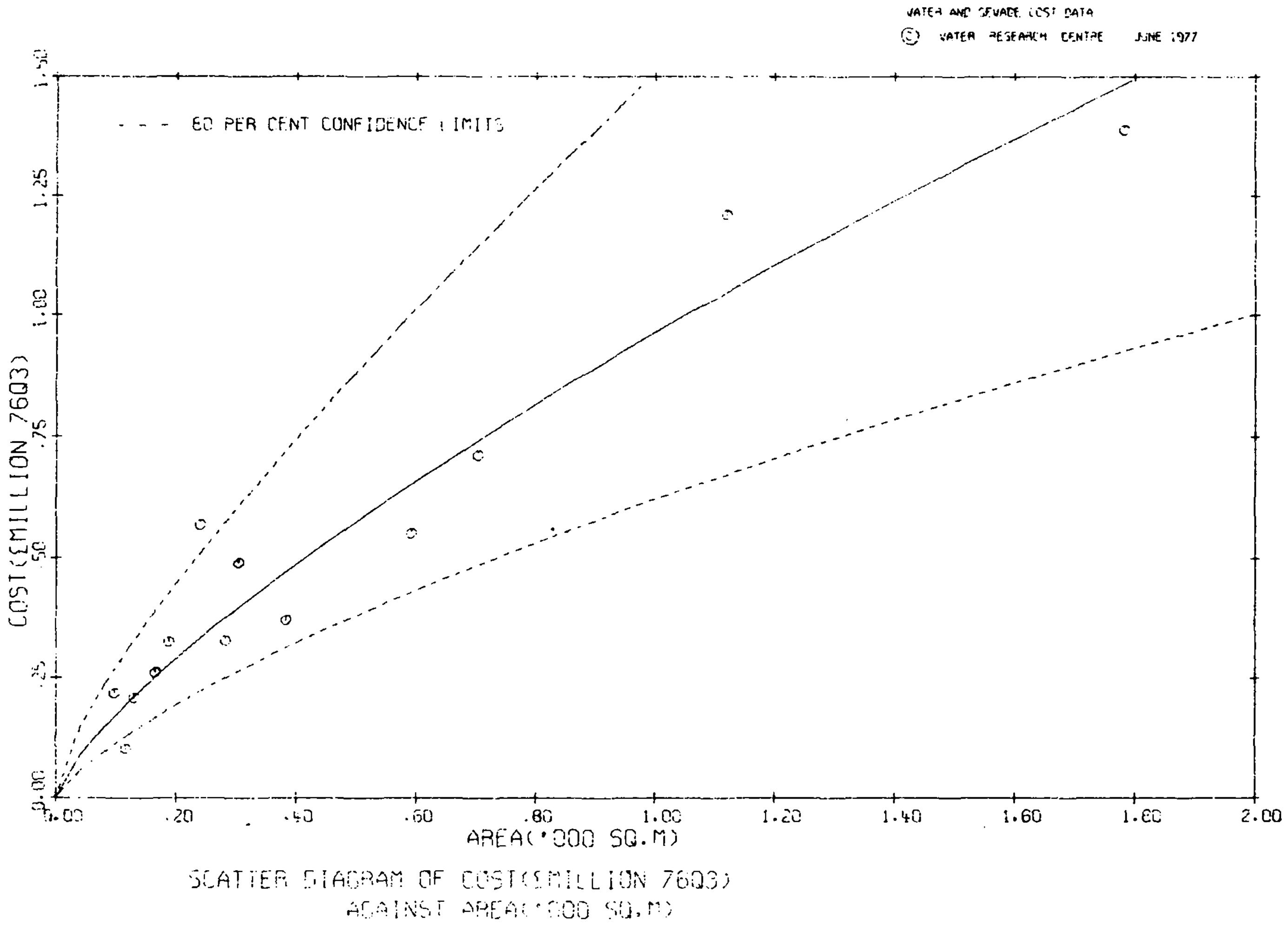


Figure 12-9. Rapid gravity filters

12.3.4. PRESSURE FILTRATION

A. General modelling approach

Pressure filter shells are constructed for use in one of two orientations: horizontal or vertical. In the horizontal mode, the steel pressure shells are constructed to be used with the cylindrical axis horizontal. They are usually 9.15 m long and 2.44 m in diameter, with the filter media filling the bottom half of the cylinder. Filter backwashing practice is similar to rapid gravity filters with the additional use of air scour. Vertical steel pressure shells are usually 2.44 m diameter with the cylinder itself about 1.22 m high. Backwashing of the filter media is usually aided by mechanical raking rather than air scour.

Data was collected mostly from accepted water treatment plant tenders and related documents. Because of the obvious differences between the two types of pressure filters, no attempt was made to develop a common cost function.

For both types of filter, the Mechanical Engineering Index was found to be the most suitable for deflating costs in comparison with the New Construction, Basic Weekly Wage Rate and Engineering and Associated Industries Indices. Costs were taken from accepted tenders at date of contract, and were not adjusted for the type of contract. Apart from the function representing horizontal shells alone (see part B), costs include all pipeworks and valves forming a necessary part of the filter installation, and any necessary backwashing equipment. Costs represent erected plant exclusive of foundations and buildings to house equipment, details of which are given in Section 14.1.

B. The results - horizontal pressure filters

(i) Detailed modelling approach

Four explanatory variables were examined. The first of these - total filtration area of an installation - was suggested by the rapid gravity filter model. The number of filters in the installation was also thought likely to influence cost. Shell length was used as a further explanatory variable, as some filters in the sample were substantially shorter than the typical length of 9.15 m. Shell diameter, on the other hand, did not vary sufficiently to make its inclusion worthwhile. Finally, a variable TYPE was defined, taking the value 1 for those cases where only the total filter plant cost was known, and the value 2 where the cost of the completed shells alone was known.

Of these variables, total area and TYPE were found to be significant.

(ii) Data summary

Table 12-31. Horizontal pressure filters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost (corrected to 1976 Q3)	HORCOS	£'000	42.6	158	92.1	37.4
Total filtration area	AREA	m^2	34.2	179	101	51.6
Whether total cost or shell cost	TYPE	-	1	2	1.46	0.519
Number of filters	NUM	-	2	8	4.77	2.20
Omnibus 13 (see Section 8.3.3)	Z13	-	15.2	122	54.5	36.8

Note:
1. Number of cases: 13.
2. The Mechanical Engineering Index was used for deflation.
3. TYPE is 1 if HORCOS refers to total cost, and
   2 if HORCOS refers to shell cost only.

Mini-histograms for the main variables of interest:-

HORCOS

LOG HORCOS

AREA

TYPE

(iii) The recommended cost function

The recommended function for horizontal pressure filters is:-

$$\boxed{\text{HORCOS} = 7.29*\text{AREA}^{0.59}*\text{TYPE}^{-0.59}}$$

The statistical details of the function are as follows:-

Number of observations	:	13
Multiple correlation coefficient (R)	:	0.98
Coefficient of determination (R^2)	:	96%
Standard error of residuals (in $\log_{10}$ model)	:	0.040

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.590	0.048	150	≪0.1%
TYPE	-0.592	0.075	62.9	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.88	1.13
95%	0.81	1.23

The omnibus variable is given by:

$$Z13 = 0.684*\text{AREA}*\text{TYPE}^{-1.00}.$$

Figure 12-10 illustrates the recommended function.

(iv) The data

The horizontal pressure filter data is listed in Table A-22.

12.3.4. Pressure filtration

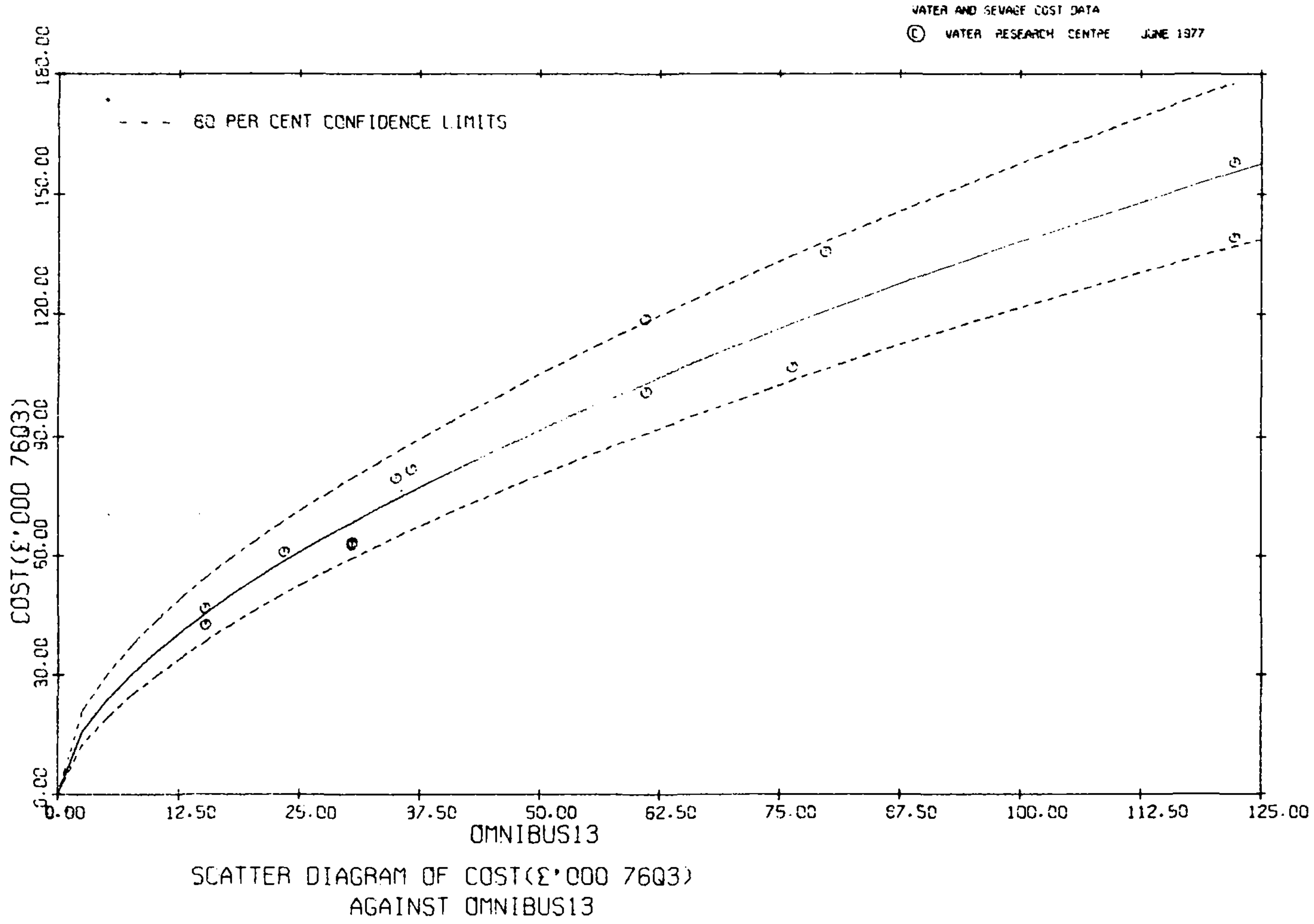


Figure 12-10. Horizontal pressure filters

C. The results - vertical pressure filters

(i) Detailed modelling approach

For the vertical pressure filters sample, both shell diameter and shell height showed insufficient variation for them to be used as explanatory variables, and so only total area of filtration and number of filter shells were considered as explanatory variables. Pressure shells used for ion exchange were not included in the sample as they are usually rubber lined and have different heights and diameters. The variable TYPE was not used because there were too few cases in which the cost of filter shells alone was known; the recommended function thus refers to the cost of the whole filtration plant only. Only total area was found to be significant.

(ii) Data summary

Table 12-32. Vertical pressure filters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	VERCOS	£'000	35.0	275	131	89.6
Total filtration area	AREA	m^2	18.7	160	76.0	54.6
Number of filters	NUM	-	4	27	11.8	8.01

Note: 1. Number of cases: 6.

2. The Mechanical Engineering Index was used for deflation.

Mini-histograms for the main variables of interest:-

VERCOS

LOG VERCOS

AREA

(ii) The recommended cost function

The recommended function for vertical pressure filters is:-

$$\boxed{\text{VERCOS} = 2.25*\text{AREA}^{0.94}}$$

12.3.4. Pressure filtration

The statistical details of the function are as follows:-

Number of observations	:	6
Correlation coefficient (R)	:	0.99
Coefficient of determination (R^2)	:	98%
Standard error of residuals (in $\log_{10}$ model)	:	0.045

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.942	0.060	249	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.85	1.17
95%	0.75	1.33

Figure 12-11 illustrates the recommended function.

(iii) <u>The data</u>

The vertical pressure filter data is listed in Table A-23.

12.3.4. Pressure filtration

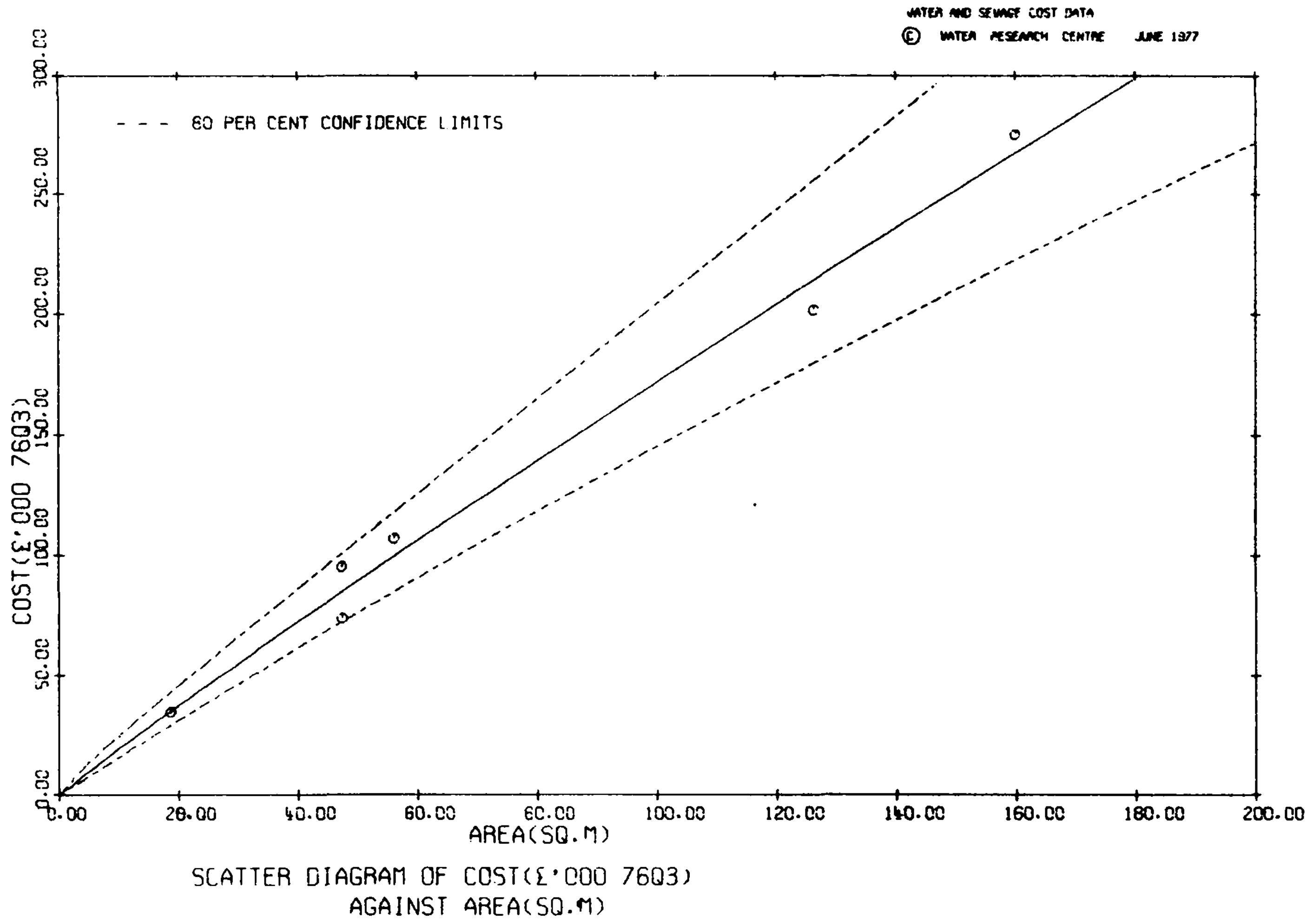


Figure 12-11. Vertical pressure filters

12.3.5. UPFLOW FILTRATION

A. The modelling approach

Most upflow filters in the UK are of the Immedium type. The filter shell is constructed of concrete or steel, or a combination of the two. The filter bed usually has about 2 m of coarse and fine sand which is held down by a grid just below the top of the sand as pressure across the bed develops during filtration. Backwashing usually involves separate air scour and water wash.

Data was collected from BoQs and associated documents, and from summaries of costs. For a few of the cases, some adjustment of the civil or plant costs had to be made to account for items not directly associated with the upflow filters. Costs covered civil engineering, building and plant costs for the filter shells, all pipes and valves immediately associated with the filters, backwash water pumps, air blowers, control equipment, and housing of the mechanical and electrical plant. The New Construction Index was used for deflation as this had been found most suitable for rapid gravity filters. Total plan area available for filtration and the number of filters were used as explanatory variables; only area was found to be significant.

Examination of the scatter about the model (see Figure 12-12) revealed two cases which were markedly cheaper than the others. The smaller of these installations was found to have been designed and procured in-house. No explanation, however, could be found for the other case.

B. The results

(i) Data summary

Table 12-33. Upflow filters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	88.2	1340	497	415
Total filtration area	AREA	m^2	25.2	552	192	194
Number of filters	NFIL	-	2	12	6.00	3.42

Note: 1. Number of cases: 7.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-


COST


LOG COST


AREA

(ii) The recommended cost function

The recommended function for upflow filters is:-

$$\boxed{\text{COST} = 15.1*\text{AREA}^{0.68}}$$

The statistical details of the function are as follows:-

Number of observations : 7

Correlation coefficient (R) : 0.91

Coefficient of determination (R^2) : 83%

Standard error of residuals (in $\log_{10}$ model) : 0.164

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.676	0.135	25.3	< 1.0%

12.3.5. Upflow filtration

Approximate multipliers for confidence intervals about a prediction:-

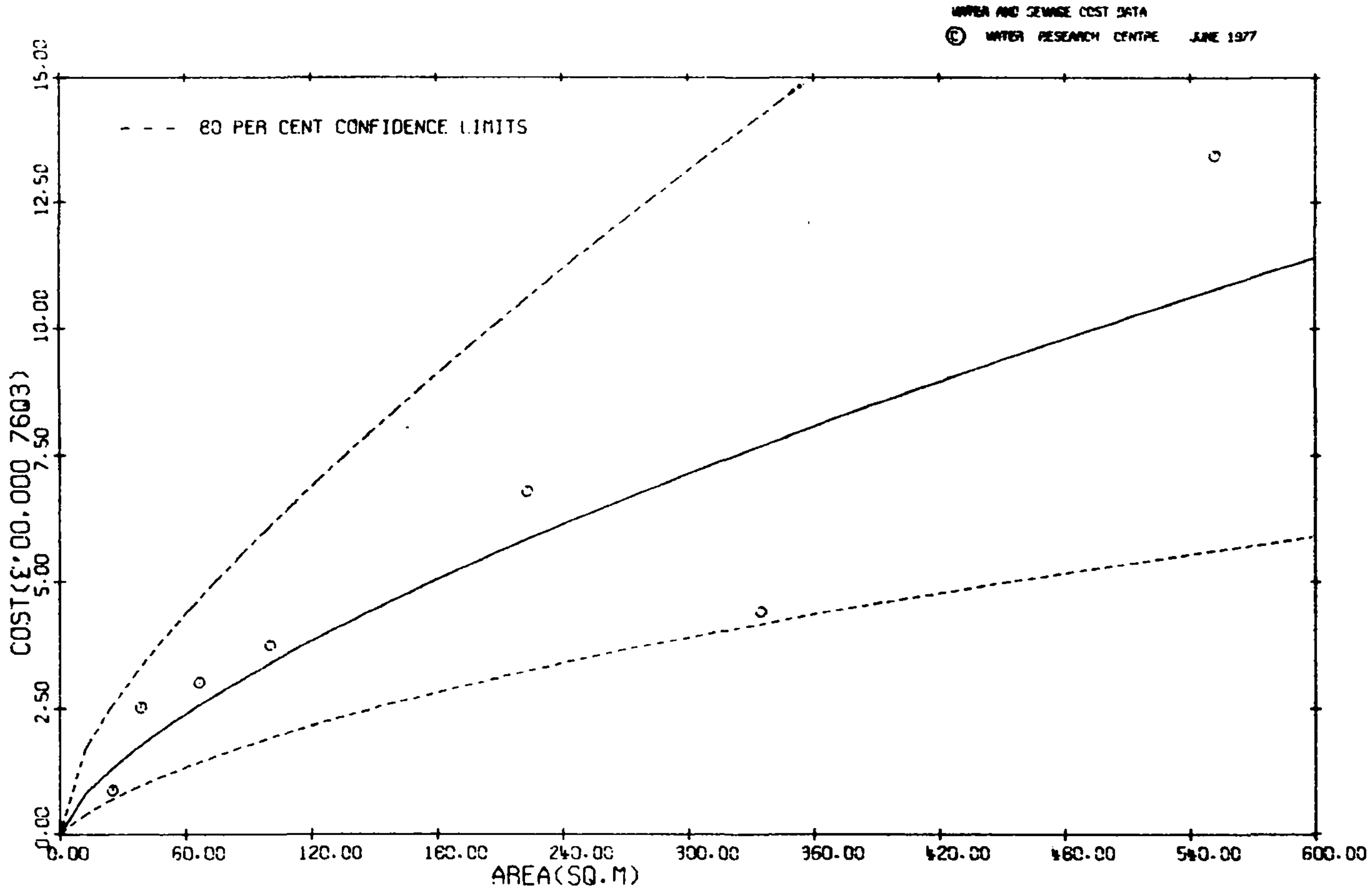
Confidence level	Lower	Upper
80%	0.57	1.75
95%	0.38	2.64

Figure 12-12 illustrates the recommended function.

(iii) <u>The data</u>

The upflow filter data is listed in Table A-24.

12.3.5. Upflow filtration



SCATTER DIAGRAM OF COST(£'00.000 76Q3)
AGAINST AREA(SQ.M)

Figure 12-12. Upflow filters

12.3.6. SLOW SAND FILTRATION

A. The modelling approach

Data was collected from accepted contract BoQs and associated documents. Half of the examples represent relatively small areas of slow sand filters, most of which were constructed at one site over a period of nine years. The explanatory variables considered were total filtration area, total filter wall length, individual filter length and width and number of filters. Number of filters and filtration area were both significant.

The Basic Weekly Wage Rate Index was found more suitable than the DQSD, Construction Materials and New Construction Indices for deflation. Costs were taken at date of tender and were not adjusted for the type of contract. The cost function only represents the cost of the filter shell; the costs of valves, pipeworks and filter media, together with their proportional share of indirect costs such as site establishment and general siteworks, were excluded. These amounted on average to a further 44% on the cost. Also excluded was the cost of any mechanical plant associated with filter bed cleaning or sand washing, and of civil engineering associated with sand washing bays.

B. The results

(i) Data summary

Table 12-34. Slow sand filters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost of filter shells (corrected to 1976 Q3)	COST	£ million	0.0380	2.87	0.763	1.02
Total filtration area	AREA	'000 m^2	0.158	112	17.5	30.9
Number of filters	NUM	-	1	34	7.00	9.62

Note: 1. Number of cases: 13.

2. The Basic Weekly Wage Rate Index was used for deflation.

Mini-histograms of the main variables of interest:-


COST


LOG COST


AREA

(ii) The recommended cost function

The recommended function for slow sand filtration is:-

$$\boxed{\mathrm{COST} = 0.0653 * \mathrm{AREA}^{0.86}}$$

The statistical details of the function are as follows:-

Number of observations	:	13
Correlation coefficient (R)	:	0.94
Coefficient of determination (R^2)	:	88%
Standard error of residuals (in $\log_{10}$ model)	:	0.255

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.863	0.096	81.0	$\ll 0.1\%$

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.45	2.23
95%	0.27	3.64

Figure 12-13 illustrates the recommended function.

(iii) Other cost functions

If the number of filters in the facility (NUM) is also known, the following function should be used:-

$$\boxed{\text{COST} = 0.0576 * \text{AREA}^{0.34} * \text{NUM}^{0.82}}$$

The statistical details of the function are as follows:-

Number of observations	:	13
Multiple correlation coefficient (R)	:	0.98
80% confidence interval multipliers	:	0.58, 1.72
Standard error of residuals (in $\log_{10}$ model)	:	0.172

(iv) The data

The slow sand filter data is listed in Table A-25.

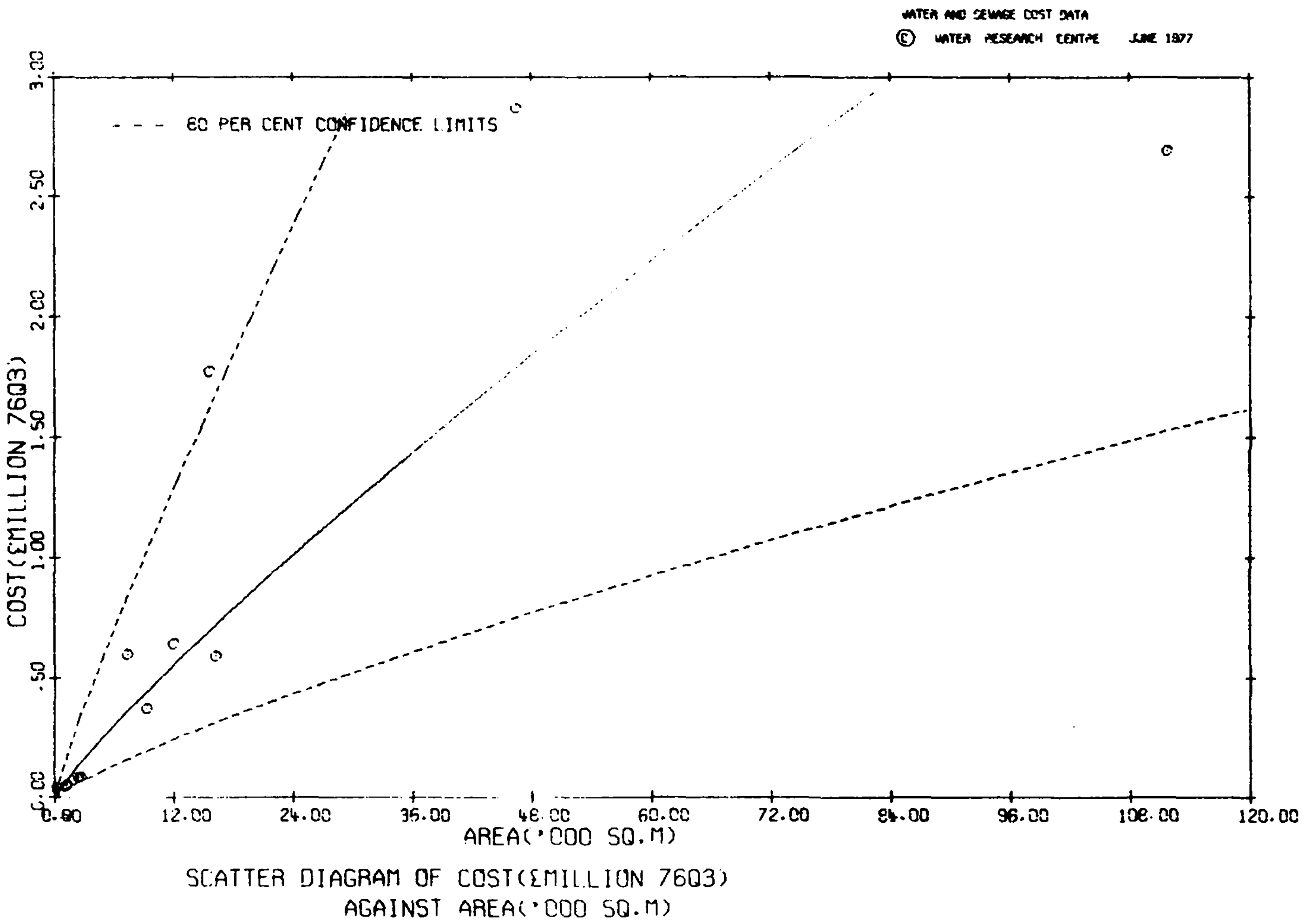


Figure 12-13. Slow sand filters

12.4. DISINFECTION

12.4.1. CHLORINATION

A. General

The cost of chlorination depends on a number of factors which are discussed in (i) to (iii) following.

(i) Rate of application

This depends on the quality of the water and the reason for application. The presence of organic matter - whether through pollution or algae, or simply as evidenced by the water colour - causes a need for greater chlorine doses. Greater doses are also required for high pH waters, as the effectiveness of chlorine decreases with increase in pH.

Although chlorine will be applied after any other treatment to disinfect the water, some chlorine might also be added before and during treatment, to improve not only disinfection but also chemical clarification to assist removal of algae and animals, to reduce colour concentration, or to utilize ferrous sulphate as the coagulant.

Ammonia in the water will also affect chlorine requirements.

(ii) Source of chlorine

Chlorine is usually purchased in the liquid form. This has to be vaporized, put into solution with water and then applied to the main stream of water. A simple alternative is the direct application of hypochlorite solution. Less commonly, chloramines or chlorine dioxide can be used, or the on-site electrolytic generation of gaseous chlorine.

(iii) Chlorination control

The control equipment required will depend on the method of chlorination, as discussed below. (Further information on chlorination practice should be obtained from standard texts (11).)

I. Simple chlorination is likely to be used when the water quality is consistent, and the dose required is not very great and easily ascertained. A final chlorine concentration meter might be used for monitoring the success of the manual control of chlorine dosing.

II. Breakpoint chlorination is dependent on the use of a chlorine residual controller to measure the available free chlorine concentration and keep this greater than the breakpoint concentration.

III. Superchlorination (followed by dechlorination) is the application of chlorine to produce a free residual chlorine concentration so large that dechlorination is required before the water is subsequently used. In addition to the greater quantities of chlorine required, dechlorination adds to the expense of superchlorination. Usually sulphur dioxide is the dechlorinating agent, dosed with the aid of a chlorine residual controller.

IV. Chloramination consists of the use of ammonia in conjunction with chlorine, and is most likely to be used for maintaining a chlorine residual in distribution for periods longer than is normally necessary. Gaseous ammonia, or sometimes ammonium sulphate solution, is dosed to the water either before or after chlorination, depending on the purpose of chloramination.

12.4.1. Chlorination

B. The modelling approach

Section 12.2.3 shows how the cost of chlorination, dechlorination and ammoniation equipment can be allowed for as part of the overall chemical treatment equipment. However, that result can not be used for estimating the cost of disinfection equipment alone.

The principal factors affecting the cost of a chlorination installation have been summarized in part A. Insufficient information was collected for models to be developed for each method of chlorination control. Because capital cost is heavily dependent on the equipment required, advice and estimates should be obtained from potential contractors. However, to provide an indication of the magnitude of chlorination equipment costs a cost function was produced relating cost solely to the total chlorination capacity (expressed as 1000 kg/d). The function does not distinguish multiple point dosing systems or between high or low dose systems, and this will account for some of the scatter about the model.

Bulk storage of chlorine will involve an additional cost of about 50%.

No data was available on the cost of ammoniation equipment. The few examples of sulphonation equipment costs ranged from 23 to 44% of the cost of the chlorination equipment.

Costs are for installed plant and were adjusted for inflation by the Engineering and Allied Industries Index.

C. The results

(i) Data summary

Table 12-35. Chlorination equipment data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Chlorination equipment cost (corrected to 1976 Q3)	COST	£'000	3.88	89.1	30.1	23.7
Total chlorine capacity	CHLCAP	'000 kg/d	0.00818	2.10	0.614	0.737

Note: 1. Number of cases: 13.

2. The Engineering and Allied Industries Index was used to deflate costs.

Mini-histograms for the main variables of interest:-

COST

LOG COST

CHLCAP

(ii) The recommended cost function

The recommended function for chlorination equipment is:-

$$\boxed{\text{COST} = 45.1*\text{CHLCAP}^{0.46}}$$

The statistical details of the function are as follows:-

Number of observations : 13

Correlation coefficient (R) : 0.91

Coefficient of determination (R^2) : 84%

Standard error of residuals (in $\log_{10}$ model) : 0.166

12.4.1. Chlorination

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CHLCAP	0.461	0.062	55.9	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.60	1.68
95%	0.43	2.32

Figure 12-14 illustrates the recommended function.

(iv) The data

The chlorination equipment data is listed in Table A-26.

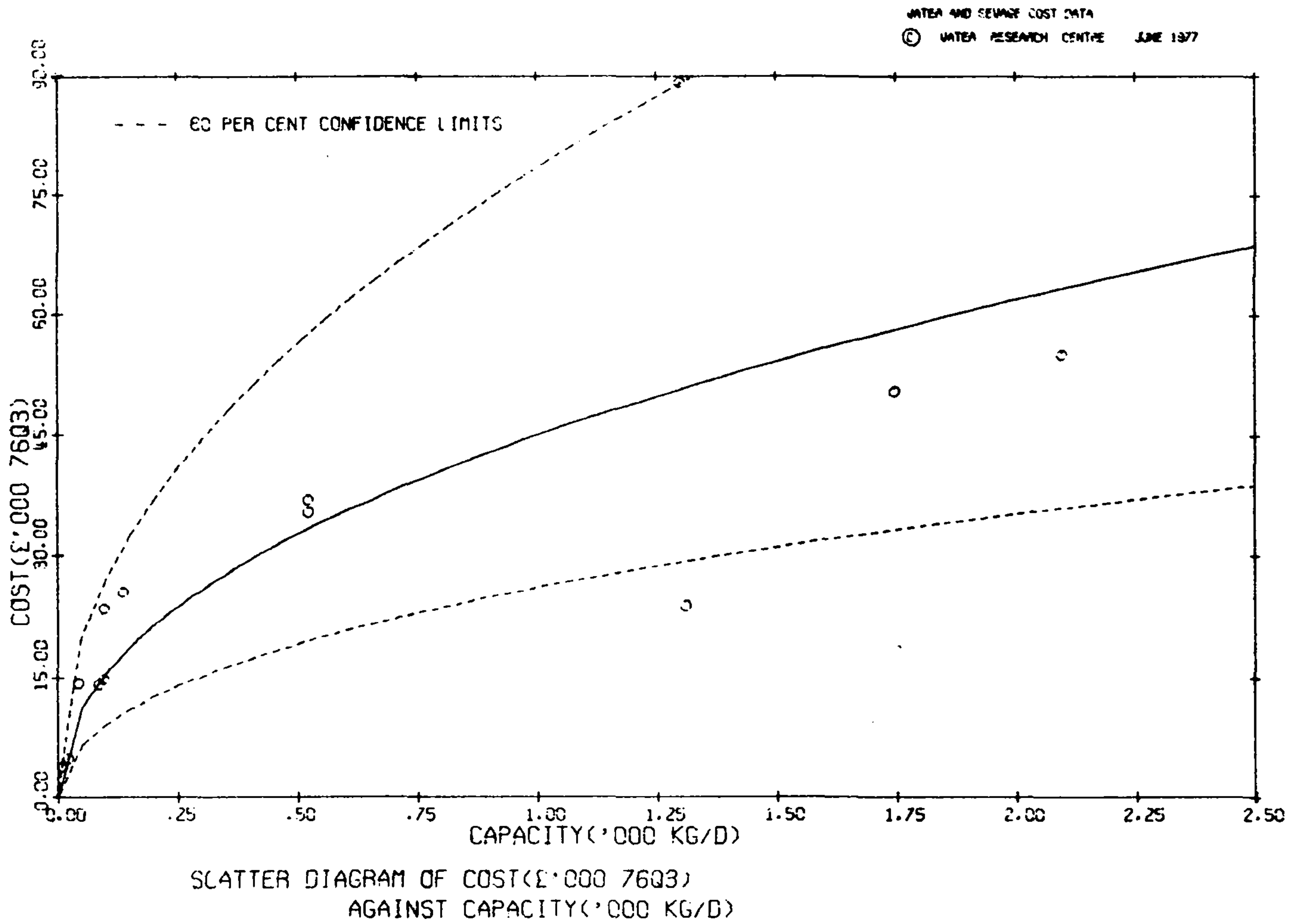


Figure 12-14. Chlorination equipment

12.4.2. OZONATION

A. General

Ozone is not used in the UK as a final treatment disinfectant because a residual concentration cannot be maintained to protect the water during distribution. Where ozone treatment plant has been installed it is primarily for the reduction of low colour concentrations as an alternative to coagulation, thereby avoiding the disposal of the resulting hydroxide sludge. Ozone treatment is also considered for taste and odour control. Mitchell (12) has reviewed the use of ozone.

The ozone dose for disinfection or colour reduction depends on the quality of the raw water. Consequently pre-treatment by sand filtration or microstraining is normally carried out to reduce the ozone requirements. For this reason, and because there are so few examples of ozone treatment, it is not possible to give typical ozone doses or plant arrangements. However, ozone doses catered for do lie in the range 2 to 8 mg/l.

B. Costs

The methods used for generating ozone and for ozone-water contacting are still evolving; this is likely to make the use of ozone more economic in the future. Ozone costs are largely dependent both on power costs and the dose rate applied. The information available suggests that generating plant costs should be related to the ozone generating capacity, and that civil engineering costs for the ozone-water contacting should at present be related to water throughput.

Table 12-36 summarizes the cost information available. Also, O'Donovan (13) has reported that capital expenditure for ozone-based treatment varies from about 50 to 68% of that for coagulation-based treatment according to treatment works size.

Table 12-36. Costs of ozonation

Throughput ('000 m^3/d)	Ozone dose rate (kg/h)	Civil cost (£'000 1976 Q3)	Plant cost (£'000 1976 Q3)	Power consumption (kW/kg O_3)	Comments
11.4	0.95	43.9	53.4	25	Estimate for taste and colour control
22.7	1.9	46.9	85.5		
45.5	3.8	46.9	118		
30.0	8.0	261	241	36	Colour reduction
81.8	7.0	815	406	27 to 37	
450	33.0	554	906	-	
				27	Other estimates
				27	
				23 to 25	

12.5. SLUDGE PROCESSES

Practices in water works sludge disposal are still changing in response to anti-pollution legislation, especially that introduced since 1963. The immediate past is therefore an unreliable guide to the future, and will remain so until practices become more clearly standardized.

It is generally agreed that the target must be to consign sludges to permanent disposal at the rate at which they are produced. Water works sludges arise as liquids with very low concentrations of solids. The purpose of sludge treatment is to achieve a solids content which allows the most economical method of disposal. Because of the great volume changes involved, full treatment is usually carried out in two stages: concentration, followed by dewatering. The transition depends on the particular sludge and individual characteristics of the processes involved. Disposal is regarded as the third and final part of the sludge treatment system.

The processes which have been considered here are only those involved in the principal sludge treatment and disposal routes.

Items in civil engineering BoQs regarded as sludge works include:-

(i) wastewater disposal;
(ii) lagoons, drying beds, sludge tanks, etc.;
(iii) sludge houses, filter press house, sludge pumping station.

Items in mechanical engineering BoQs regarded as sludge equipment include:-

(i) washwater disposal equipment;
(ii) settling tank equipment, sludge picket fence thickeners, etc.;
(iii) sludge presses, sludge centrifuges, etc.;
(iv) sludge transfer pumps.

The proportions of total cost in civil and mechanical engineering BoQs relating to sludge works and equipment are given in Table 12-37. They appear not to be related to size of treatment works. In a number of cases separate costs for sludge works or equipment could not be identified, probably through the expenditure arising at a much later date in the development of the works. However, current studies indicate that, with the adoption of a satisfactory sludge disposal strategy at the conception of new water treatment works, sludge processing costs will be greater than those shown by this survey to have occurred in the past.

Table 12-37. Sludge civil and mechanical engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of total civil engineering costs
U	5.5	2.0
U	7.8	0
U	8.7	3.2
L	9.1	0
U	11.4	3.0
U	13.6	0
L	14.5	0
U	15.0	5.5
U	18.2	3.2
L	20.5	3.3
L	22.7	6.5
U	27.3	5.9
L	54.5	7.6
L	68.2	0.4
U	72.7	2.4
L	109	2.7
L	145	1.8
U	159	3.7
		% of total mechanical engineering costs
U	3.6	0
U	5.5	0
U	7.8	0
U	8.7	1.8
L	9.1	0
U	15.0	4.4
L	20.5	1.8
L	22.7	8.2
U	27.3	4.0
L	54.5	0
U	72.7	0
L	109	3.3
L	145	3.1
U	159	7.9

12.5.1. CONCENTRATION

A. General

Concentration of sludge of a particularly low solids concentration for dewatering might require two stages: settlement, and thickening. For more concentrated sludges, the settlement stage might be unnecessary but might occur because a balance tank is required. Tanks used for flow balancing, settling and thickening are of three kinds:-

(i) Rectangular. These are often referred to as washwater settling tanks, and have usually been constructed in pairs. However, when sludge is produced as a relatively continuous stream an automated group of these tanks would be more appropriate. These can be regarded as flow balancing and settling tanks only. The main design variation occurs with the tank floor: some are flat and usually sloping gently to the outlet end, whilst others have one or two large sumps or hoppers at the outlet end. (Large, deeper tanks constructed with sloping walls have been considered as lagoons.)

(ii) Pyramidal. These tanks are often found where floc blanket sedimentation tanks are also pyramidal shaped. They are used for flow balancing, settling and thickening.

(iii) Conical. These are normally built specifically for thickening. A picket fence stirrer-scraper is usually fitted within the cone to aid thickening and removal of the thickened sludge. Adequately designed and operated tanks can produce quite thick sludges in a single stage on a continuous basis. The upper part of the tank with vertical walls is sometimes constructed square in plan.

Data was collected from BoQs and associated documents. The modelling approach is discussed separately for each type of tank in parts B, C and D.

No useful examples of picket fence costs were collected, but an estimate based on budget prices can be made as follows:-

	Tank diameter (m)	Approximate cost (£'000 1976 Q3)
Full bridge	2	5.8
	15	18.2
Half bridge	15	18.2
	32	46.6

B. The results - rectangular tanks

(i) Detailed modelling approach

The sample included some cases with hoppers and others with simple flat bases. The costs were found to be lower than those for rectangular storm and aeration tanks for sewage treatment (see Section 13.3.2). The reasons for this have not been established, although it might have arisen through the use of different length/width/depth ratios or different design standards.

Total cost was related to total available volume, length, width, maximum depth exclusive of any hopper, and number in the group. In addition, two other factors were examined: whether the base was completely flat or contained hoppers, and whether or not the scheme included a small pumphouse which was difficult to remove from the cost. However, neither of these factors was significant. Volume was found to be the principal explanatory variable, with width and number of secondary importance. The last two are technically acceptable in that they represent the benefit of grouping rather than having individual tanks.

Total cost was defined to include all items usually associated with the civil engineering contract, but excluding any special mechanical plant to assist sludge removal. The tender price at contract date was used. The Basic Weekly Wage Rate Index was chosen for deflation in preference to the DQSD, Construction Materials and New Construction Indices.

(ii) Data summary

Table 12-38. Rectangular tanks (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	WASHCOS	£'000	14.1	100	49.3	26.6
Total volume of tanks in facility	VOL	'000 m^3	0.240	2.53	1.13	0.836
Mean width of tanks in facility	WIDTH	m	4.00	14.0	8.14	3.59
Number of tanks in facility	NTANK	-	1	3	2.08	0.515

Note:
1. Number of cases: 12.
2. The Basic Weekly Wage Rate Index was used for deflation.

Mini-histograms for the main variables of interest:-

WASHCOS

LOG WASHCOS

VOL

(iii) The recommended cost function

The recommended function for rectangular tanks is:-

$$\boxed{\text{WASHCOS} = 47.1 * \text{VOL}^{0.71}}$$

The statistical details of the function are as follows:-

Number of observations : 12

Correlation coefficient (R) : 0.93

Coefficient of determination (R^2) : 86%

Standard error of residuals (in $\log_{10}$ model) : 0.102

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.714	0.090	63.2	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.73	1.38
95%	0.59	1.69

Figure 12-15 illustrates the recommended function.

(iv) Other cost functions

If the mean width of tank is known in addition to the total volume of the tanks, the following function may be used:-

$$\boxed{\text{WASHCOS} = 16.2*\text{VOL}^{0.57}*\text{WIDTH}^{0.52}}$$

The statistical details of the function are as follows:-

Number of observations	:	12
Multiple correlation coefficient (R)	:	0.99
80% confidence interval multipliers	:	0.86, 1.17
Standard error of residuals (in $\log_{10}$ model)	:	0.049

A still more detailed model including the number of tanks as a significant explanatory variable is:-

$$\boxed{\text{WASHCOS} = 28.4*\text{VOL}^{0.64}*\text{WIDTH}^{0.37}*\text{NTANK}^{-0.34}}$$

The statistical details of the function are as follows:-

Number of observations	:	12
Multiple correlation coefficient (R)	:	0.99
80% confidence interval multipliers	:	0.88, 1.14
Standard error of residuals (in $\log_{10}$ model)	:	0.040

(v) The data

The rectangular tanks civil engineering data is listed in Table A-27.

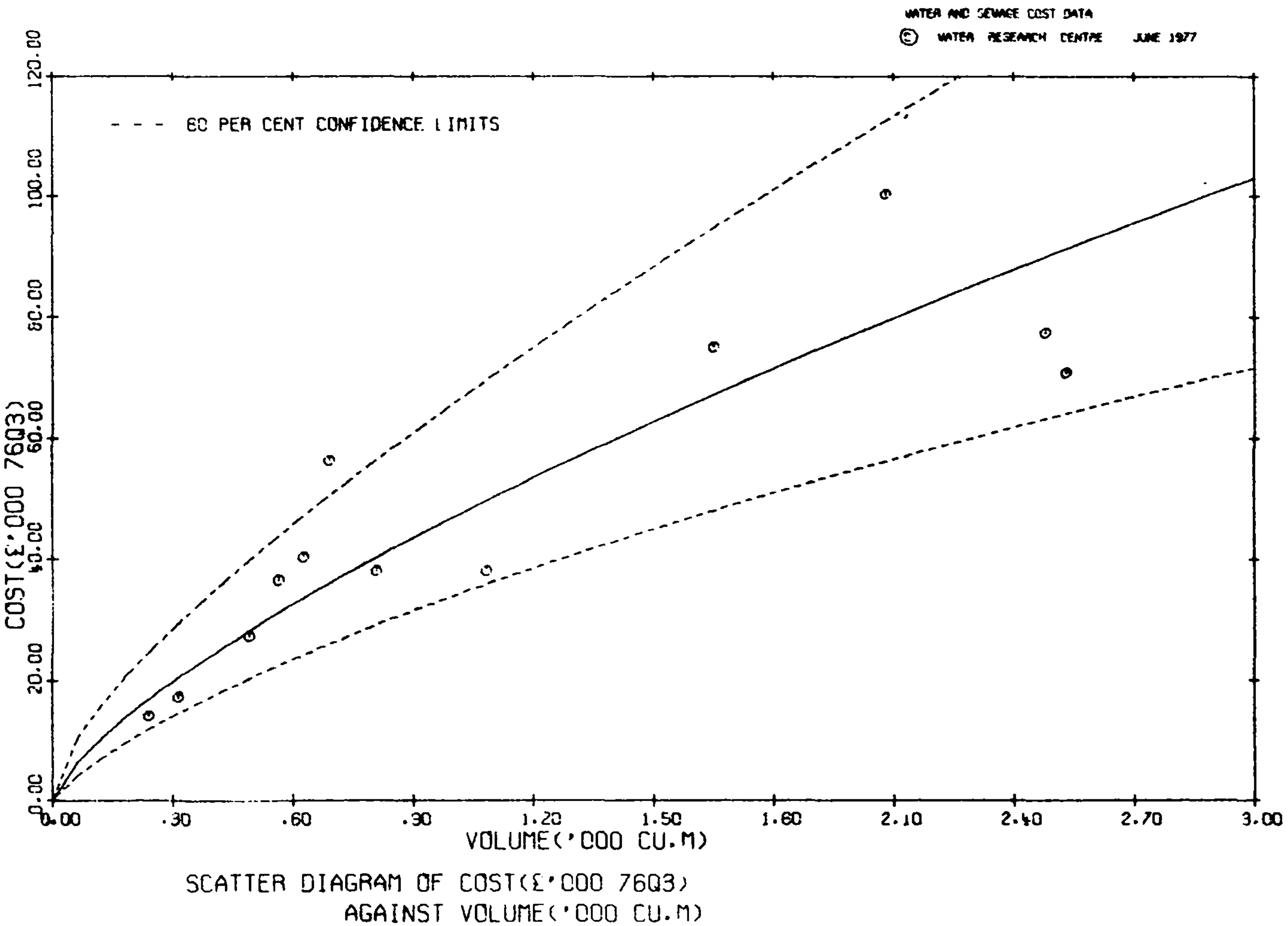


Figure 12-15. Rectangular tanks (civil engineering)

C. The results - pyramidal tanks

(i) Detailed modelling approach

The sample of pyramidal tanks constructed for treating water works sludge was increased by including similar tanks built in groups of not more than four tanks for floc blanket sedimentation. The sample is therefore different from that used in Section 12.3.1 in that it represents just the small end of the size range found with floc blanket sedimentation.

The explanatory variables considered were total available volume, length of side of individual tanks, available depth of parallel section, number in the group and whether constructed for sludge thickening or floc blanket sedimentation. However, only volume was found to be significant.

The costs of pyramidal humus tanks in sewage treatment (see Section 13.3.3) were also examined to see whether they could have been included in the sample of water works tanks. However, because of differences in the range of values of the explanatory variables and different principles of design and construction, the samples were not compatible. In particular, the method of construction could influence cost by a factor of two.

Costs were taken at date of tender with no allowance made for the type of contract. The New Construction Index was found more suitable than the DQSD, Construction Materials and the Basic Weekly Wage Rate Indices for deflation.

(ii) Data summary

Table 12-39. Pyramidal tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost (corrected to 1976 Q3)	PYRCOS	£'000	20.5	110	55.2	26.7
Total volume of tanks in facility	VOL	'000 m^3	0.110	2.04	1.06	0.665

Note: 1. Number of cases: 11.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

PYRCOS

LOG PYRCOS

VOL

(iii) The recommended cost function

The recommended function for pyramidal tanks is:-

$$\boxed{PYRCOS = 55.4*VOL^{0.56}}$$

The statistical details of the function are as follows:-

Number of observations	:	11
Correlation coefficient (R)	:	0.95
Coefficient of determination (R^2)	:	90%
Standard error of residuals (in $\log_{10}$ model)	:	0.076

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.563	0.062	81.5	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

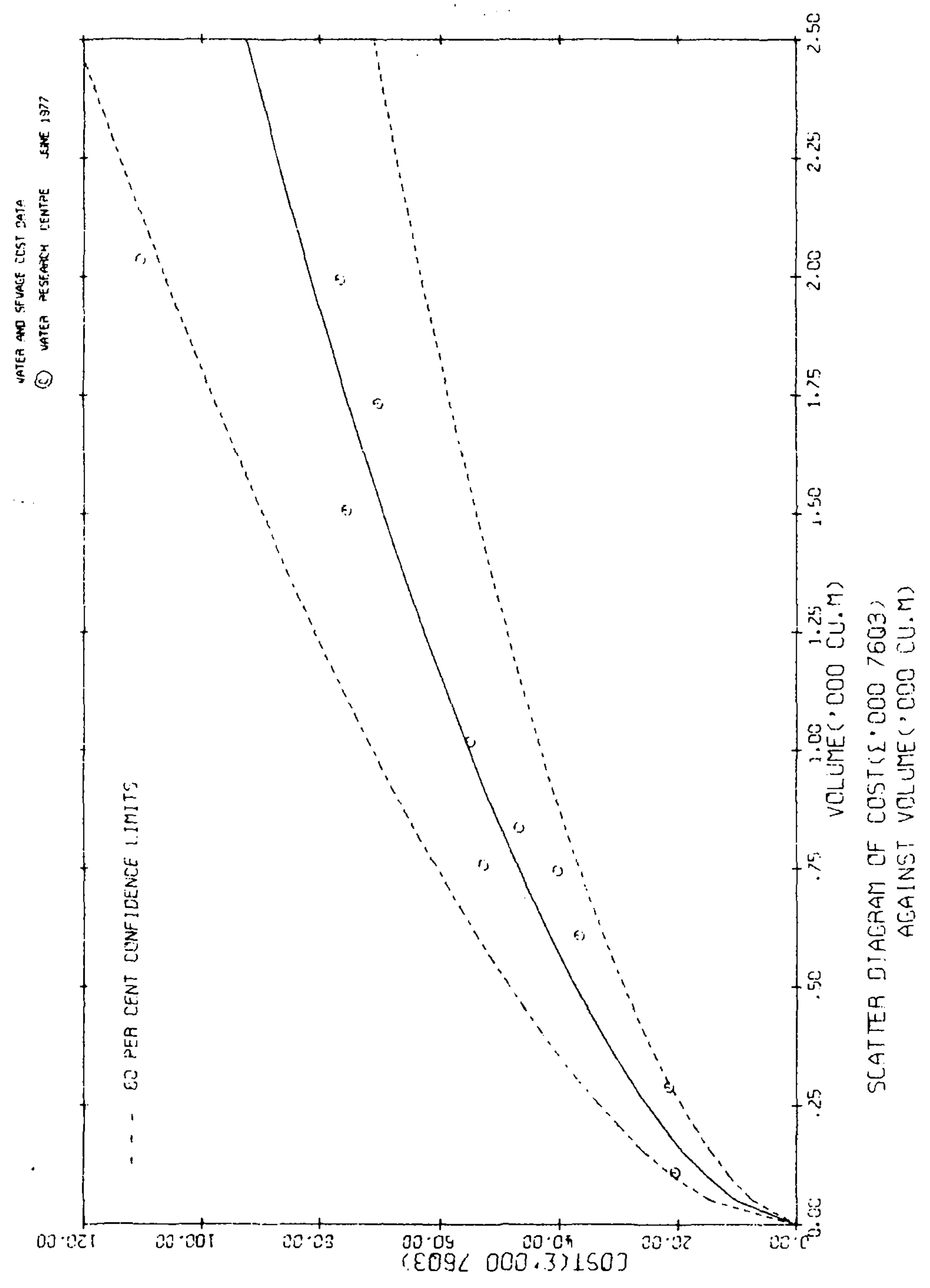
Confidence level	Lower	Upper
80%	0.79	1.27
95%	0.67	1.49

Figure 12-16 illustrates the recommended function.

(iv) The data

The pyramidal tanks data is listed in Table A-28.

Figure 12-16. Pyramidal tanks



D. The results - conical tanks

(i) Detailed modelling approach

The small sample available of conical tanks constructed for water works sludge thickening consisted of seven examples, arising from only five schemes, and represented only the cheap and expensive extremes of design. The more expensive tanks had complex bases and side walls, and could be twice as expensive as the cheaper tanks. The expensive and cheaper designs corresponded roughly to the upper and lower 80% confidence limits about the cost functions both for pyramidal water works sludge settling tanks and sewage circular sedimentation tanks (Section 13.3.1). The expensive design bore similarities to the more expensive humus pyramidal tanks (Section 13.3.3), both having stepped walls. The pyramidal water works tanks cost function is recommended for relating total cost to total volume of tanks.

Two examples of conical sewage sludge thickening tanks were available but represented much larger installations. A cost function based on civil engineering cost per tank was developed from the combined sample. It was found that cost per tank was most closely related to tank diameter, and that type of tank (whether constructed for sewage or water sludge), complexity of individual tank construction or number of tanks were not significant. A cost function is recommended which has diameter as the only explanatory variable. The Construction Materials Index was chosen in preference to the DQSD, New Construction and Basic Weekly Wage Rate Indices for deflating costs.

(ii) Data summary

Table 12-40. Conical tanks (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Civil engineering cost per tank corrected to 1976 Q3)	CONCOS	£'000	4.66	48.8	27.6	16.1
Diameter of tank	DIAM	m	6.1	21.4	12.4	5.76

Note: 1. Number of cases: 9.

2. The Construction Materials Index was used to deflate costs.

12.5.1. Concentration

Mini-histograms for the main variables of interest:-

CONCOS

LOG CONCOS

DIAM

(iii) The recommended cost function

The recommended function for conical tanks is:-

$$\boxed{\text{CONCOS} = 0.758*\text{DIAM}^{1.40}}$$

The statistical details of the function are as follows:-

Number of observations	:	9
Correlation coefficient (R)	:	0.84
Coefficient of determination (R^2)	:	71%
Standard error of residuals (in $\log_{10}$ model)	:	0.197

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DIAM	1.40	0.337	17.1	<1.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.53	1.90
95%	0.34	2.92

Figure 12-17 illustrates the recommended function.

(iv) The data

The conical tank civil engineering data is listed in Table A-29.

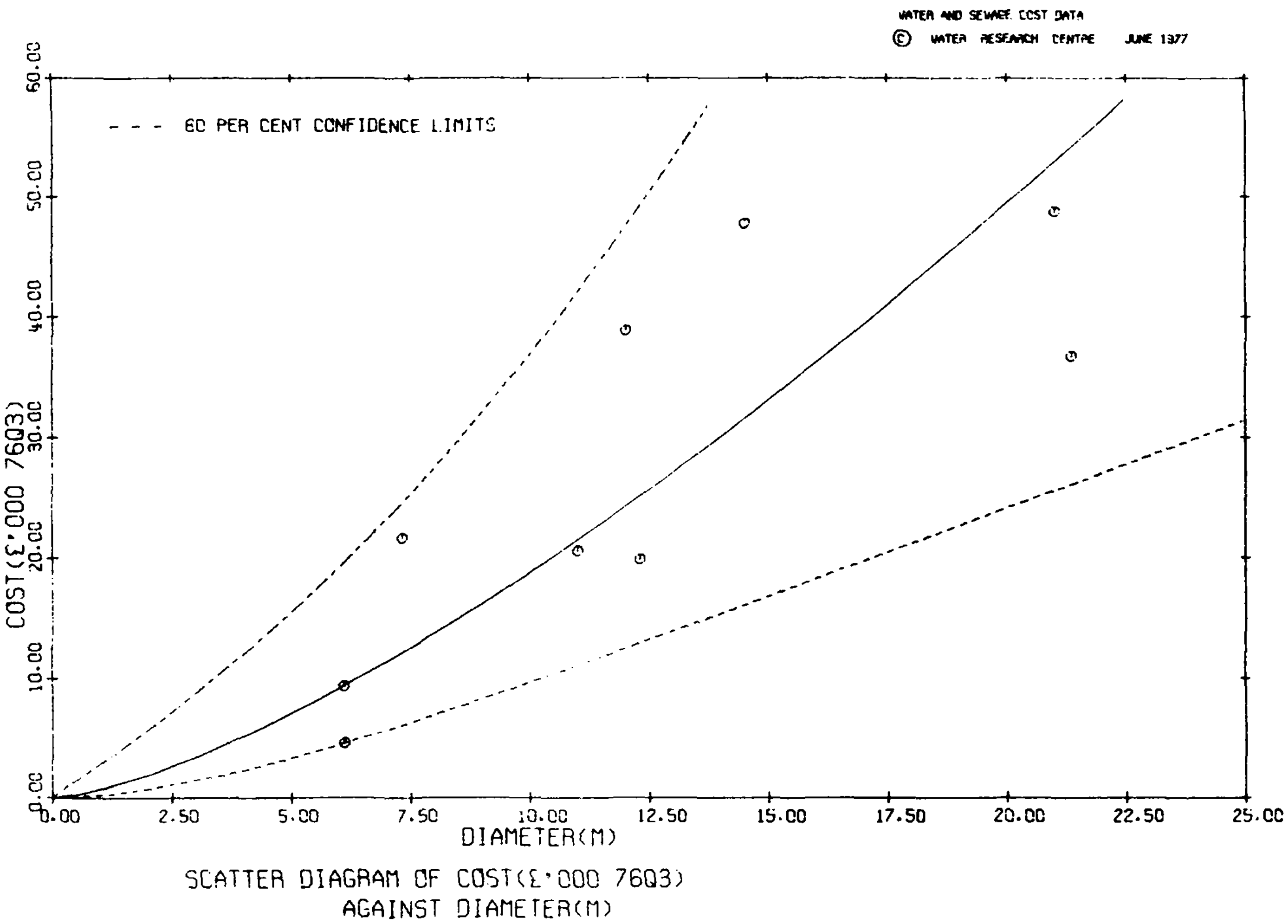


Figure 12-17. Conical tanks (civil engineering)

12.5.2. DEWATERING

A. General

The objective of dewatering is to produce a sludge of manageable quality for the chosen means of ultimate disposal. Thickening is usually all that is needed for pumping to sea or sewer or for spraying on land. Disposal by lorry to a recognized waste disposal site usually requires the production of a manageable sludge cake. Such dry sludge can be produced by using sludge drying beds, plate presses or vacuum filters. Centrifuging is a fairly new method of mechanical dewatering, and is not considered here. Sludge lagoons are included in this section although they are constructed for a variety of reasons, ranging from short-term emergency storage to settling over a period of many years. Sludge lagoons should not be regarded as a long-term means of ultimate disposal.

A cost function for sludge drying beds is given in part B. Costs of plate presses and lagoons are then discussed in parts C and D respectively.

B. The results - sludge drying beds

(i) Detailed modelling approach

Data was collected from BoQs and associated documents. Because of the limited sample sizes, drying beds used for water works sludge and sewage sludge were examined together. Some water works sludge drying beds are built without concrete slab bases although the drained water is collected. The few examples of this sort were not included in the sample used for developing the cost function.

Total area, total perimeter and dividing wall length, number of beds and purpose (water works or sewage sludge) were used as explanatory variables. However, only area was found to be significant.

Costs were taken at tender date with no account made for the type of contract. The cost covers all work usually found in the civil engineering contract and includes underdrains, media and pipeworks in the immediate vicinity of the beds, but excludes any provision of mechanical plant such as monorails and skips. Monorails will add about 15% to the civil engineering cost. The DQSD Index was preferred for deflation to the Construction Materials, New Construction and the Basic Weekly Wage Rate Indices.

(ii) Data summary

Table 12-41. Sludge drying beds data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Civil engineering cost (corrected to 1976 Q3)	BEDCOS	£'000	3.81	111	28.4	30.9
Total area of beds	AREA	'000 m^2	0.0570	5.19	0.892	1.46

Note:
1. Number of cases: 12.
2. The DQSD Index was used for deflation.

12.5.2. Dewatering

Mini-histograms for the main variables of interest:-

BEDCOS

LOG BEDCOS

AREA

(iii) The recommended cost function

The recommended function for sludge drying beds is:-

$$\boxed{BEDCOS = 36.8*AREA^{0.71}}$$

The statistical details of the function are as follows:-

Number of observations	:	12
Correlation coefficient (R)	:	0.97
Coefficient of determination (R^2)	:	94%
Standard error of residuals (in $\log_{10}$ model)	:	0.111

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.708	0.055	165	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.70	1.42
95%	0.57	1.77

Figure 12-18 illustrates the recommended function.

(iv) The data

The sludge drying beds data is listed in Table A-30.

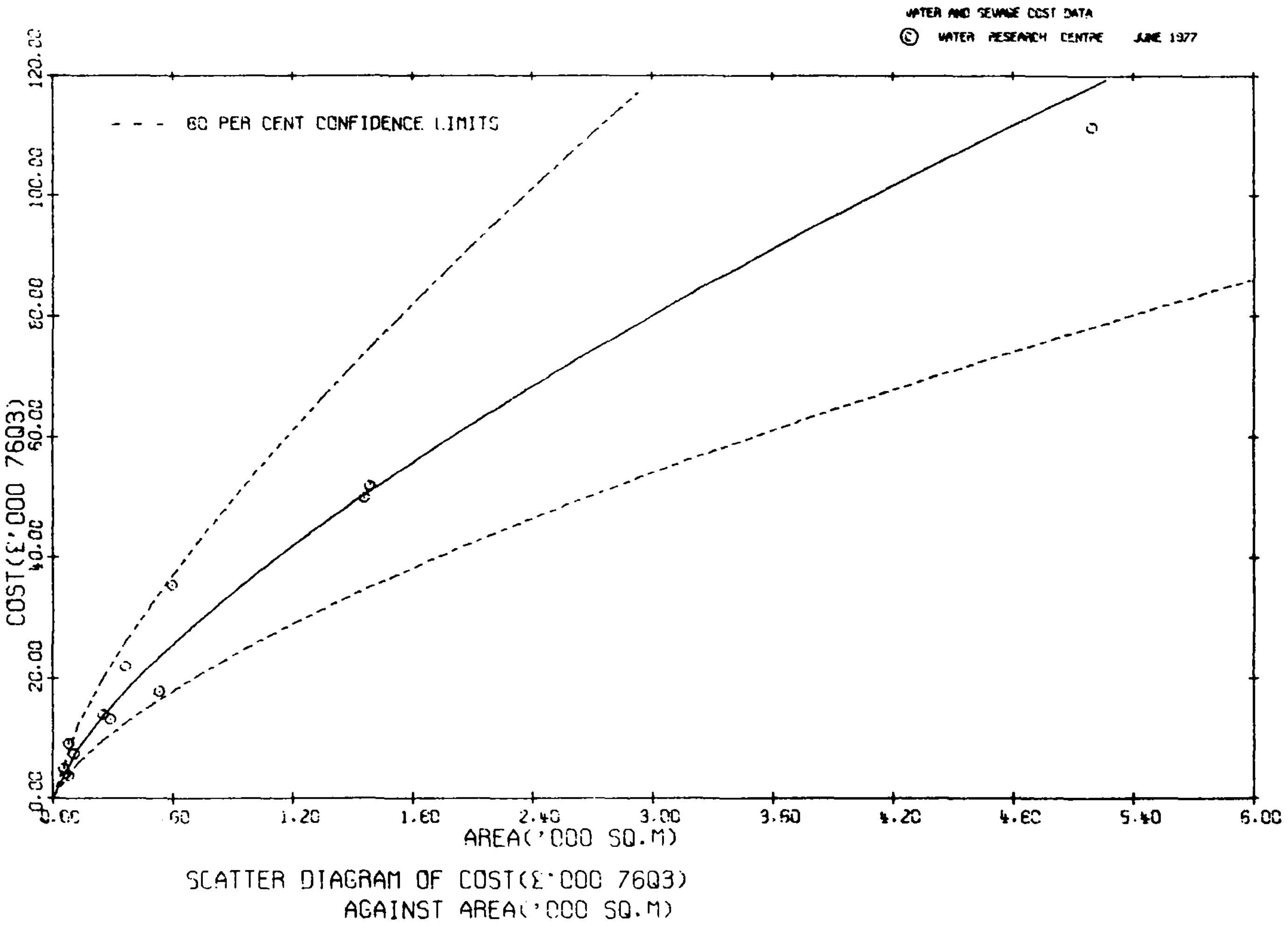


Figure 12-18. Sludge drying beds

C. The results - plate presses

Costs of presses used for sewage sludge are given in Section 13.7.3. Installations for water treatment are unlikely to be as large as those represented in the sewage sludge pressing sample. Nevertheless, budget prices indicate that, for installations greater than about 400 m^2, the cost functions in Section 13.7.3 can be used for water works sludge, except that the costs of civils works should be reduced by 10%. The reason why the civils costs were found to be cheaper for water works sludge is that copperas is not used in conditioning, whereas it is for sewage sludge.

D. The results - sludge lagoons

Data for sludge lagoons was collected from BoQs and associated documents. Lagoons were found to have been constructed in a variety of ways depending on their purpose, and consequently it was not possible to derive a cost function from the lagoons data alone. However, when this data was combined with the data for raw water reservoirs it was possible to take some account of construction type, and two cost functions were developed for raw water reservoirs and sludge lagoons; these are presented in Section 11.2E.

The sludge lagoons data is listed with some comments in Table 12-42.

Table 12-42. Sludge lagoons data

Example	Cost (£'000 1976 Q3)	Volume ('000 m^3)	Cost/ volume (£ 1976 Q3/m^3)	Comments
1	33.1	95.4	0.347	Large earth/clay bunded.
2	232	109	2.13	Excavated, rolled clay, concrete-faced bunding.
3	39.1	10.9	3.59	Rectangular excavation membrane lined.
4	13.5	2.26	5.96	Excavated and earth banked with sand drainage blanket.
5	20.4	3.20	6.39	Excavated and earth banked.
6	19.1	2.50	7.63	Excavated and earth banked.
7	34.1	4.10	8.31	Excavated with sand drainage blanket.
8	181	21.7	8.35	Excavated, concreted floor with sand and tiles.
9	423	47.1	8.98	Concrete walls.
10	12.8	0.72	17.7	Earth bank walls, concrete floor.
11	158	4.30	36.7	Irregular shaped, Frodingham piled walls, concrete floor.
12	33.6	0.53	63.4	Concrete tank.

12.6. ADDITIONAL PROCESSES

12.6.1. AERATION AND DESORPTION

A. General

The contacting of water with air can be for a variety of purposes, including:-

(i) aeration for the oxidation of dissolved iron and manganese;
(ii) aeration to increase oxygen concentration prior to raw water storage or biological nitrification of ammonia;
(iii) desorption of carbon dioxide, hydrogen sulphide or ammonia.

There are other gas-liquid situations in water treatment which are best considered in the context of the appropriate section. These include:-

(i) dissolving air under pressure for dissolved air flotation (Section 12.3.2);
(ii) ozonation (Section 12.4.2);
(iii) dissolving carbon dioxide for artificial hardening or recarbonizing (Section 12.6.3);
(iv) degassing (carbon dioxide desorption) of dealkalized water (Section 12.6.3).

Contacting of air and water can be achieved by a variety of methods. In water treatment these are mostly concerned with dispersing water in air, and include the use of:-

(i) open or enclosed systems of sprays, fountains or stepped cascades;
(ii) natural or forced draughts, produced by blowing or sucking, towers packed with coke, rings, grids or trays.

Alternatively air may be dispersed in water, by bubbling or mechanical agitation. Aeration also occurs at free flowing water surfaces in open channels, especially where flow is turbulent at bellmouths, corners, flumes, weirs, penstocks and collecting launders.

Desorption of carbon dioxide from groundwater is only used when carbon dioxide concentrations are greater than about 20 mg/l. Otherwise it is cheaper to use only an alkali to neutralize the acidity.

B. Costs

The cost of aeration and desorption will depend not only on which of the variety of methods is adopted, but also on the extent of aeration or desorption required. The examples of capital costs collected are summarized in Table 12-43. They are inadequate for making estimates but do give some indication of the variability to be expected.

Table 12-43. Examples of capital costs of aeration and desorption

Purpose	Description	Capacity ('000 m^3/d)	Approximate cost (£'000 1976 Q3)
CO_2 desorption	Spray	1.64	19.9
	Forced draft, plastic grid	3.27	12.3
	Forced draft, plastic grid	4.55	17.0
	Forced draft, trays	5.45	30.2
	Forced draft, trays	7.27	36.5
CO_2 desorption and iron oxidation	Natural draft, coke combined with filter	12.7	16.6
Oxygenation	3-tier weir	30.2	17.5
	3-tier weir	63.6	34.6
	Mechanical agitation	81.8	44.5

12.6.2. ACTIVATED CARBON TREATMENT

A. General

Activated carbon might be used in water treatment for:-

(i) taste and odour control;

(ii) reduction of blanket measurements of organic content such as TOC and COD;

(iii) removal of specific organic compounds.

These have been discussed in detail elsewhere (14).

The carbon can be used either as a powder or in granular form. Powdered carbon is usually dosed as a slurry at an appropriate stage in chemical clarification, and the quantity required can be easily adjusted. Granular carbon might be used in downflow pressure or gravity filters or in upflow moving beds, with or without regeneration of the exhausted carbon. The choice depends on what the treatment is for and the quantity of carbon required.

For simple taste and odour control, carbon doses are typically in the range 5 to 15 mg/l but can exceed 30 mg/l under certain circumstances. There is limited experience in the use of carbon for removal of organic compounds but doses are likely to be in the range 40 to 100 mg/l. The dose required will depend not only on what is to be removed but also on the choice of carbon. In addition, the use of granular carbon beds generally results in a lower carbon dose because the carbon is used more effectively. It is necessary to conduct laboratory and pilot tests to determine the powdered and granular carbon doses for the treatment of a particular water.

Two basic factors are required for the design and costing of an activated carbon system for a particular application: the minimum contact time, and the carbon dose or rate of exhaustion.

B. Costs

(i) Source of data

Burley and Short (15) have made a theoretical examination of the costs of various carbon systems to determine which will be the most economic. They were obliged to make a large number of assumptions based on a consensus of published work and suppliers' recommendations. However, there is evidence to suggest that their predicted costs are in good agreement with actual costs (multiplying their costs by 2.0 to adjust to 1976 Q3 prices).

(ii) Powdered carbon dosing systems

Burley and Short proposed the following function for equipment cost:-

$$\underset{(\pounds\ 1976\ Q3)}{\text{COST}} = 5000{*}(\underset{(kg/h)}{\text{CARBON RATE}})^{0.5}.$$

If the carbon rate or dose is not known, the cost of carbon equipment can be allowed for as part of the other chemical equipment (see Section 12.2.3).

(iii) Powdered carbon treatment costs

Burley and Short proposed the following approximate function for unit cost, including both capital (over 15 years at 9%) and operating costs:-

$$\underset{(p/m^3\ 1976\ Q3)}{\text{TOTAL UNIT RATE}} = 0.022{*}(\underset{(mg/l)}{\text{CARBON DOSE}}).$$

Capital cost is related to the maximum dose whereas operating cost depends on average dose. However, as the capital component is less than 10% of the total unit rate of doses greater than about 20 mg/l, the relationship can be assumed to be independent of equipment size and to represent average doses.

(iv) Granular carbon systems: taste and odour control

Burley and Short concluded that, for the conditions they examined, the cheapest systems are likely to be based on gravity filters although other circumstances could favour either pressure filters or moving beds. They also concluded that at throughputs of 85 000 m^3/d regeneration is always used, at 8500 m^3/d it is never used, and at intermediate throughputs it is used for only part of the dose range considered (2 to 12 mg/l).

(v) Granular carbon systems: removal of organic compounds

For all the plant sizes and carbon doses they examined, Burley and Short concluded that the cheapest solution is likely to be the moving bed system with regeneration.

12.6.3. SOFTENING AND HARDENING

A. General

There are two principal methods of softening municipal water supplies: precipitation softening, in which insoluble compounds of calcium and magnesium are formed which can be removed from water by sedimentation, filtration or deposition in a pellet reactor; and ion exchange, involving the exchange of calcium and magnesium ions for ions which cannot cause hardness.

Another method is the addition of polyphosphates. These remove the effect of hardness but not the hardness itself, by combining with calcium and magnesium to form soluble compounds. The method is sometimes considered as stabilization, but will not be discussed further here.

The method chosen for softening depends on:-

(i) the composition of the untreated water;
(ii) the extent of softening required; and
(iii) local circumstances, especially relating to the disposal of wastes.

Lime (or some other suitable alkali) added to hard water brings about precipitation softening. In contrast, lime added to soft acidic water will increase the hardness. It is common practice to add small quantities of lime to adjust the pH of water before distribution, to reduce general corrosion and plumbosolvency.

In the case of a very soft water, a stable alkaline pH with a tendency to form a protective scale can be produced only by a substantial degree of artificial hardening. This can be achieved in one of two ways depending on the scale of application:-

(i) by dosing lime with carbon dioxide for stabilization; or
(ii) by dissolution of calcined dolomitic limestone or similar materials, adding carbon dioxide if necessary to increase the dissolution.

B. Costs

(i) Precipitation softening

Precipitation softening is usually carried out either in hoppers or in certain proprietary sedimentation tanks (see Section 12.3.1). When a surface water is softened, precipitation is usually coincident with coagulation. Capital costs additional to those for normal coagulation treatment might be for larger storage of lime, caustic or soda ash, as allowed for in chemical equipment costs (see Section 12.2.3), and for treatment of larger quantities of sludge solids. Operating costs additional to those for normal coagulation treatment will be for the extra chemicals required and the small amount of labour and power associated with handling these.

An alternative method of precipitation softening suitable for treatment of some waters is the use of pellet reactors, as described by Hilson and Law (16) and Gledhill and McCaulis (17). Hilson and Law listed costs associated with pellet reactors; these need to be multiplied by about 3.0 to adjust to 1976 Q3 prices. They considered the pellet reactor system to be the cheaper for their application. A KIWA report (18) also found that the pellet reactor could be the cheaper system.

(ii) Ion exchange

There are a variety of plant arrangements for softening water by ion exchange. However, for municipal water treatment three systems are of most interest:-

I. the sodium chloride regenerated strong cation exchange system;
II. the acid regenerated strong cation exchange system; and
III. the acid regenerated weak cation exchange system (known as dealkalization).

The last two systems usually include carbon dioxide desorption by aeration and final pH adjustment with caustic soda. The desired quality of final water for supply is achieved by blending with unsoftened water. The choice of a system and its costs depends on the quality of the unsoftened water and the extent of softening required, and estimates of costs should be obtained for individual applications from plant contractors. However, Table 12-44 summarizes capital costs of some ion exchange plants and can be used as a rough guide.

12.6.3. Softening and hardening

A comparison of the operating and capital costs of various methods of softening 27 000 m^3/d water (18), to remove hardness in the range 0 to 500 mg/l $CaCO_3$, found the acid regenerated weak cation exchange system more expensive than the acid regenerated strong cation exchange system, which in turn could be more expensive than precipitation softening.

Table 12-44. Examples of plant costs for ion exchange softening

Blended output ('000 m^3/d)	Blend with unsoftened (%)	Hardness reduction (mg/l)	Type	Plant cost (£'000 1976 Q3)
2.27	40	440 to 190	Dealkalization	88.0†
5.45	44	347 to 160		87.2††
87.5	30	290 to 125		706
3.41	55	369 to 200	Strong acid cation brine regenerated	51.1
6.82	55	365 to 200		48.2
6.82	50	240 to 120 (360 to 0)		62.3

† Cost includes spray aeration and iron removal filtration.

†† Cost excludes degassing.

(iii) Hardening

The use of hardening to improve the quality of soft waters for supply is increasing but experience to date is limited and so little cost data is available.

Hardening based on lime will involve the additional cost of using greater quantities of lime than required for simple pH adjustment. The cost of carbon dioxide will depend upon whether it is purchased as a liquid or generated on-site. An allowance for plant costs can be made when considering clarified waters (see Section 12.2.3).

Hardening based on dissolution of calcined limestone or marble will usually involve the cost of the filters containing the material, although in some circumstances the material could be loaded into existing sand filters.

12.6.4. AMMONIA AND NITRATE REMOVAL

A. General

(i) Ammonia removal

The presence of ammonia in water for public supply can cause difficulties in the control of chlorination for disinfection. Groundwaters are generally free of ammonia but most surface waters contain a small concentration. This concentration may be increased by the discharge to a water course of raw or treated sewage, industrial and agricultural wastes. Short (19) has shown that biological suspended growth nitrification is the cheapest and most effective method available for the removal of ammonia from river water, in the approximate concentration range 0.1 to 2.0 mg of ammonia nitrogen per litre. The application of biological suspended growth nitrification could be extended to higher ammonia levels by the addition of a second stage and interstage aeration. Injection of oxygen into the feedwater is also possible. However, a multi-stage arrangement might not be much cheaper than percolating filtration.

If biological denitrification is not always necessary, the alternative is chlorination of the ammonia.

(ii) Nitrate removal

Health problems arising from high nitrate concentrations in drinking water are not new, and have been discussed extensively. Methods of overcoming these problems include: -

I. blending with other sources of low nitrate waters;
II. storage of water when nitrate concentration is low;
III. provision of bottled water;
IV. direct treatment of water by biological denitrification or ion exchange.

As yet, there is no established operational plant for nitrate removal in the UK. Biological denitrification using sand-based suspended growth has been shown to be effective for surface waters (20). It can be compared with the equivalent for nitrification; the major difference is that it takes place in anaerobic conditions assisted with a carbon food source, probably methanol. Ion exchange can be used for denitrification of groundwaters (21) but its capital and operating costs are high (20).

12.6.4. Ammonia and nitrate removal

B. Costs

(i) Ammonia removal - chlorination

Approximately 8.5 mg chlorine per litre is needed to remove 1 mg ammonia nitrogen per litre. The ammonia is converted to chloramines and ultimately to nitrogen. Chloramines do have a disinfectant power but are slow-acting compared with free chlorine. They are sometimes formed deliberately when it is required to maintain a residual disinfectant concentration for a number of days. Section 12.4.1 considers the costs of chlorination and disinfection.

(ii) Ammonia removal - biological suspended growth nitrification

Hopper upflow tanks like those used for floc blanket sedimentation (for which costs are given in Section 12.3.1) are used for biological suspended growth nitrification. The suspended biological growth is based on fine sand and is developed mainly from the material present in the raw river water. The fluidized biomass uses the natural dissolved oxygen in the water to convert the ammonia to nitrate. The amount of oxygen required to convert ammonia to nitrate is 4.57 mg per mg of ammonia nitrogen. As a single stage process, the method is effective for removing up to 2 mg ammonia nitrogen per litre, for water temperatures above 6°C, with a contact time of less than eight minutes at an upflow velocity of 15 m/h.

There should be a minimum of two operational tanks.

(iii) Ammonia removal - biological filtration

Costs of percolating filters are given in Section 13.5.1. Short (19) suggests filtration rates between 1 and 3 m/h with 2 m depth of gravel packing, followed by chlorination of any remaining ammonia.

(iv) Nitrate removal - biological suspended growth denitrification

Hopper upflow tanks (see Section 12.3.1 for costs) are used here similarly as in nitrification with a fluidized biomass. At 15 m/h upflow velocity, more than 10 mg nitrate nitrogen per litre can be removed in a contact time of 20 minutes at 2°C. The rate of denitrification doubles for a 10°C rise in temperature. Methanol dosing, or some other carbon and energy source, must be used. The required dose of methanol (mg) is approximately equal to the concentration of dissolved oxygen (mg) plus 2.5 times the nitrate nitrogen (mg) to be removed.

The cost of removing 10 mg nitrate nitrogen per litre from water containing 10 mg dissolved oxygen per litre is 0.25 to 0.30 p/m^3 (1976 Q3).

(v) Nitrate removal - ion exchange

Ion exchange can be used to reduce nitrate concentrations in groundwater. Commercially available resins have poor selectivity for nitrate, particularly over sulphate, requiring large quantities of regenerant in relation to the nitrate removed. This causes high running costs for the supply of sodium chloride for regeneration and for subsequent disposal of the spent regenerant. Capital costs for ion exchange are also high, with a continuous loop system being about 15% more expensive than a fixed bed system. However, a continuous loop system produces a smaller volume of waste for disposal. Costs of ion exchange will be closely related to individual circumstances, and so budget prices should be sought for planning.

Approximate operating costs at 1976 Q3 for nitrate removal by ion exchange can be given. Assuming a flow rate of 45 000 m^3/d and 10 to 12 mg nitrate nitrogen per litre to be removed from groundwater, the rates are:-

low sulphate (20 mg SO_4/l)	1.8 p/m^3
high sulphate (120 mg SO_4/l)	3.6 p/m^3.

Tankering spent regenerant could double the cost.

12.6.5. FLUORIDATION

If fluoridation is to be included in the estimate for a new treatment works, it should be regarded as an item of chemical plant as described in Section 12.2.3. However, the general cost function given in that section cannot be used for estimating the cost of installing fluoridation alone. Insufficient information has been obtained to establish the typical cost of providing a fluoridation facility, although some indication can be given of the process equipment and running costs (at 1976 Q3) as follows:-

(i) Chemical costs

The delivered cost of hydrofluorosilicic acid is £47 per tonne.

(ii) Equipment costs

The cost of pump and dilutor package only is £2450. Installed cost would be £7250 for an output of 14 800 m^3/d, and £20 800 (using sodium fluorosilicate) for an output of 54 500 m^3/d.

(iii) Running costs

These would vary from 5 to 10p per person per year, depending on size of plant.

(iv) Building costs

Building costs depend on the floor area needed to house the equipment (see Section 14.1), and also on the need to satisfy safety requirements.

12.7. WATER STORAGE TANKS

Covered storage tanks for treated water can be of three principal types: rectangular, circular or tower.

Rectangular tanks are constructed on a partially or totally excavated site with the length to width ratio rarely exceeding two. The larger capacity tanks are usually constructed with a full dividing wall so that the tank functions as two units. Tanks are occasionally trapezoidal because of site limitations; on treatment works such tanks might be used for providing contact time for disinfection and for storage of water used for backwashing filters.

Circular tanks are constructed either with prestressed concrete or with welded steel; the taller examples are sometimes referred to as towers or standpipes. Water towers also are constructed with concrete or steel; because of their obvious environmental impact they usually receive special architectural attention.

Items regarded as water storage tanks in civil engineering BoQs for water treatment works include:-

(i) washwater, clearwater and contact tanks;
(ii) service reservoirs, reservoirs.

The proportions of total costs relating to water storage tanks in civil engineering BoQs are given in Table 12-45. Although the two greatest values are for small treatment works, expenditure does not in general seem to be related to treatment works size. In the three cases where costs of tanks could not be isolated, the costs of buildings were much greater than normal.

If an unusually expensive or large reservoir is to be built as part of a treatment works, it should be considered as an extra item (see Section 12.8.3).

During the modelling work, four indices were examined: the DQSD Index, the Construction Materials Index, the New Construction Index and the Basic Weekly Wage Rate Index. The New Construction Index was considered the most suitable for all three forms of tank.

Table 12-45. Proportions of total treatment works civil engineering costs relating to water storage tanks

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of total civil engineering costs
U	5.5	34.8
U	7.8	16.5
U	8.7	13.1
L	9.1	0
U	11.4	36.3
U	13.6	27.4
L	14.5	0
U	15.0	0
U	18.2	27.9
L	20.5	7.7
L	22.7	17.5
U	27.3	12.3
L	54.5	14.2
L	68.2	13.4
U	72.7	18.3
L	109	22.7
L	145	19.1
U	159	11.2

Costs were taken at date of tender, with no adjustment made for type of contract, since most of the data refers to pre-1973 contracts. Total cost was defined as the total contract tender price inclusive of general siteworks but exclusive of any mainlaying beyond the immediate vicinity of the tank, or any major special construction work such as extensive piling.

The recommended models cannot be used for predicting the cost of special shapes or construction techniques.

12.7.1. RECTANGULAR TANKS

A. The modelling approach

Raw data was collected in the form of tender BoQs for tanks built alone or as part of a treatment works. The data was categorized according to the designated purpose of the tanks. The majority of the data related to service reservoirs, and so a cost function was first developed for this sub-category, using storage volume as the explanatory variable so that the cost function could be compared with the corresponding cost function in TP 60 (2). These were not fundamentally different, but no further use was made of the TP 60 data because of some uncertainties about its comparability.

An attempt was made to improve the function by introducing length, breadth and depth of tank in place of storage volume. However, this was unsuccessful because of the limited variation both in depths and in length-breadth ratios.

The remaining data categories (contact tanks, washwater tanks and clearwater and treated water reservoirs) were too sparse to be studied individually, and were therefore treated as a combined group. The cost function for this set of 22 cases was very similar to the service reservoir model.

The storage volume for the entire data ranged from 340 to 114 000 m^3. As the extreme sizes are of special engineering interest it was decided to build separate cost functions for small tanks (<7000 m^3) and large tanks (>20 000 m^3). The large tanks model was similar to the service reservoir function, but the small tanks model was substantially different.

Three functions are therefore recommended for rectangular concrete storage tanks:-

(i) the 'service reservoir' model (see part B), which is appropriate for volumes between 7000 and 20 000 m^3;

(ii) the small tanks model (see part C), which should be used for volumes of less than 7000 m^3;

(iii) the large tanks model (see part D), which should be used for volumes of greater than 20 000 m^3.

12.7.1. Rectangular tanks

B. The results - service reservoirs

(i) Data summary

Table 12-46. Rectangular concrete service reservoir data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£ million	0.034	1.46	0.382	0.318
Capacity of tank	CAP	'000 m^3	0.340	114	19.0	24.3

Note: 1. Number of cases: 47.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-


COST


LOG COST


CAP

(ii) The recommended cost function

The recommended function for service reservoirs is:-

$$\boxed{\text{COST} = 0.0636*\text{CAP}^{0.64}}$$

The statistical details of the function are as follows:-

Number of observations : 47
Correlation coefficient (R) : 0.95
Coefficient of determination (R^2) : 90%
Standard error of residuals (in $\log_{10}$ model) : 0.122

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.644	0.031	429	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.69	1.44
95%	0.57	1.76

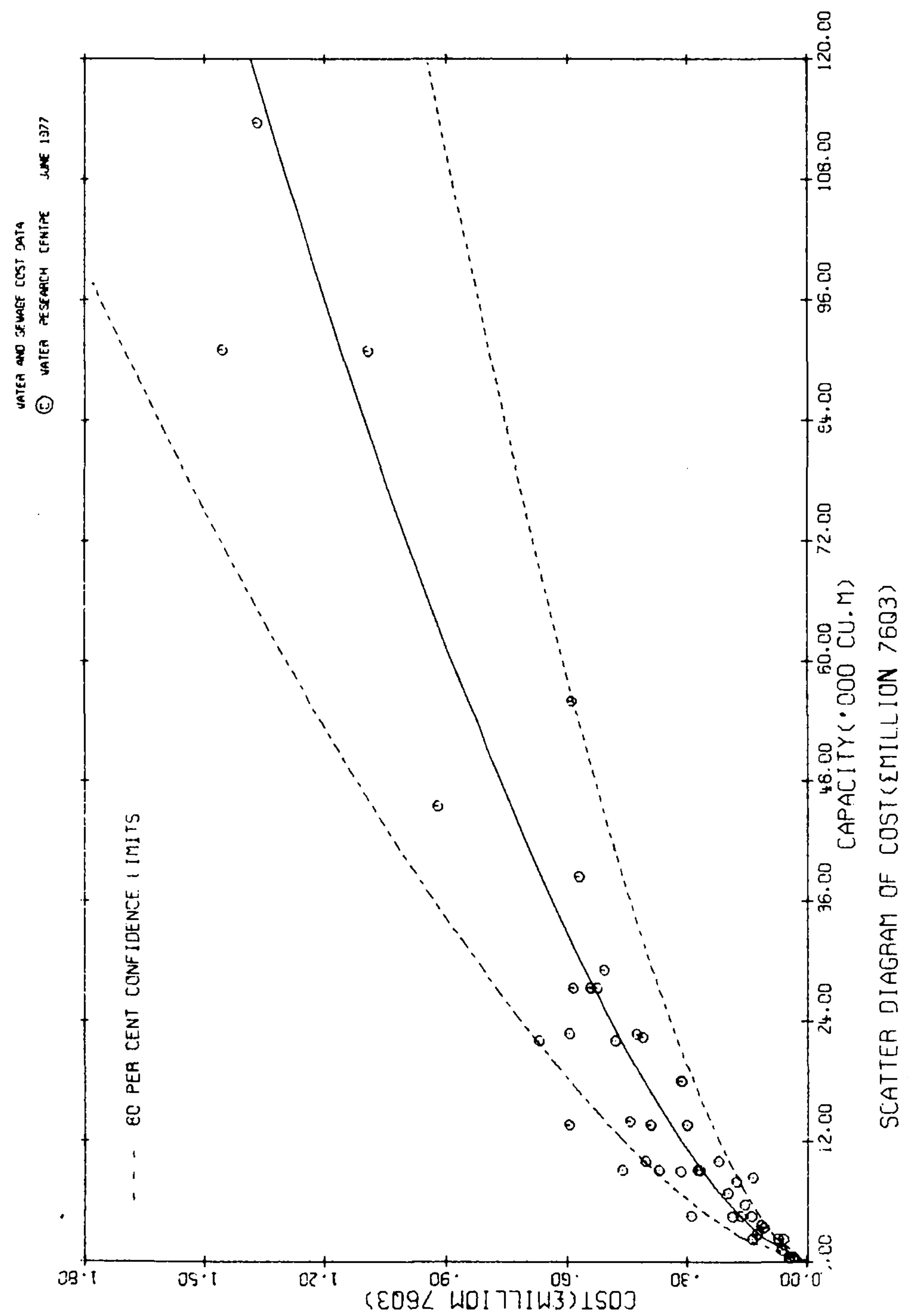
Figures 12-19 and 12-20 show the five standard diagrams in support of the function.

(iii) The data

The rectangular concrete service reservoirs data is listed in Table A-31.

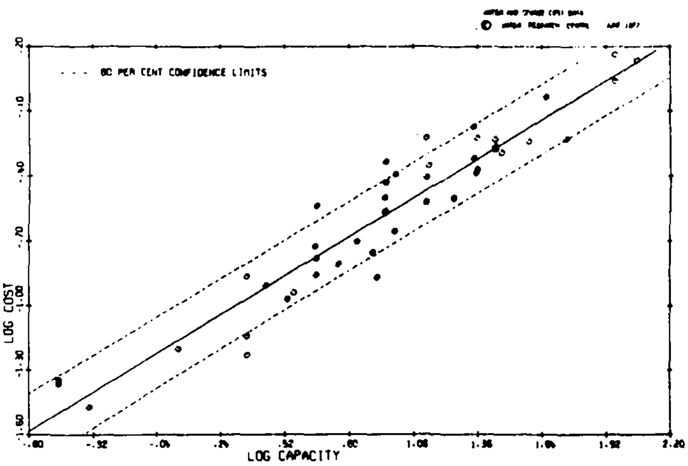
12.7.1. Rectangular tanks

Figure 12-19. Rectangular concrete service reservoirs

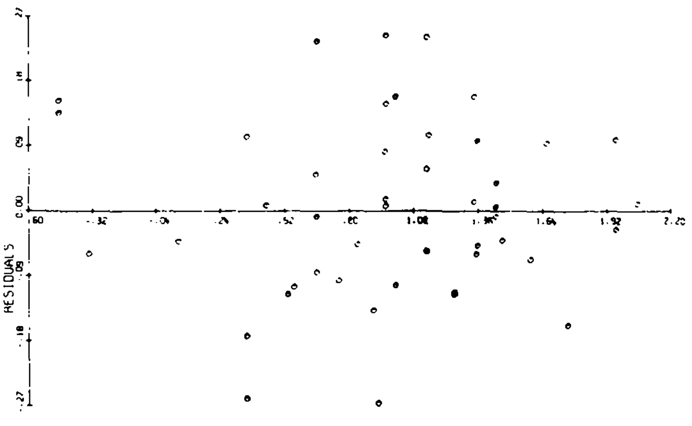


12.7.1. Rectangular tanks

Figure 12-20. Rectangular concrete service reservoirs

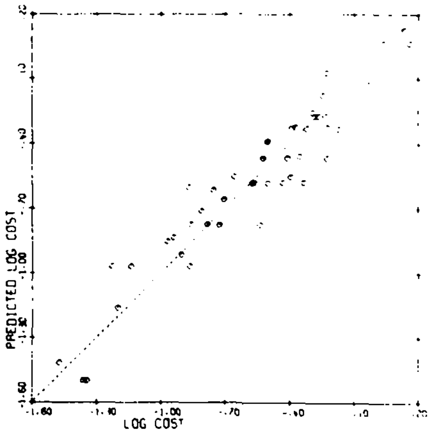


SCATTER DIAGRAM OF LOG COST
AGAINST LOG CAPACITY



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG CAPACITY

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - small tanks

(i) Data summary

Table 12-47. Small rectangular concrete covered tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	29.9	290	106	60.9
Capacity of tank	CAP	'000 m^3	0.200	6.85	2.61	2.02

Note: 1. Number of cases: 25.

2. The New Construction Index was used for deflation.

3. The data refers to tanks with capacities less than 7000 m^3.

Mini-histograms for the main variables of interest:-

COST

LOG COST

CAP

(ii) The recommended cost function

The recommended function for small rectangular concrete covered tanks is:-

$$\boxed{COST = 69.1*CAP^{0.48}}$$

The statistical details of the function are as follows:-

Number of observations : 25

Correlation coefficient (R) : 0.86

Coefficient of determination (R^2) : 73%

Standard error of residuals (in $\log_{10}$ model) : 0.135

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.484	0.061	63.4	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

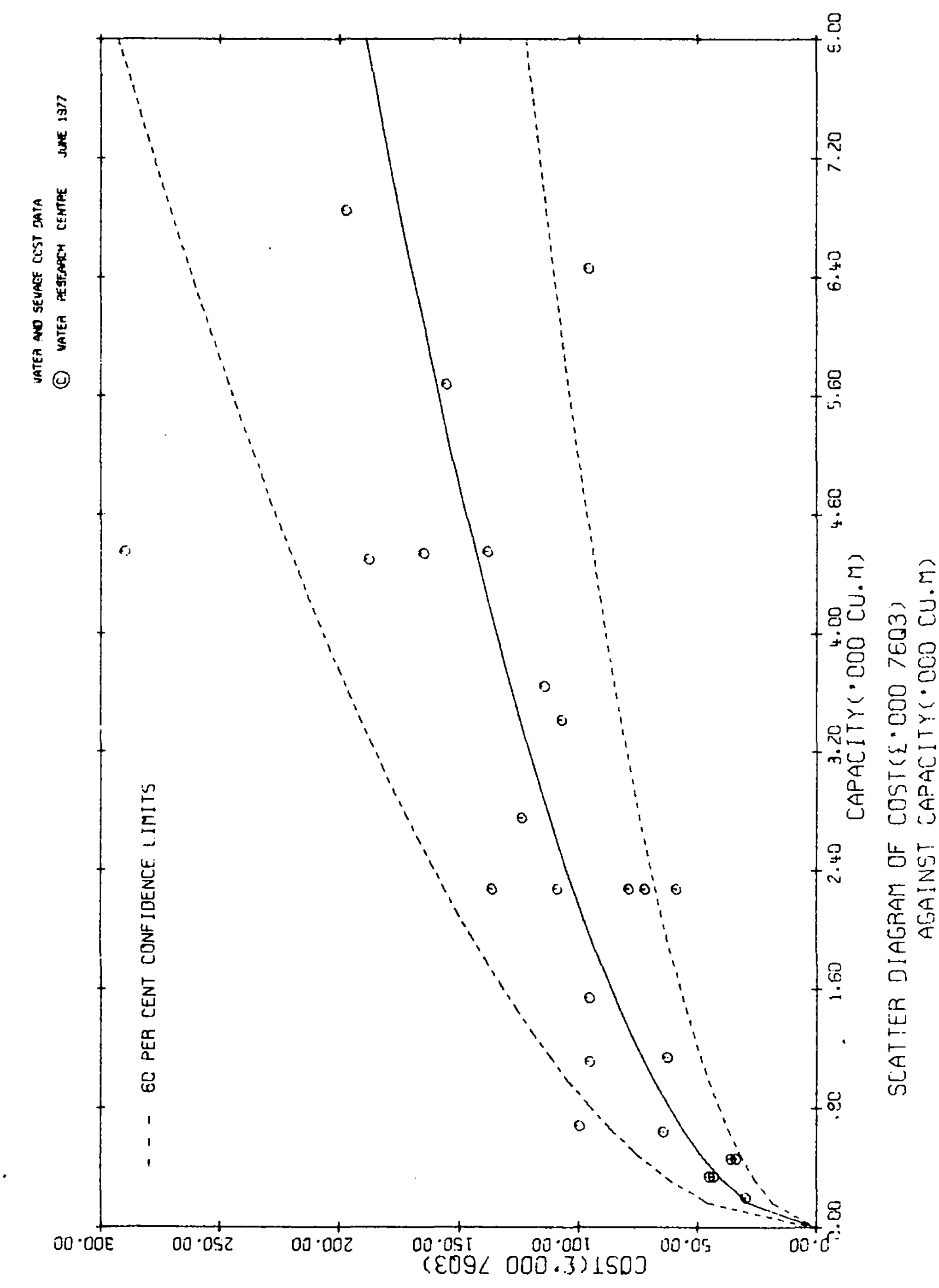
Confidence level	Lower	Upper
80%	0.66	1.51
95%	0.53	1.90

Figure 12-21 illustrates the recommended function.

(iii) The data

The small rectangular tanks data is listed in Table A-32.

Figure 12-21. Small rectangular concrete covered tanks



D. The results - large tanks

(i) Data summary

Table 12-48. Large rectangular concrete covered tanks data summary

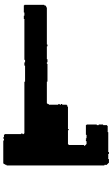
Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£ million	0.409	1.61	0.754	0.340
Capacity of tank	CAP	'000 m^3	22.0	114	44.2	29.9

Note: 1. Number of cases: 22.

2. The New Construction Index was used for deflation.

3. The data refers to tanks with capacities greater than 20 000 m^3.

Mini-histograms for the main variables of interest:-



COST

LOG COST

CAP

(ii) The recommended cost function

The recommended function for large rectangular concrete covered tanks is:-

$$\boxed{COST = 0.0726*CAP^{0.62}}$$

The statistical details of the function are as follows:-

Number of observations : 22

Correlation coefficient (R) : 0.88

Coefficient of determination (R^2) : 0.77%

Standard error of residuals (in $\log_{10}$ model) : 0.083

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.624	0.075	68.6	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.78	1.29
95%	0.67	1.49

Figure 12-22 illustrates the recommended function.

(iii) The data

The large rectangular concrete covered tanks data is listed in Table A-33.

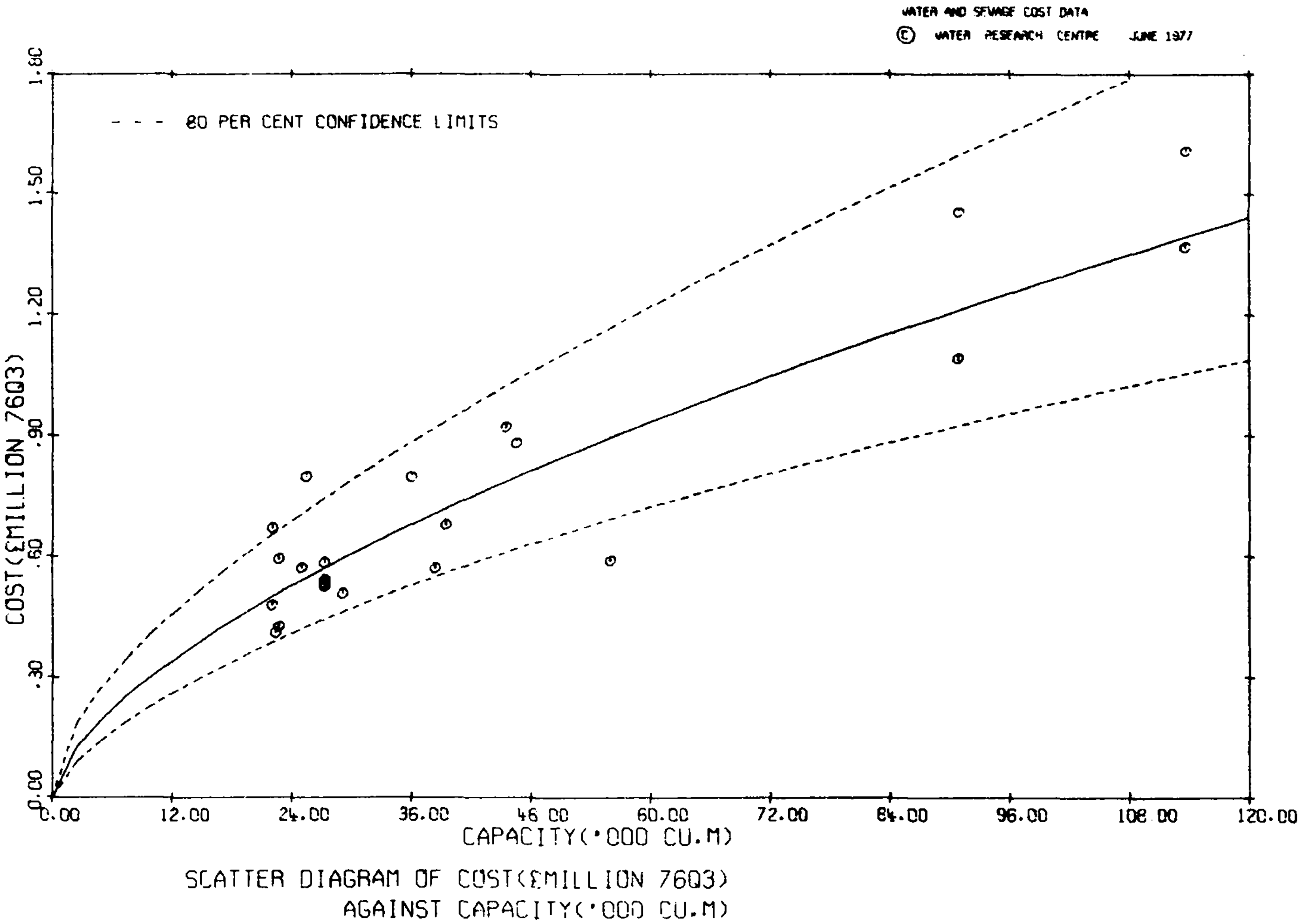


Figure 12-22. Large rectangular concrete covered tanks

12.7.2. CIRCULAR TANKS

A. The modelling approach

Raw data was collected as tender BoQs for both concrete and steel circular tanks, with a few additional examples taken from the TP 60 (2) survey. In the case of steel circular tanks the provision and erection of the steel tank was usually a separate contract, as was the steel surface cleaning and protection. A few of the concrete circular tanks were constructed as part of treatment works.

In addition to capacity, diameter and height of tank were considered as explanatory variables, but these brought no significant reduction in scatter. The construction material was taken account of by the variable TYPE, which took the value 1 for concrete and 2 for steel. This was found to be significant and appears in the recommended model. The type of concrete tank construction (i.e. ring stressed or simple reinforced concrete), however, could not be distinguished.

Costs were taken at date of tender with no adjustment made for type of contract since most of the data refers to pre-1973 contracts. The cost is the total contract tender price inclusive of general siteworks, but exclusive of any mainlaying beyond the immediate vicinity of the tank, or any major special construction work.

B. The results

(i) Data summary

Table 12-49. Circular tanks data summary

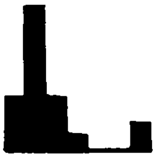
Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Cost (corrected to 1976 Q3)	COST	£'000	14.0	396	106	103
Capacity	CAP	'000 m^3	0.360	13.6	5.02	4.27
Material of construction	TYPE	-	1	2	1.36	0.492
Omnibus 15 (see Section 8.3.3)	Z15	-	0.168	13.6	3.92	3.99

Note: 1. Number of cases: 22.

2. The New Construction Index was used for deflation.

3. TYPE is 1 for concrete circular tanks, and
   2 for steel circular tanks.

Mini-histograms for the main variables of interest:-



COST

LOG COST

CAP

TYPE

(ii) The recommended cost function

The recommended function for circular tanks is:-

$$\boxed{COST = 40.7*CAP^{0.70}*TYPE^{-0.77}}$$

Thus, the cost estimate for concrete circular tanks is:-

$$\boxed{COST = 40.7*CAP^{0.70}}$$

and for steel circular tanks is: -

$$\boxed{\text{COST} = 23.9 * \text{CAP}^{0.70}}$$

The statistical details of the function are as follows:-

Number of observations	:	22
Multiple correlation coefficient (R)	:	0.91
Coefficient of determination (R^2)	:	83%
Standard error of residuals (in $\log_{10}$ model)	:	0.160

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.701	0.073	92.1	≪0.1%
TYPE	-0.770	0.241	10.2	<1.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.61	1.63
95%	0.46	2.15

The omnibus variable is given by:-

$$Z15 = \text{CAP} * \text{TYPE}^{-1.10}.$$

Figures 12-23 and 12-24 show the five standard diagrams in support of the function.

(iii) The data

The circular tanks data is listed in Table A-34.

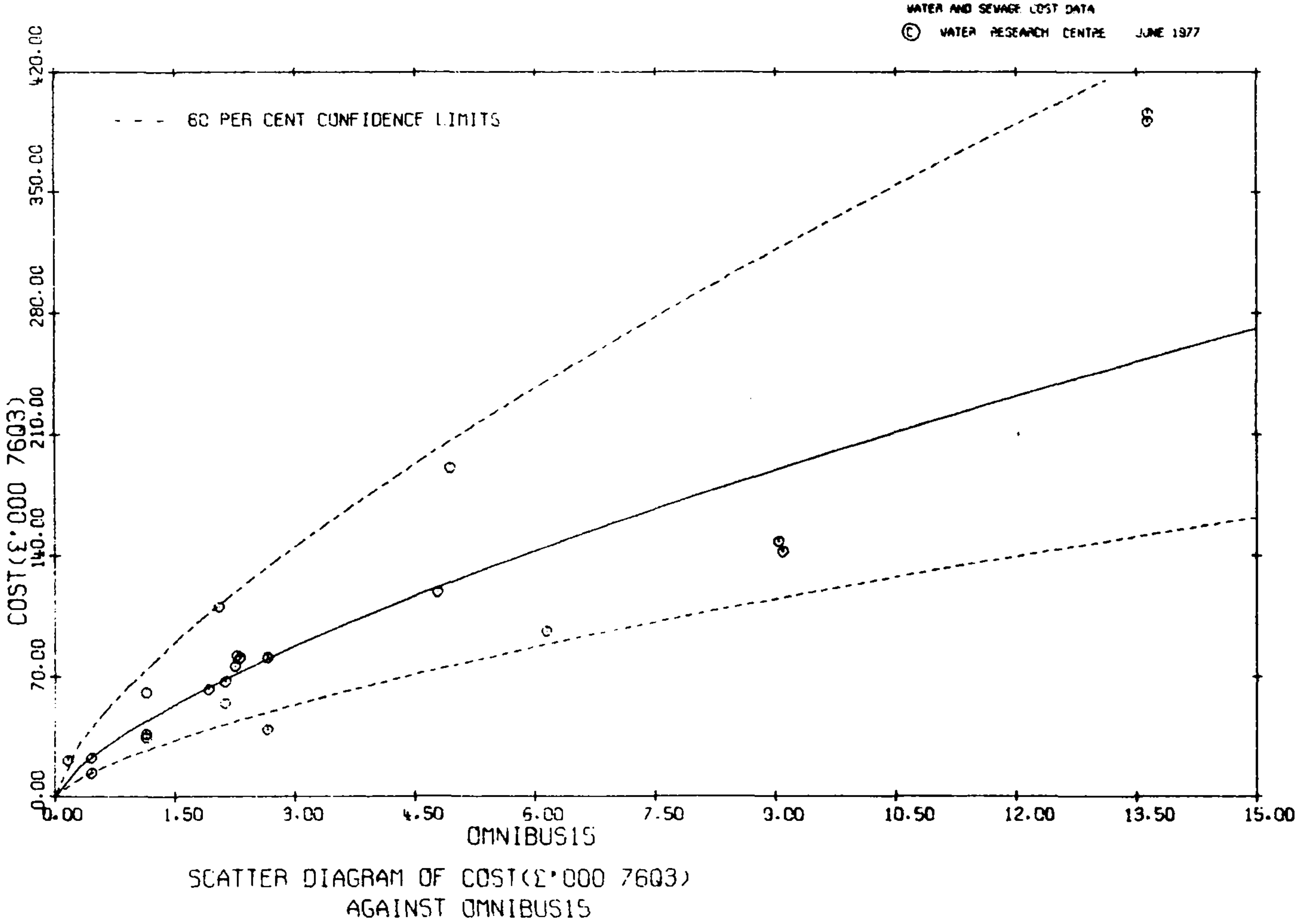
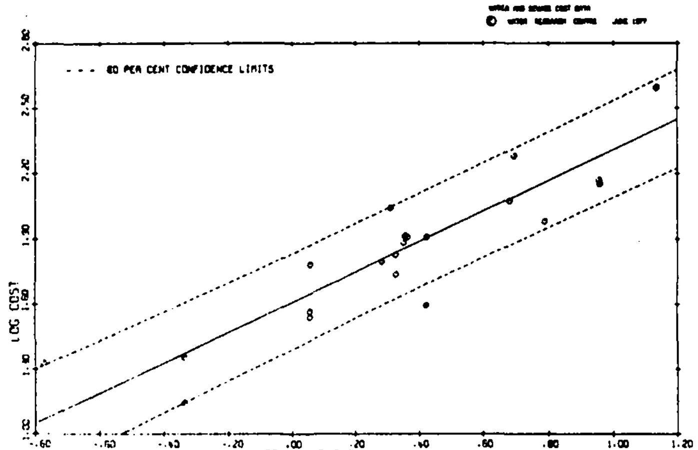


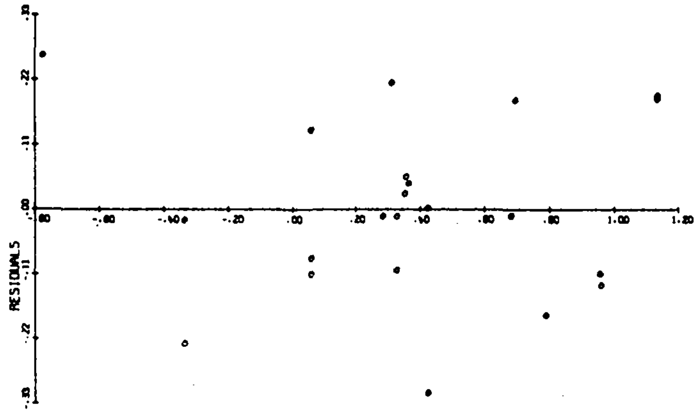
Figure 12-23. Circular tanks

12.7.2. Circular tanks

Figure 12-24. Circular tanks

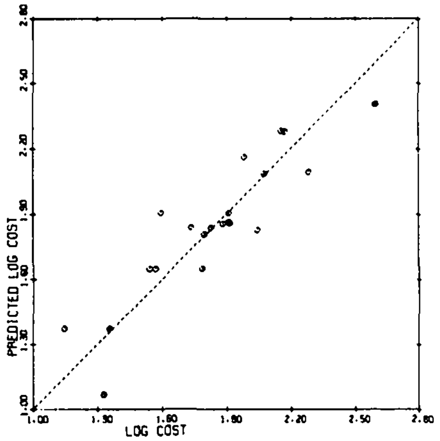


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS15



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS15

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

12.7.3. WATER TOWERS

A. The modelling approach

Data was assembled from tender BoQs, TP 60 (2) and Water and Water Engineering, covering a wide range of tower and tank designs from square to circular and from simple single column to complex lattice towers. Most towers are built in concrete and the sample contained only three examples of steel construction.

A cost function was sought using the explanatory variables storage capacity, material of construction, overall height, storage depth and overall diameter. There was no other outstanding design feature that could easily be included. Cost was more strongly correlated with tank capacity than with a combination of storage depth and overall diameter. Overall height did not appear to be a significant factor, probably because of the limited variation of heights within the sample. As with the circular tanks model, construction material had a significant effect on cost. The wide variety of architectural styles, however, appeared to have little effect on cost.

Costs were taken as tender prices at date of tender with no adjustment made for type of contract. It should be noted that two of the most expensive towers were contracted at about the time of maximum inflation. Total cost was defined as the total contract tender price inclusive of general siteworks but exclusive of any mainlaying beyond the immediate vicinity of the tower or of any major special construction work.

12.7.3. Water towers

B. The results

(i) Data summary

Table 12-50. Water towers data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	11.5	514	180	142
Capacity of tank	CAP	'000 m^3	0.060	3.41	1.21	0.947
Material of construction	TYPE	-	1	2	1.14	0.359
Overall height of tower	HEIGHT	m	15.3	43.6	25.1	6.17
Omnibus 14 (see Section 8.3.3)	Z14	-	0.036	3.41	1.17	0.964

Note:
1. Number of cases: 21.
2. The New Construction Index was used for deflation.
3. TYPE is 1 for concrete water towers, and
   2 for steel water towers.

Mini-histograms for the main variables of interest:-

COST

LOG COST

CAP

HEIGHT

(ii) The recommended cost function

The recommended function for water towers is:-

$$\boxed{COST = 162*CAP^{0.77}*TYPE^{-0.56}}$$

Thus, the cost estimate for concrete water towers is:-

$$\boxed{\text{COST} = 162*\text{CAP}^{0.77}}$$

and for steel water towers is:-

$$\boxed{\text{COST} = 110*\text{CAP}^{0.77}}$$

The statistical details of the function are as follows:-

Number of observations	:	21
Multiple correlation coefficient (R)	:	0.96
Coefficient of determination (R^2)	:	91%
Standard error of residuals (in $\log_{10}$ model)	:	0.118

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
CAP	0.768	0.062	154	$\ll$0.1%
TYPE	-0.556	0.256	4.72	<5.0%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.70	1.43
95%	0.57	1.77

The omnibus variable is given by:-

$$Z14 = \text{CAP}*\text{TYPE}^{-0.72}.$$

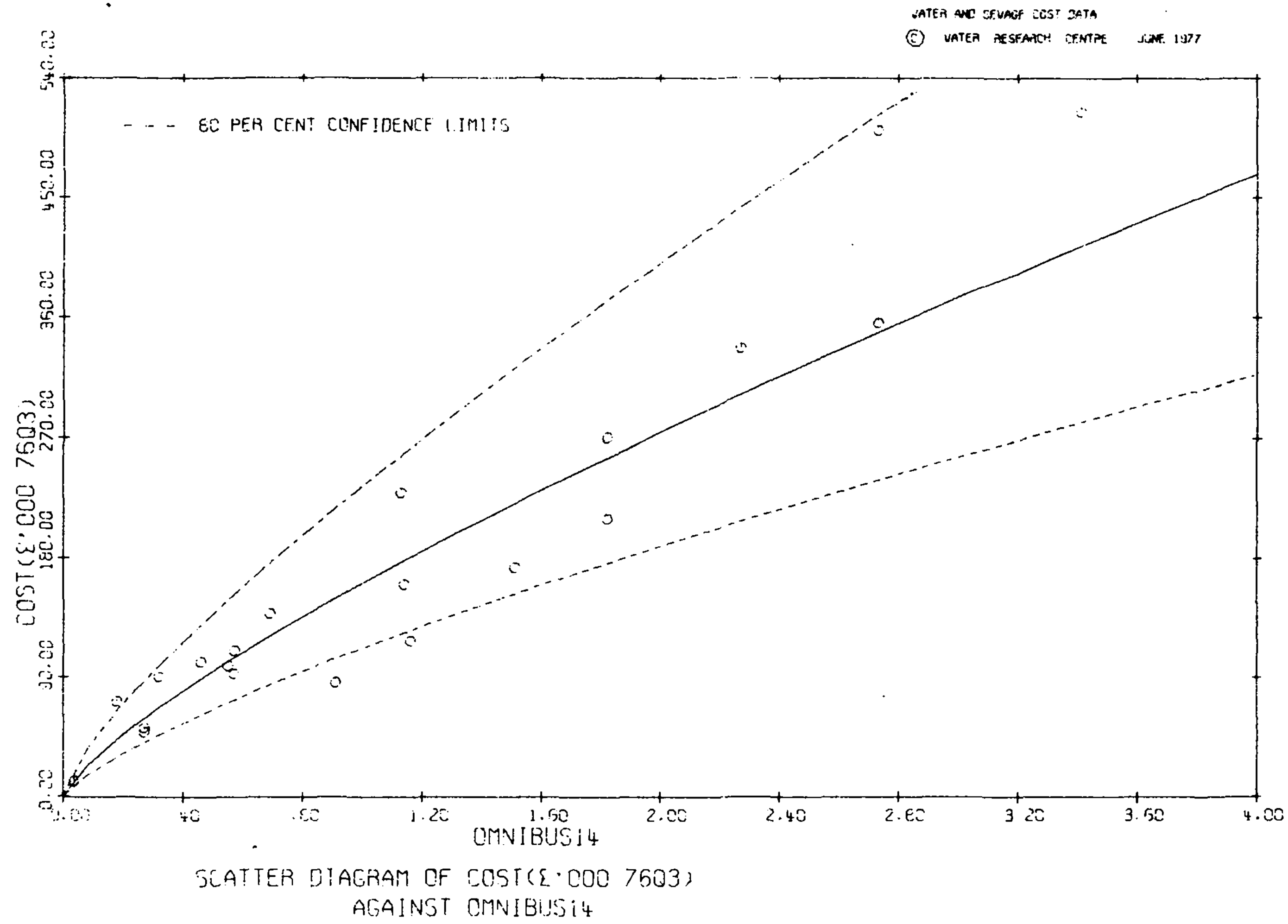
Figures 12-25 and 12-26 show the five standard diagrams in support of the function.

(iii) The data

The water towers data is listed in Table A-35.

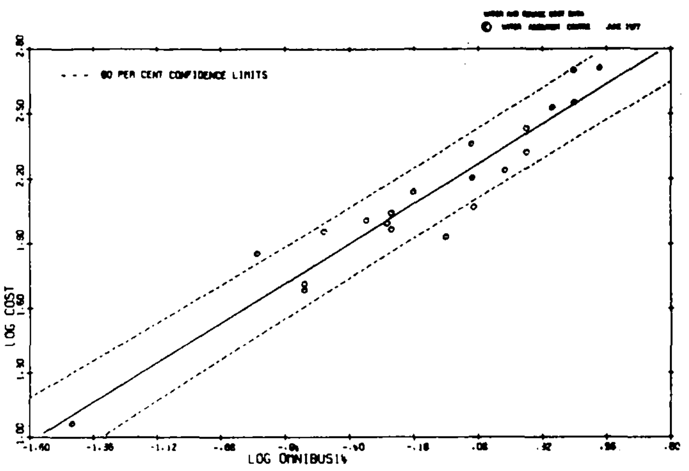
12.7.3. Water towers

Figure 12-25. Water towers

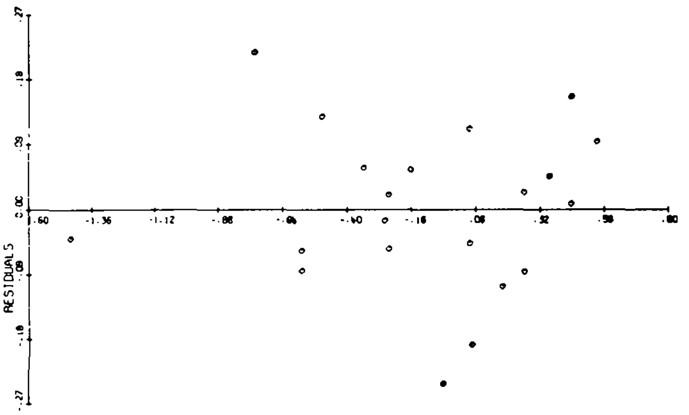


12.7.3. Water towers

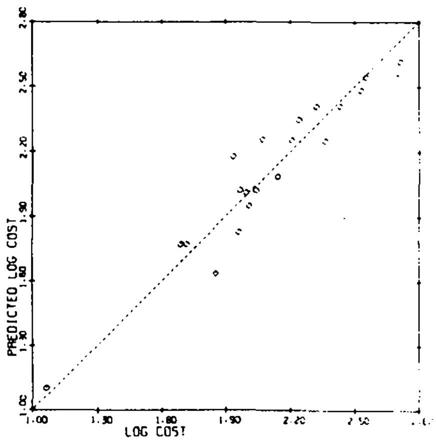
Figure 12-26. Water towers



SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS14



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS14



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

HISTOGRAM OF RESIDUALS

12.8. OTHER WORKS ITEMS

12.8.1. SITEWORKS AND PIPEWORKS

Items in civil engineering BoQs regarded as siteworks include:-

(i) earthworks (not allocatable to other items);
(ii) drainage;
(iii) roads, footpaths, fences, walls and gates;
(iv) landscaping;
(v) sewers and sewage works.

Items in civil engineering BoQs regarded as pipeworks include:-

(i) pipelines within works, including air and surge vessels;
(ii) interconnecting process pipework;
(iii) pipe ducts.

The proportions of cost in civil engineering BoQs represented by siteworks and pipeworks are given in Table 12-51 and summarized in Figure 12-27. They appear not to be related to the size of the treatment works, but are likely to be influenced by site topography and ground conditions. In five cases, separate costs for pipeworks were not identified. This was mainly due to the arrangement of the bills whereby costs of pipeworks were included in the bills for the process plant.

Major landscaping should be regarded as an extra item, as this is not typical and would be covered by a separate contract.

Major pipeworks within the treatment site occasioned by untypical topography should also be regarded as an extra item.

12.8.1. Siteworks and pipeworks

Table 12-51. Siteworks and pipeworks civil engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	% of total civil engineering costs	
		Siteworks	Pipeworks
U	5.5	8.9	0
U	7.8	6.3	5.6
U	8.7	5.2	0
L	9.1	7.5	14.6
U	11.4	13.9	11.4
U	13.6	12.2	0
L	14.5	9.2	0
U	15.0	8.8	10.5
U	18.2	12.4	15.8
L	20.5	37.2	11.8
L	22.7	1.6	0
U	27.3	6.4	3.4
L	54.5	10.8	2.6
L	68.2	17.6	6.7
U	72.7	6.5	15.3
L	109	4.9	10.8
L	145	11.9	14.8
U	159	8.7	12.7

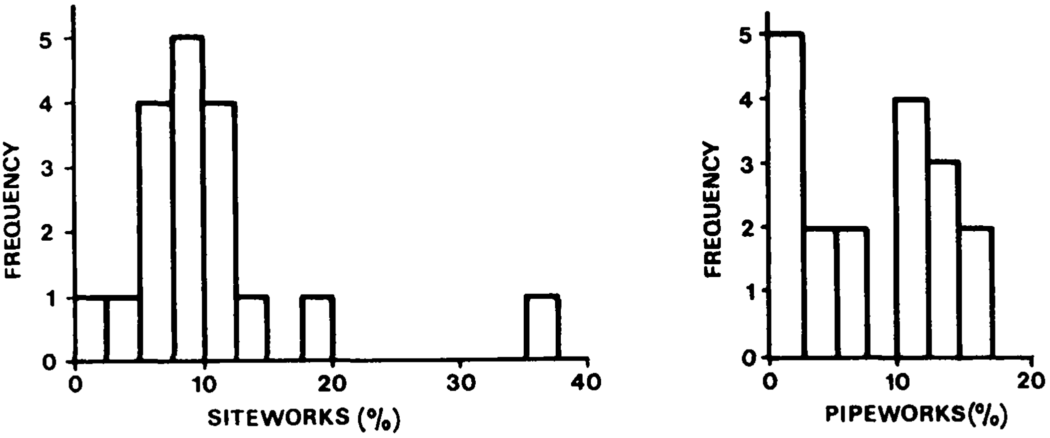


Figure 12-27. Civil engineering siteworks and pipeworks costs as percentages of total civil engineering costs

12.8.2. PUMPING AND POWER

Items in civil engineering BoQs regarded as pumping include:-

(i) intakes;
(ii) low and high lift pumping stations.

Items in civil engineering BoQs regarded as power include:-

(i) boiler and generator houses;
(ii) bulk fuel storage;
(iii) transformer enclosures, cabling and electrical works.

Items in mechanical engineering BoQs regarded as pumps, power and switchgear include:-

(i) low, high and re-lift pumps;
(ii) standby generators;
(iii) transformers, electrical cabling and wiring;
(iv) lighting, heating and ventilation;
(v) motor control centres and starters.

The civil engineering costs relating to pumping and power were considered together. They are detailed in Table 12-52 and summarized in Figure 12-28. The proportions of civil engineering costs for these items are apparently not related to the size of treatment works. In four cases costs did not appear. This was because separate contracts were let for what were probably untypical pumphouses and therefore regarded as extra items. For one of the cases there was a very high cost of buildings associated with chemical treatment (see Section 12.2.3).

Table 12-53 and Figure 12-29 show the distribution of costs associated with pumps, power and switchgear in mechanical engineering. These are spread over a wide range, and there is no simple typical value. Inspection of the sample suggests that it splits into two distinct groups: cases which include major pumping plant for pumping into and/or out of the treatment works, and cases which exclude such major pumping plant. Typical values might then be respectively 50 and 12.5%.

12.8.2. Pumping and power

Major pumping and power installations which cannot be regarded as typical or commensurate with the size of the treatment plant should be regarded as extra items. Further information can be found in Section 10.4.

Table 12-52. Pumps and power civil engineering costs

Raw water type (upland or lowland)	Output ('000 m^3/d)	Pumps and power cost as % of total civil engineering costs
U	5.5	8.1
U	7.8	17.2
U	8.7	18.6
L	9.1	0
U	11.4	0
U	13.6	9.0
L	14.5	11.0
U	15.0	15.5
U	18.2	7.2
L	20.5	0
L	22.7	0
U	27.3	16.3
L	54.5	9.2
L	68.2	14.7
U	72.7	12.0
L	109	12.9
L	145	7.8
U	159	16.6

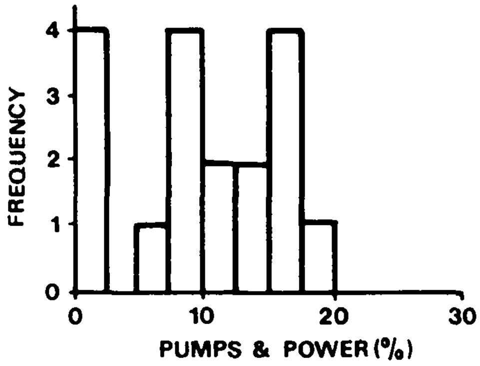


Figure 12-28. Civil engineering pumps and power costs as a percentage of total civil engineering costs

12.8.3. EXTRA ITEMS

'Extra items' of civil and mechanical engineering are items which cannot be regarded as part of a typical water treatment works and are not part of the water treatment system. Major pumping and power installations and major items of pipeworks and siteworks come into this category. Other extra items could include:-

(i) raw water reservoir, river intake, pumping station and aqueducts;

(ii) large treated water reservoir or water tower;

(iii) staff housing;

(iv) access roads and bridges;

(v) pipelines ex-works.

As a general rule such items are often part of contracts separate from those for the treatment works itself.

It should be noted that, in making up the total cost for a treatment works, extra items are considered separately from other components (see Section 12.1.4).

12.9. OPERATING COSTS

The main components of operating cost for a water treatment works are:-

(i) chemicals;
(ii) power (electricity);
(iii) labour and maintenance.

In principle, models could be developed for these categories in the same way that capital cost functions have been derived for unit processes and certain treatment plant arrangements. However, no corresponding source of comprehensive information on operating costs could be found apart from the original TP 60 (2) data. Consequently, there was generally insufficient data available for useful functions to be developed. Those functions which could be derived are given in Section 12.9.3.

To fill the gaps, 'synthetic' costs were constructed. Section 12.9.1 presents unit costs of chemicals, power and labour, and these form the basis of the estimated operating costs assembled in Section 12.9.2. Costs due to local authority rates, engineering and management have not been considered.

12.9.1. CHEMICAL, POWER AND LABOUR UNIT COSTS

A. Chemical costs

The costs of chemicals depend on the quality and quantity purchased, and sometimes even more on the delivery charges. Approximate costs (at 1977 Q3) are given in Table 12-54 for chemicals commonly used in water treatment. More satisfactory estimates for specific sites, especially those more than about 50 miles from the major centres of population, should be obtained directly from potential suppliers.

Whilst costs of individual chemicals in practice increase in steps, as an approximation the Chemical and Allied Industries Index could be used for updating.

Table 12-54. Approximate costs of chemicals used in water treatment

Chemical	Grade/container	Cost (£/tonne 1977 Q3)
Activated carbon, powdered	Tote bins	>150
Activated carbon, granular	Tote bins	450 to 650
Aluminium sulphate, liquid	7.5% as Al_2O_3, bulk tanker	35
Aluminium sulphate, kibbled	16 to 17% as Al_2O_3, bags	106
Ammonia, gas	Cylinders	330 to 655
Ammonium sulphate	Bags	100
Calcium hydroxide	Bulk ('LIMBUX')	19
Calcium hypochlorite	70% granular 60% powdered	950 750
Carbon dioxide, gas	34 kg cylinders Bulk 9 tonne installation	74 to 55
Chlorine	71 kg cylinder Bulk	253 to 86
Copper sulphate	Bags	280
Ferric chloride, solution	38% wt./wt. carboys 38% wt./wt. bulk	174 to 66
Ferric sulphate, solution	40% wt./wt., bulk	40
Ferrous sulphate	Bulk	15
Fluosilicic acid	20% solution, bulk	47

Table 12-54 (continued)

Chemical	Grade/container	Cost (£/tonne 1977 Q3)
Hydrochloric acid	36%, commercial bulk	40
Liquified petroleum gas	Cylinders - fixed installation	115 to 166
Methanol	Bulk	75 to 80
Potassium permanganate	Bags	945
Semi-calcined dolomite	Bulk (20 tonnes)	93
Sodium aluminate	25% as Al_2O_3, bulk	122
Sodium carbonate	Bulk	67
Sodium chloride	Bulk	22
Sodium chlorite, liquid	76% wt./wt., bulk	297
Sodium hydroxide, liquid	47% wt./wt., bulk	45
Sodium hypochlorite, liquid	14 to 15% as Cl_2, bulk	35 to 40
Sodium silicate, liquid	38%, bulk	51
Sodium silicofluoride	Bulk	196
Sodium alginate	Bags	1870
Sodium hexametaphosphate	Bags	519
Sulphur dioxide	Cylinders	263 to 600
Sulphuric acid	77%, bulk	32
Starch polymer	Bulk	265
Synthetic polymer	Bulk	350 to 1000
Tannin polymer	Bulk	354 to 468

B. Power costs

Most of the power used in water treatment works operation is in the form of electricity purchased from the grid. (In the treatment of upland sources, hydroelectricity can be generated in some cases.) The principal alternative - on-site diesel generation - is usually reserved for standby provision of electricity, especially where a dual grid supply is not feasible in a major pumping scheme.

Grid supply tariffs depend on locality and other factors, and so when preparing estimates for specific sites reference should be made to the appropriate tariffs. However, although tariffs in practice increase in steps, as an approximation the Fuel and Light Retail Price Index could be used for updating.

To prepare an estimate of power cost for water treatment, the power consumption must first be estimated for the water treatment processes, and also any basic low and high lift pumping into and out of the treatment works. Table 12-55 summarizes typical power consumption rates in terms of kWh per '000 m^3 of water. No allowance is made for space heating, lighting and similar items.

12.9.1. Chemical, power and labour unit costs

Table 12-55. Typical power consumption rates for water treatment processes

Process		Power consumption (kWh/'000 m^3)
Screening, from bar to micro screens		0.2 - 2.0
Chemical equipment and chlorination		1.5 - 4.5
Sample pumping		0.2 - 0.5
Flash mixing and flocculation		2 - 7
Dissolved air flotation: 6% recycle at 4 bar		11
Filter backwash air for 24 h filter runs		0.2
Backwash water pumping		0.5 - 1.5
Sludge and washwater transfer and recycle		1.0 - 4.5
Flotation sludge transfer[†]		0.3 - 2.0
Sludge conditioning, thickening and pressing		2.5 - 6.0
Sub-total, excluding flotation[†]		8 - 26
	Headloss (m)	
Screening and flow measurement	0.5 - 1.0	2 - 4
Aeration	1.0 - 3.0	4 - 12
Flash mixing	0.5 - 1.5	2 - 6
Sedimentation	0.5 - 1.5	2 - 6
Filtration	3.0 - 5.0	12 - 20
Chlorine contacting	0.5 - 1.0	2 - 4
Sub-total	6.0 - 13.0	24 - 52[†]
Total due to equipment and headloss		32 - 78

[†] Assuming 70% power-pumping efficiency.

C. Labour costs

The cost of labour in water treatment depends on the wage rates in force and the amount of labour required for operation of the treatment works. Wage rates depend on local and national agreements. The labour requirements for treatment works operation are more difficult to identify. They are largely dependent on the attitude of the Authority towards 24-hour manning and the use of roving teams for routine maintenance of plant and grounds, and emergency maintenance of plant (especially for works smaller than about 20 000 m^3/d). The mix of skilled, semi-skilled and unskilled staff also will depend on the Authority and on local agreements.

If suitable information on labour quality and rates is not available, an estimate of labour wage rates could be based on the Average Weekly Earnings of Manual Workers in the Gas, Electricity and Water Industry.[†] The related Basic Weekly Wage Rate Index would be appropriate for updating other information on labour costs. It is suggested that the cost of management and other administration be kept separate from the cost of labour associated with operation and maintenance.

Suitable information was not available on the number of men required for operating a water treatment works. A synthetic estimate was therefore built up from assumptions about the basic tasks involved, the time required for each task and the effectiveness of a man's time.

The basic tasks and duties considered were:-

Group 1: Control inlet and outlet flows;
maintain records and information transfer;
provide reception and security.

Group 2: Receive and prepare chemicals;
check dose rates, flush and clear dosing lines;
desludge sedimentation and control blanket level;
backwash filters;
sludge processing and conditioning;
changeover of standby plant and power failure practice.

Group 3: Inspection and cleaning of screens;
transfer of wet and dry sludge;
interior cleaning of premises;
exterior cleaning of premises and groundswork;
simple preventative maintenance.

Group 4: Breakdown maintenance.

[†] Monthly Digest of Statistics, Central Statistical Office, HMSO.

By and large the categorization reflects both the frequency pattern of the tasks and the quality of labour required. The labour required for Group 1 is largely independent of works size; Group 2 mainly depends on the complexity of treatment; Group 3 is dependent on the physical size of the buildings and site; and Group 4 depends both on complexity and works size.

A figure of two men per shift has been assumed, with the remaining labour made up of day men. Making appropriate allowances for leave and sickness, usual conditions of employment and the generally experienced effectiveness of labour, Table 12-56 was prepared. This presents estimated labour requirements (including maintenance) for a range of treatment works throughputs and raw water types, based on an assessment of the tasks detailed above.

Table 12-56. Estimated labour requirements for water treatment works

Throughput ('000 m^3/d)	Number of men (shift + day)				
	Upland rock raw water Type (ii)	Rock and moorland raw water Type (iii)		Moorland raw water Type (iv)	Lowland raw water Type (v)
	Straining and chlorination	Pressure filtration	Gravity filtration	Sedimentation-filtration	
2	1	3	3	-	-
5	1	4 + 1	4 + 1	4 + 1	4 + 1
10	1	6 + 1	6 + 1	6 + 2	6 + 2
20	2	6 + 2	6 + 2	8 + 2	8 + 2
50	2	8 + 2	8 + 2	8 + 3	8 + 3
100	3	8 + 3	8 + 3	8 + 4	8 + 4
200	4	-	8 + 4	8 + 5	8 + 5
500	4 + 1	-	8 + 5	8 + 6	8 + 6

Note: For works smaller than 20 000 m^3/d, 24-hour manning has progressively been reduced to 16 and 12 hours.

12.9.2. SYNTHETIC COSTS

A. The general approach

In Section 12.9.1, synthetic figures are presented which can be used to build up estimates of operating costs for water treatment works of various configurations. As the estimates have not been developed statistically, confidence limits cannot be quoted. However, the results given in Section 12.9.3, which are based on actual data, provide a broad check on the acceptability of these synthetically estimated costs. Furthermore, the reader may if he wishes easily rework the calculations given in part C, using any assumptions that he feels are more appropriate.

B. Assumptions

The assumptions made concerning chemical, power and labour rates and costs are set forth in (i) to (iii) below. They make no distinction between pressure filtration and gravity filtration treatment.

(i) Chemical doses

The average doses assumed for each raw water type are as follows:-

Chemical	Average chemical doses (mg/l)			
	Raw water type			
	(ii)	(iii)	(iv)	(v)
Aluminium sulphate (as Al)	-	1.5	4.0	3.5
Sulphuric acid	-	-	-	5.0
Sodium hydroxide	2.5	5.0	7.5	7.5
Powdered activated carbon	-	-	-	10.0
Chlorine	1.0	1.5	4.0	5.0

The costs of these chemicals were estimated from Table 12-54 assuming constant design throughput.

12.9.2. Synthetic costs

(ii) Power rates

The following power consumption rates were assumed:-

Raw water type	(ii)	(iii)	(iv)	(v)
Power consumption (kWh/'000 m^3)	5	30	40	40

These values include power used for operating plant and also allow for the headloss through the various processes. The cost of electricity was taken as 1.2p per kWh at constant design throughput (equivalent to 1.5p per kW and 80% throughput).

(iii) Labour rates

The labour costs were based on the figures in Table 12-56, using an average cost per man of £3900 per annum: this included employers' National Insurance contributions but excluded the cost of administration and management.

C. The results

The results of the calculations outlined in part B are given in Tables 12-57 to 12-60. These show that for throughputs less than about 20 000 m^3/d operating costs are predominated by labour costs, whilst for throughputs greater than 50 000 m^3/d chemicals become the most costly component.

The results in Table 12-59 for raw water Type (iv) differ from the results in Section 12.9.3 by about a factor of two. More reliance can probably be placed on the synthetic results in this section; the functions in Section 12.9.3 are less clearly defined, and are based on historical data without interim data to substantiate the indices chosen for updating. It is also possible that the treatments represented by the two sets of results are not in fact comparable.

Table 12-57. Estimated annual operating costs for treatment of raw water Type (ii), by screening-chlorination-pH adjustment

Throughput ('000 m^3/d)	Annual cost (£'000 1976 Q3)			
	Chemicals	Power	Labour	Total cost
2	0.35	0.044	3.9	4.29
5	0.90	0.11	3.9	4.91
10	1.79	0.22	3.9	5.80
20	3.21	0.44	7.8	11.5
50	8.03	1.10	7.8	16.9
100	14.2	2.19	11.7	28.1
200	24.8	4.38	15.6	44.8
500	62.0	11.0	19.5	92.5

12.9.2. Synthetic costs

Table 12-58. Estimated annual operating costs for treatment of raw water Type (iii), by gravity or pressure filtration

Throughput ('000 m^3/d)	Annual cost (£'000 1976 Q3)			
	Chemicals	Power	Labour	Total cost
2	1.59	0.26	11.7	13.6
5	3.99	0.66	19.5	24.2
10	7.70	1.31	27.3	36.3
20	14.8	2.63	31.2	48.6
50	36.3	6.57	39.0	81.9
100	71.5	13.1	42.9	128
200	141	26.3	46.8	214
500	353	65.7	50.7	469

Table 12-59. Estimated annual operating costs for treatment of raw water Type (iv), by sedimentation-filtration

Throughput ('000 m^3/d)	Annual cost (£'000 1976 Q3)			
	Chemicals	Power	Labour	Total cost
5	9.61	0.88	19.5	30.0
10	18.5	1.75	31.2	51.5
20	35.3	3.50	39.0	77.8
50	86.4	8.76	42.9	138
100	170	17.5	46.8	234
200	335	35.0	50.7	421
500	839	87.6	54.6	981

Table 12-60. **Estimated annual operating costs for treatment of raw water Type (v), by sedimentation-filtration**

Throughput ('000 m^3/d)	Annual cost (£'000 1976 Q3)			
	Chemicals	Power	Labour	Total cost
5	12.4	0.88	19.5	32.8
10	23.9	1.75	31.2	56.9
20	45.7	3.50	39.0	88.2
50	112	8.76	42.9	163
100	222	17.5	46.8	284
200	434	35.0	50.7	520
500	1090	87.6	54.6	1230

12.9.3. . REPORTED COSTS

A. The modelling approach

During the collection of capital cost data, requests were also made for operating cost data. It was generally found that the operating cost records available were inadequate for the purposes of this study. Only a few historically well-organized undertakings provide enough information to assess the performance of individual water supply and treatment units, and the Water Authorities have in fact identified this as an area for improvement. Reference was therefore made to the original TP 60 (2) data.

Operating costs were examined in four categories:-

(i) labour;
(ii) maintenance;
(iii) chemical;
(iv) electricity.

Annual operating costs reported in the TP 60 questionnaires for 42 water treatment works were first adjusted to 1976 Q3 using appropriate indices, namely:-

(i) and (ii) Basic Weekly Wage Rate of Manual Workers in Gas, Electricity and Water Industry Index;
(iii) Chemical and Allied Industries Index;
(iv) Fuel and Light Retail Price Index.

The adjusted costs were then related to treatment works output for each raw water type (see Section 12.1.2). However, there was insufficient data to allow reliable cost functions to be established for any but raw water Type (ii) (upland two-stage treatment). The data was also limited in that nearly all cases represented treated water outputs below 65 000 m^3/d, with the majority of cases falling in the range 5000 to 25 000 m^3/d.

Even for the Type (ii) data, no model for power costs could be produced. Power costs vary substantially according to the tariff, and in addition the costs will often have included sums for pumping into and out of the works in addition to process costs.

Initially, separate models were estimated for labour and maintenance costs. However, these were not very satisfactory, probably because of the difficulty of distinguishing between the two categories in some cases. It was therefore found more convenient to consider labour and maintenance costs together.

B. The results - upland raw water treated by sedimentation and filtration

(i) Data summary

Table 12-61. Operating cost data summary for upland raw water treated by sedimentation-filtration

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Annual labour and maintenance cost (corrected to 1976 Q3)	LAMACOS	£	9240	69 500	26 000	18 900
Annual cost of chemicals (corrected to 1976 Q3)	CEMCOS	£	4110	47 400	16 700	13 000
Annual cost of labour, maintenance and chemicals (corrected to 1976 Q3)	LAMA-CEMCOS	£	14 000	112 000	42 700	30 400
Annual total operating cost (corrected to 1976 Q3)	TOTCOS	£	14 800	169 000	60 900	42 300
Treatment works output	CAP	m^3/d	3380	115 000	32 600	34 700

Note:
1. The Basic Weekly Wage Rate of Manual Workers in Gas, Electricity and Water Industry Index was used to deflate labour and maintenance costs.
2. The Chemical and Allied Industries Index was used to deflate chemical costs.
3. The Fuel and Light Retail Price Index was used to deflate power costs.

(ii) The recommended cost functions

The recommended function for labour and maintenance costs is:-

$$\boxed{\text{LAMACOS} = 195*\text{CAP}^{0.47}}$$

The statistical details of the function are as follows:-

Number of observations	:	14
Correlation coefficient (R)	:	0.80
80% confidence interval multipliers	:	0.60, 1.68
Standard error of residuals (in $\log_{10}$ model)	:	0.166

12.9.3. Reported costs

The recommended function for chemical costs is:-

$$\boxed{\mathrm{CEMCOS} = 19.3*\mathrm{CAP}^{0.65}}$$

The statistical details of the function are as follows:-

Number of observations	:	14
Correlation coefficient (R)	:	0.84
80% confidence interval multipliers	:	0.55, 1.83
Standard error of residuals (in $\log_{10}$ model)	:	0.194

The recommended function for labour, maintenance and chemical costs is:-

$$\boxed{\mathrm{LAMACEMCOS} = 169*\mathrm{CAP}^{0.54}}$$

The statistical details of the function are as follows:-

Number of observations	:	14
Correlation coefficient (R)	:	0.86
80% confidence interval multipliers	:	0.63, 1.60
Standard error of residuals (in $\log_{10}$ model)	:	0.150

(iii) Other cost functions

A further model was developed for total operating cost (including cost of power as well as the labour, maintenance and chemical costs). This should be used with caution, however, as the costs of power used for items other than treatment processes are included in addition to process power costs.

$$\boxed{\mathrm{TOTCOS} = 244*\mathrm{CAP}^{0.53}}$$

The statistical details of the function are as follows:-

Number of observations	:	14
Correlation coefficient (R)	:	0.80
80% confidence interval multipliers	:	0.56, 1.80
Standard error of residuals (in $\log_{10}$ model)	:	0.189

13. SEWAGE TREATMENT

13.1. TOTAL SEWAGE TREATMENT WORKS COSTING

13.1.1. INTRODUCTION

Throughout the study, capital costs have usually been related to simple, readily understood engineering variables such as volume of tanks or effective area of filter plate presses. Very often, however, the planner knows only that a sewage treatment works is required to treat a certain quantity of effluent of a particular type to a specified standard. In order to build up an estimate of total cost of a works, therefore, he must draw up a list of the component process units and assume suitable performance relationships in order to calculate the cost of each component. In addition he has the problem of estimating all those costs which are not directly related to specific items of treatment plant but which, when taken together, can represent a substantial proportion of the total capital cost of civil engineering work. These costs are summarized in Section 13.1.2. The choice of component process units is considered in Section 13.1.3, and performance data for each main process is then given in Section 13.1.4. Next, the proposed method of estimating total cost is illustrated in Section 13.1.5 by a worked example.

In the absence of detailed information on the effluent standard to be achieved and the processes to be included, the planner is likely to estimate the costs of works under average conditions. To avoid the need for a number of readers independently to repeat these standard calculations, the costs of works for a range of throughputs for each of four effluent standards have been estimated in the manner of the example in Section 13.1.5; these are presented in Section 13.1.6. In addition, confidence intervals have been derived for these estimates by the simulation method described in Section 8.4.2.

Finally, in Section 13.1.7, a cost function is briefly presented which was developed using data from 24 whole works designed to treat to the 30/20 standard. This 'whole works' function is necessarily extremely crude, and is offered primarily as an independent broad check on the more reliable estimates built up by the 'component costs' approach.

13.1.2. COSTS OTHER THAN PROCESS COSTS

These costs are summarized in Table 13-1. The data is presented in detail in Sections 13.8.1 and 13.8.2, and the way these items are incorporated into the total cost is illustrated by the example in Section 13.1.5. It should be noted that the approach taken is slightly different from that adopted in Chapter 12 for water treatment.

Table 13-1. Sewage treatment items other than process costs

Costs associated with major identifiable tasks and hence classified under major headings or cost centres as shown	Costs for work likely to be done in connection with all major tasks and therefore distributed across all cost centres	(i) Contractors' overheads (ii) Design costs[†] (iii) Costs associated with land purchase[†]
Siteworks Including site clearance, roads, paths, stairways, distribution of top soil, construction of embankments and landscaping, fences, walls, gates and cattle grids; permanent supply of water and electricity, restoration of drains and roads, retaining walls and site dewatering. Inter-process pipework Buildings other than those housing equipment Offices, stores, workshops, laboratories, canteens and toilets. Additional costs[†] Major diversion of public roads; major diversion of streams; major diversion of public sewers; major permanent access road; demolitions; piling.	These costs usually constitute the preliminary bill less the contractor's overheads. Typically the following items are included:- Contingencies, variations and extra work as ordered by the R. E., day works, labour allowances including watchman, setting out, provision of materials and shuttering, provision and running of machinery and plant, top soil excavation and levelling, extra for excavating in rock, poor ground and provision and placing of filling, boreholes and drilling.	(i) Insurance, surety bond, service company charge, site telephone, supply of books and protective clothing, temporary site buildings, temporary supply of water and electricity, photography, testing of materials and opening up for inspection. (ii) Designers' fees, resident engineers' and staff costs; legal fees. (iii) Land; freehold; lease; rent; easement and other access rights.

[†] Very little data was available for these items, and cost functions have not been developed for them.

13.1.3. SEWAGE TREATMENT PROCESS STAGES

Where the proposed site is known the designer will be in a position to decide on the process stages in a works, whereas in general planning only the type of receiving water (i.e. river, estuarine or sea) may be known. Table 13.2 below gives typical process stages for each common situation.

Table 13-2. Process stages in sewage treatment works

Process stage	Section	Receiving water type		
		River	Estuarine	Sea
Preliminary treatment	13.2.	*	*	*
Storm tanks	13.3.2.	*	*	
Primary treatment	13.3.	*	*	
Secondary biological treatment	13.5.	*		
Final separating tanks	13.3.	*		
Tertiary treatment	13.6.	*†		
Sludge treatment	13.7.	*	*	
Sea outfalls	13.4.			*

† Tertiary treatment is only necessary when an effluent standard more stringent than 30/20 (SS/BOD) is required.

13.1.4. PERFORMANCE DATA

When estimating costs for national and regional planning purposes, a simple method of determining the approximate size of each process is needed so that the cost functions given later in Chapter 13 may be used. When only flow or population served is known it will be necessary to use a set of performance relationships to determine plant capacities. In view of the degree of accuracy required, the basic performance data offered in Table 13-3 should be adequate for use in preliminary planning studies.

Table 13-3. Values for rate of flow, strength of sewage and rate of production of sewage sludge per head of population in the United Kingdom

	Typical value	Units
Daily flow of sewage (domestic alone)	0.16	m^3/d. person
Daily flow of sewage (including industrial wastes)	0.22	
Level of BOD in settled sewage (including industrial waste)	44	g/d. person
Weight of sludge produced daily (dry solids)	82	

Note: In some instances figures have been based on limited data and are not necessarily representative. These values should therefore be used solely as a guide.

Performance relationships for the main processes are discussed in (a) to (g) following.

(a) Preliminary treatment

Maximum design flow (MDF) = 6*average daily flow.

When the sequence of processes to be used in preliminary treatment is known, so that the treatment description variable L can be determined, the costs may be built up as indicated in Section 13. 2B(i). For convenience, total costs have been calculated for a number of typical configurations for a range of works sizes, and these are given in Table 13.4.

Table 13-4. Civil and mechanical engineering costs of preliminary treatment

Equipment installed	Total value of L††	Civil engineering cost (£'000 1976 Q3)					Mechanical engineering cost (£'000 1976 Q3)†				
		Maximum design flow ('000 m^3/d)					Maximum design flow ('000 m^3/d)				
		10	30	100	300	1000	10	30	100	300	1000
Screens	3	8.2	16	-	-	-	6.4	15	-	-	-
Screens, grit removal	6	16	33	72	140	300	16	32	60	110	230
Screens, disintegrator, grit removal	6	-	-	74	143	310	-	-	65	121	265
Comminutor	4	11	22	-	-	-	4.9	11	-	-	-
Comminutor, grit removal	7	19	38	82	164	349	14	28	52	96	216
Screens, comminutor, grit removal	9	25	49	105	210	449	20	41	73	138	317

† Cost is inclusive of flow recording equipment.

†† See Section 13.2B.

(b) Storm sewage treatment (normally rectangular tanks)

Tank capacity = 6 hours' retention for average daily flow.

(c) Primary treatment

The performance data in Table 13-5 is based on Unit Processes Primary Sedimentation, Manuals of Practice in Water Pollution Control, Institute of Water Pollution Control.

Table 13-5. Performance data for primary treatment

Type of tank	Surface loading or upward flow velocity		Retention time at 1 DWF (h)	Depth (m)	Maximum dimensions (m)
	At 1 DWF	At max. flow			
Rectangular	$10\ m^3/m^2.d$	$30\ m^3/m^2.d$ $(45\ m^3/m^2.d)$†	6	2	100 long × 30 wide
Circular	$15\ m^3/m^2.d$	$45\ m^3/m^2.d$	6 (4.5)+	1.5††	50 diam.
Upward flow	0.4 m/h $(10\ m^3/m^2.d)$	1.2 m/h $(30\ m^3/m^2.d)$	6-9		9 × 9 (5 × 5 min.)

† Higher loadings and shorter retention times are sometimes employed when more than 3 DWF passes to secondary treatment stages.

†† Minimum side wall depth.

(d) Secondary biological treatment

Although no hard and fast rule can be given, the activated sludge process will normally be used for works serving populations greater than about 15 000 ($3000\ m^3/d$). Smaller works will usually employ biological filtration.

(i) Biological filters

The volume of media required is derived from values shown in Table 13-6. The normal depth is 1.83 m and the diameter is usually not greater than 50 m. At least two filters would normally be installed.

The performance data for the associated final separating tanks (humus tanks) is given in Table 13-7.

Table 13-6. Methods of operating biological filters and corresponding design criteria

Type of operation	Typical value for organic loading (daily average mass of BOD in settled sewage applied to unit volume of filter medium (kg BOD/m^3. d))	Volume of filter media required per unit daily flow of settled sewage† (m^3/m^3. d)	Comments
Simple or single filtration without recirculation	0.07	2.9	The most simple method; often used at small works.
As above but with recirculation of about 1 DWF final effluent	0.15	1.3	Additional humus tank capacity may be required.
Double filtration	0.15 - 0.18	1.1 - 1.3	Intermediate humus tanks are sometimes installed between primary and secondary filters.
Alternating double filtration	0.19	1.0	The most complex but most efficient system; often used in medium-sized works (flows up to about 5000 m^3/d).

† Values calculated for settled sewage containing 200 mg/l BOD.

(ii) Activated sludge

Retention time = 6 hours DWF,

although a longer retention time would be required for nitrification. Expected value for installed power per m^3 of DWF = 0. 0079 kW (see Section 13. 5. 2).

The performance data for the associated final settling tanks (normally circular scraped tanks) is given in Table 13-7.

Table 13-7. Performance data for final separating tanks

	Type of secondary biological treatment	
	Biological filters	Activated sludge
Minimum retention time at 1 DWF (h)	4. 0	4. 5
Maximum upward flow velocity at 3 DWF (m/h)	2. 7	2. 1
Minimum number of tanks	2	2
Maximum diameter (m)	25	25

(e) Tertiary treatment

(i) Rapid gravity filters

Maximum flow per unit area = 250 m^3/m^2. d (at 3 DWF).

(ii) Microstrainers

Maximum flow per unit area = 300 to 700 m^3/m^2. d (at 3 DWF).

The lower loadings would be used for units with fine cloth (15 micron openings) and the higher loadings for more open fabrics (65 micron openings).

(f) Sludge treatment

The mass flow of sludge solids is determined from a production rate per unit volume of sewage of 0. 50 kg/m^3, although in practice the figure may vary from 0. 25 to 0. 75 kg/m^3. The volumetric flow of sludge is calculated assuming a dry solids concentration of 4. 5 wt. %.

(i) Mesophilic digestion

Volume of digesters is based on retention time of up to 30 days.

(ii) Filter plate presses

Area of filtration, AREA ('000 m^2), is calculated from DWF ('000 m^3/d) by

$$AREA = 1.5*DWF*SPV/N,$$

where SPV is the solids production (kg per m^3 of DWF),
and N is the number of pressings per week.

Typical values of SPV and N are given in Table 13-43 in Section 13.7.3.

(iii) Filter belt presses

The performance of belt presses depends upon the type and dryness of the sludge being dewatered. The machine may be expected to operate at the approximate rates shown below, which have been estimated from operational data (recovery of dry solids = 98%, downtime = 15%).

Table 13-8. Operational rates for filter belt presses

Sludge	Sludge DS concentration (wt. %)	Loading† (kg/m. h)	Cake solids (wt. %)	Polyelect. concentration (wt. %)
Primary	5.0	250	35	0.2
Co-settled	4.5	150	28	0.3

† Loading figures are expressed in terms of effective belt width, which is 0.2 m less than actual belt width.

(iv) Lagoons

The performance relationships for treatment lagoons are not well established. The following rough guide may be used for preliminary cost estimation, but must not be used for design purposes without confirmatory evidence.

For a works where the average daily flow is 10 000 m^3/d, the volume of lagoon required is shown below for each of three values of sludge produced per unit volume of sewage (SPVS).

13.1.4. Performance data—sewage treatment

Table 13-9. Approximate performance data for lagoons

SPVS (kg DS/m^3)	Volume of sludge produced in two years (m^3)†	Total capacity of lagoons (m^3)††
0.26	27 000	40 000
0.51	53 000	79 000
0.77	80 000	120 000

† During 3 months' filling, sludge thickens from 4.5 to 7% DS.

†† Values allow for 3 months' filling time and discharge of treated sludge in summer only.

The concentration of dry solids (DS) in untreated incoming sludge is 4.5%, so that each tonne of DS occupies a volume of 22 m^3. After two years' treatment the weight of DS is reduced by 35%; furthermore, the sludge consolidates to 10% DS, so for each tonne of untreated sludge only 0.65 tonnes remains and this occupies only 6.5 m^3. The volume of sludge which must be taken from the treatment lagoon and transported to the disposal site therefore amounts to no more than 30% of the volume of untreated sludge.

(v) Drying beds

These would be used for purely domestic sewage.

$$\text{Area } (m^2) = 0.36 * \text{population served},$$

or equivalently,

$$\text{area } (m^2) = 2.2 * \text{DWF}(m^3/d).$$

(g) Sea outfalls

The diameter of a sea outfall pipe will often be such that the maximum velocity does not exceed 1.5 m/s. The length of the outfall will depend upon local conditions - in the sample studied, length varied from 0.7 to 5.0 km.

13.1.5. WORKED EXAMPLE

This section presents a worked example to illustrate how the total capital cost of a sewage treatment works may be estimated using the cost functions given in Sections 13.2 to 13.7 (and elsewhere). Where operating costs are included these relate only to the consumption of power and materials, as no data is available on manpower requirements. The example has been selected arbitrarily and should not be regarded as 'typical'. It is concerned with estimating the cost of building a works to treat a dry weather flow of 10 000 m^3/d (this would represent a contributing population of about 45 000 persons). An effluent standard of 10/10/10 (BOD/SS/ammoniacal nitrogen) is required, necessitating the inclusion of tertiary treatment. The process stages are given in Figure 13-1 below.

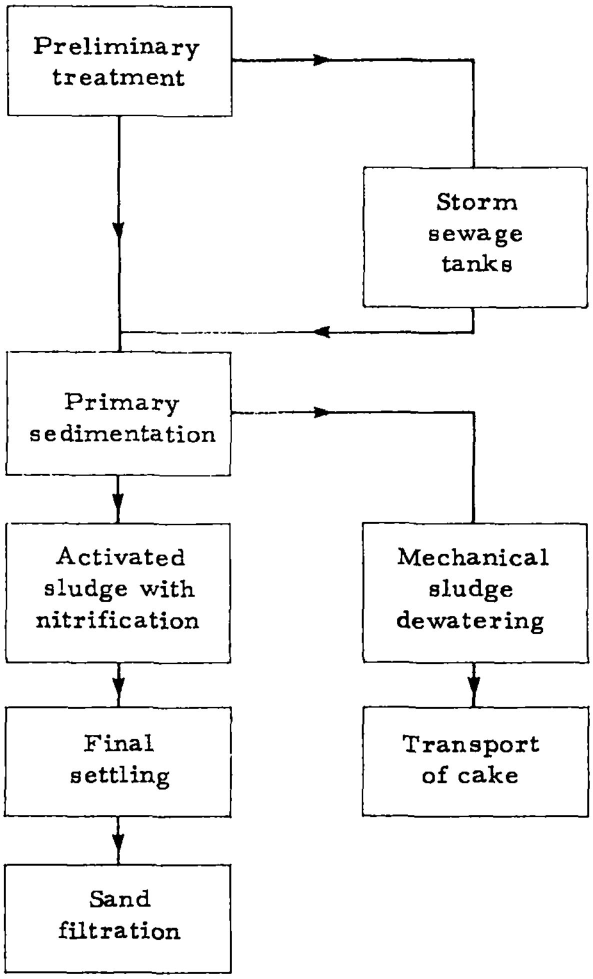


Figure 13-1. Process stages in sewage treatment worked example

For simplicity, cost estimates have been rounded to the nearest £'000.

13.1.5. Worked example—sewage treatment

(a) Preliminary processes

Assumption: the maximum design flow (MDF) is six times average flow.

Thus MDF = 60 000 m^3.

(i) Capital costs

From Section 13. 2B(i), the treatment description variable L is chosen as

$$L = 3 + 3 + 1 = 7.$$

Thus, from 13. 2B(iii),

civil engineering cost CIVCOS = $4.50(7/7)(60)^{0.63}$, i.e. £59 000.

Two comminutors will be specified. Thus MDF per machine is 30 000 m^3, and from Section 13. 2D(iii) the cost for mechanical engineering for one machine will be

COST/MAC = $2.22(30)^{0.27}$, i.e. £5600.

For two machines the cost is £11 000.

From Section 13. 2E(iii) the cost for the detritus removal equipment is

COST/MAC = $2.57(60)^{0.56}$, i.e. £25 000.

One flow recorder with an alarm system will be used, for which a figure of £5000 is given in Section 13. 2F.

Thus the capital costs for preliminary treatment may be summarized as follows:-

	£
Civil engineering	59 000
Mechanical engineering:	
comminutors	11 000
detritors	25 000
flow recorders	5 000
Total cost	100 000

(ii) Operating costs

From Section 13.9.1(a),

power required for two comminutors = 20 000 kVAh/yr,

and power required for two detritus removal units = 7000 kVAh/yr.

(b) Storm sewage tanks

Assumptions: 1. Capacity of tanks is equivalent to six hours of dry weather flow.

2. Rectangular tanks are used with mechanical scrapers.

$$\text{Capacity required} = \frac{6}{24} * 10\,000 = 2500 \text{ m}^3.$$

Two tanks of 1250 m^3 capacity will be used. From Section 13.3.2, the cost for these tanks is

$$\text{CIVCOS} = 68.4(2.5)^{0.73}, \text{ i.e. } \underline{£134\,000}.$$

From Section 13.3.2C(iii), the cost for one scraper is £6600. Thus the cost of two scrapers is £13 000.

(c) Primary treatment

Assumptions: 1. The design is based on the surface loading and retention criteria, typical values of which are given in Table 13-5. This table shows that for planning purposes a single condition of six hours' retention time is consistent with both surface loading and depth requirements for rectangular and circular tanks.

2. A circular (radial flow) sedimentation tank is chosen arbitrarily in preference to a rectangular (horizontal flow) design.

(i) Capital costs

$$\text{Capacity required} = \frac{6}{24} * 10\,000 = 2500 \text{ m}^3.$$

Two tanks of 1250 m^3 capacity will be used, of depth 3.5 m and tangent of angle of inclination of floor equal to $\frac{1}{7}$.

If diameter of each tank is D, then

$$\text{volume of a tank} = 1250\ \text{m}^3 = \frac{\pi D^2}{4}\left(3.5 + \frac{1}{3}*\frac{D}{2}*\frac{1}{7}\right),$$

and by trial substitution a value of D = 20 m can be found to satisfy this equation.

The wetted area of a tank is required for estimating the civil engineering costs. This is calculated by

$$\pi D(3.5) + \frac{\pi D^2}{4}\sqrt{1 + \left(\frac{1}{7}\right)^2} = 537\ \text{m}^2.$$

Thus, from Section 13.3.1B,

$$\text{CIVCOS} = 74.2*0.537, \text{ i.e. } \pounds 40\ 000,$$

and so the cost of two tanks is £80 000.

From Section 13.3.1C, the cost of a mechanical scraper for one tank is

$$\text{COST/MAC} = 1.45(20)^{0.51}, \text{ i.e. } \pounds 6700.$$

Thus the cost of two scrapers is £13 000.

(ii) Operating costs

From Section 13.9.1B, the power required for two scrapers = 13 000 kVAh/yr.

(d) Activated sludge

For the purpose of cost estimating it is possible to base the process design for aeration tanks on the concept of sludge loading rate (SLR), defined by

$$\text{SLR} = Q*\Delta\text{BOD}/(V*\text{MLSS}),$$

where SLR = sludge loading rate (d^{-1}),
Q = flow of settled sewage (m^3/d),
ΔBOD = BOD of settled sewage less BOD of final effluent (mg/l),
V = volume of aeration tanks (m^3),
and MLSS = concentration of mixed liquor in the aeration tanks (mg/l).

For plants not required to produce a nitrified effluent, suitable numerical values are SLR = 0.25 and MLSS = 2500; for a typical municipal sewage containing trade wastes, ΔBOD may approximate to 180. For these conditions the retention time will be about six hours. For a plant which is required to nitrify, a substantially lower sludge loading figure must be employed but somewhat higher concentrations of MLSS can be maintained, so that a retention time of around ten hours will normally be specified.

(i) Capital costs

The mixed liquor aeration tanks will have a capacity of

$$\frac{10}{24}*10\,000 = 4200 \text{ m}^3.$$

Two tanks each having a capacity of 2100 m^3 will be used. From Section 13.3.2, the cost for these tanks is

$$\text{CIVCOS} = 68.4(4.2)^{0.73}, \text{ i.e. } \underline{£195\,000}.$$

To calculate the costs for mechanical equipment it is first necessary to determine the daily averaged hourly rate of removal of BOD. The BOD of settled sewage will be 200 mg/l and this must be reduced to 10 mg/l. The hourly removal rate is therefore

$$(200 - 10)10\,000/(24*10^3) \text{ kg/h} = 79 \text{ kg/h}.$$

From Section 13.5.2, the installed power for a nitrifying plant is between 1.2 and 1.6 kW/kg BOD removed per hour. As the works is only of medium size a figure towards the higher end of the range will be taken. Thus,

$$\text{installed power} = 1.5*79 = 120,$$

and

$$\text{COST} = 2.21(120)^{0.87}, \text{ i.e. } \underline{£142\,000}.$$

(ii) Operating costs

From Section 13.5.2, the total mass of oxygen consumed per unit of BOD removed from a nitrifying plant is in the range 1.6 to 1.9 kg O_2/kg BOD. Taking a value of 1.8, the daily rate of oxygen consumption will be

$$1.8*10\,000(200 - 10)/10^3 \text{ kg/d} = 3420.$$

At peak load the aeration efficiency will be 1.9 kg O_2/kVAh, but the effective average value will be lower - perhaps 85% of this figure. Daily power consumption will therefore be

$$3420/(1.9*0.85)\text{kVAh/d} = 2120,$$

giving a yearly value of 770 000 kVAh/yr.

From Section 13.9.1(d), the power for returned sludge pumping is

$$10^3*10\,000*2.5*9.81*365/(3.5*10^6*0.5) = \underline{51\,000\text{ kVAh/yr}}.$$

(e) Final separating tanks (circular)

Assumptions:
1. The maximum upward flow at 3 DWF should not exceed 2.13 m/h (51 m/d).
2. The retention time should not be less than 4.5 h at DWF.

(i) Capital costs

$$\text{Capacity of tanks} = \frac{4.5}{24}*10\,000 = 1900\text{ m}^3.$$

Two tanks of capacity 950 m^3 will be used, of depth 3.5 m and tangent of angle of inclination of floor equal to $\frac{1}{7}$.

If diameter of each tank is D, then

$$\text{volume of a tank} = 950\text{ m}^3 = \frac{\pi D^2}{4}(3.5 + \frac{1}{3}*\frac{D}{2}*\frac{1}{7}),$$

and by trial substitution a value of D = 17.5 m can be found to satisfy this equation.

Hence wetted area of a tank is

$$\pi D(3.5) + \frac{\pi D^2}{4}\sqrt{1 + (\frac{1}{7})^2} = 435\text{ m}^2.$$

From Section 13.3.1B,

$$\text{CIVCOS} = 74.2*0.435,\text{ i.e. } \pounds 32\,300.$$

Thus the cost of two tanks is £65 000.

From Section 13.3.1C, the cost of a mechanical scraper for one tank is

$$\mathrm{COST/MAC} = 1.45(17.5)^{0.51}, \text{ i.e. } £6200.$$

Thus the cost of two scrapers is £12 000.

(ii) Operating costs

From Section 13.9.1(e), power required to drive four 1 kVA motors = 26 000 kVAh/yr.

(f) Tertiary treatment

Assumptions:
1. Rapid gravity filters will be used.
2. The typical filter performance for the assumed effluent is taken as 250 m^3/m^2.d at 3 DWF.

(i) Capital costs

The total plan area of filter required will be

$$3*10\,000/250 \text{ m}^2 = 120 \text{ m}^2.$$

Thus from Section 12.3.3B, civil engineering cost is

$$\mathrm{CIVCOS} = 0.388(0.120)^{0.81}, \text{ i.e. } £70\,000,$$

and mechanical engineering cost is

$$\mathrm{PLANTCOS} = 0.437(0.120)^{0.68}, \text{ i.e. } £103\,000.$$

(ii) Operating costs

From Section 13.9.1(f), power required $= \dfrac{365*10\,000*4*9.81}{0.5*3600} = $ 80 000 kVAh/yr.

The chemical conditioner is assumed to be aluminium chlorohydrate (15% solution), with a dose rate of 3% as Al_2O_3 (see Table 13-51 in Section 13.9.2).

$$\text{Annual cost} = 90*1825*0.03/0.15 = £33\,000.$$

(g) Holding tanks

Assumptions:

1. Sludge holding tanks are provided as a buffer in the event of a breakdown of the sludge dewatering plant.
2. A capacity of five days is provided.
3. Dry solids concentration in sludge = 4.5 wt.%.
4. Sewage is typically domestic, so that the solids produced amount to 0.5 kg/m^3 of DWF.
5. Maximum capacity of a tank = 2500 m^3.
6. Minimum number of tanks = 2.

(i) Capital costs

Total installed volume = 5*10*0.5/0.045
= 560 m^3.
Therefore number of tanks = 2, and
volume of each tank = 280 m^3.

Thus from Section 13.3.4B, the civil engineering cost per tank is

$$\text{COST/TK} = 29.9(0.28)^{0.52}, \text{ i.e. } £15\,400,$$

and so the cost of two tanks is £31 000.

Mechanical engineering costs will be small and are not included.

(ii) Operating costs

Operating costs are assumed to be negligible.

(h) Sludge dewatering

Assumptions:

1. A filter plate press installation will be employed.
2. The sewage is typically domestic, so that the sludge produced per unit volume of DWF amounts to 0.5 kg/m^3.

(i) Capital costs

For a works treating a DWF of 10 000 m^3/d, and at which the presses operate ten pressings per week, the area required is 770 m^2 (see Table 13-43). From

Section 13.7.3B, civil engineering cost is

$$\text{CIVCOS} = 177(0.770)^{0.74}, \text{ i.e. } \underline{\pounds 146\ 000}.$$

From Section 13.7.3C, mechanical engineering cost is

$$\text{MECCOS} = 282(0.770)^{0.87}, \text{ i.e. } \underline{\pounds 225\ 000}.$$

(ii) Operating costs

From Section 13.9.1(g), power required = 100 kVAh/tonne dry solids.

Annual production of dry solids = $10\ 000 * 0.5 * 365 * 10^{-3}$ = 1825 tonnes/yr.

Thus units of electricity = 180 000 kVAh/yr.

(j) Transport of cake

Assumptions: 1. The cake consists of 30% dry solids.
2. The average distance per round trip is five miles.

From Section 13.9.1(h),

cost/dry tonne = distance travelled*12 + 47 pence = £1.10.

Dry tonnes per year = 1825.

Thus cost per year (1976 Q3) = £2000.

(k) Pumphouse

Assumption: The following pumps are installed, all in the same house:-

	Head (m)	Flow (% of DWF)	Number installed
Wet well pumps	8	0.25	2
Storm pumps	5	0.25	1
Combined	7(mean)	0.75	3

$$\text{Thus throughput of pumping station} = 0.75*10\,000$$

$$= 7500\ \text{m}^3/\text{d}$$

$$= \frac{7500*1\,000}{24*60*60} = 86.8\ \text{l/s}.$$

(i) Capital costs

From Section 14.3B, civil engineering cost of pumphouse is

$$\text{PUMPCOS} = 6.97(86.8)^{0.21}(3)^{0.6},\ \text{i.e.}\quad \underline{£34\,000}.$$

From Section 10.4.1D, cost of mechanical equipment is

$$\text{SEWCOS} = 1.63(86.8)^{0.29}(7)^{0.19}(3)^{0.89},\ \text{i.e.}\quad \underline{£23\,000}.$$

(ii) Operating costs

No information was available on pumphouse operating costs.

(1) Civil engineering cost summary

Having estimated the capital costs for civil engineering associated with each process stage it is possible to allow for costs from other works items and additional costs. Firstly the capital costs for civil engineering must be totalled as follows:-

	£'000 (1976 Q3)
Preliminary processes	59
Storm sewage tanks	134
Primary treatment	80
Activated sludge (with nitrification)	195
Final separating tanks	65
Rapid gravity sand filters	70
Holding tanks	31
Filter press house	146
Pumphouse	34
Total	814

Other works items (see Section 13.8.1) are then estimated as follows:-

Inter-process pipework (16%)	130
Siteworks (14%)	114
Contractors' overheads (4%)	33
Buildings (4.5%)	36
Total	313

Thus total civil engineering cost (excluding additional site allowances) is £1 127 000.

If little detailed information concerning the site is available, an allowance of 9% of the total process civil engineering cost, i.e. £73 000, should be made as discussed in Section 13.8.2.

Thus the grand total capital cost for civil engineering is £1 200 000.

(m) Mechanical engineering cost summary

The mechanical engineering costs may similarly be summarized, as follows:-

	£'000 (1976 Q3)
Preliminary treatment:	
comminutors	11
detritors	25
flow recorders	5
Storm tank scrapers	13
Primary treatment:	
tank scrapers	13
Secondary biological treatment:	
mixed liquor aeration tank equipment	142
Final separating tanks:	
tank scrapers	12
Tertiary treatment:	
sand filter mechanicals	103
Sludge dewatering:	
plate presses	225
Pumping plant	23
Total	572

Thus the total capital cost for mechanical engineering is £572 000.

(n) Operating cost summary

Finally, the operating costs for power and materials can be assembled:-

(i) Electrical power:

	'000 kVAh/yr
Preliminary treatment	27
Primary treatment	13
Aeration	770
Return sludge pumping	51
Final settling tanks	26
Tertiary treatment	80
Sludge dewatering	180
Total	1147

Assuming a rate of 2p/kWh, this is equivalent to an annual cost of £23 000.

(ii) Chemical conditioner:

Annual cost is	£33 000.

(iii) Transportation of cake:

Annual cost is	£2000.

Thus total annual operating cost, excluding labour (at 1976 Q3 prices), is £58 000.

13.1.6. TOTAL COST ESTIMATES FOR TYPICAL CONFIGURATIONS

A. The general approach

The worked example assembled in Section 13.1.5 shows that it is a lengthy process to gather together and evaluate all the relationships relevant to a particular treatment works. Furthermore, although an approximate method of calculating a confidence interval about a total cost estimate is described in Section 8.4.1, this is an even more laborious undertaking which has little practical appeal. For these reasons, a computer program was developed with the following aims:-

(i) to estimate total cost, in the manner of the worked example, for a number of typical flowrates and effluent standards;

(ii) to repeat the calculations a large number of times for each particular configuration, simulating the random forecasting errors associated with each component cost estimate and thereby building up a distribution of 'possible' total costs from which a confidence interval could be determined.

Four standards of effluent have been considered: these are shown in Table 13-10, together with details of the processes which would normally be necessary in each case. The two most stringent standards are those commonly applied to effluents discharged to rivers; the third is a typical standard for estuarine discharges.

Table 13-10. Sewage treatment process stages for the four effluent standards

Process stage	Effluent standard (SS/BOD/ammoniacal nitrogen)			
	River	River	Estuarine	Sea
	10/10/10	30/20	150/200	-
Preliminary treatment	*	*	*	*
Storm tanks	*	*	*	
Primary treatment	*	*	*	
Secondary biological treatment	*	*		
Final separating tanks	*	*		
Tertiary treatment	*			
Sludge treatment (optional)	*	*	*	
Sea outfalls				*

13.1.6. Total cost estimates for typical configurations

The relatively simple case of sea outfalls is dealt with separately later in the section. For the other three standards, the sewage treatment and sludge treatment costs have first been presented separately. Sludge costs are highly dependent on the equipment used and the operational practices assumed, and any user who wishes to replace the values given here by other costs based on more specific local assumptions can readily do so. Most of the performance relationships required to 'size' the various component processes have been discussed in Section 13.1.4 and elsewhere in Chapter 13; for convenience these have been summarized in Table 13-11.

The quoted costs make no allowance for contractors' overheads, for optional equipment such as administrative and laboratory buildings, or for work specific to the site such as access roads. However, allowance is made for siteworks and pipeworks by proportionally increasing the estimate of total civil engineering cost before adding on the mechanical engineering costs.

13.1.6. Total cost estimates for typical configurations

Table 13-11. Performance data and relationships for sewage treatment works

Unit process	Performance relationship	Constraints on design
Preliminary treatment		
(a) Civil engineering	MDF = 6*DWF	Treatment consists of comminutors followed by detritus basin giving a value of 7 for L in regression model
(b) Mechanical engineering		
(i) Screens	MDF = 6*DWF MDF = 40*AREA where AREA is superficial flow area at maximum design flow	AREA $\leq$ 3.5
(ii) Comminutors	MDF = 6*DWF	MDF per machine $\leq$ 90.9 Number installed $\geq$ 2
(iii) Detritors	MDF = 6*DWF	For DWF $\leq$ 5.0 detritus basins are manually raked
(iv) Flow recorders		1 installed for DWF $\leq$ 5.0 3 + panel installed for DWF > 5.0
Storm tanks	VOL = DWF*0.25 where VOL is total volume of tanks	Rectangular tanks installed For DWF $\leq$ 5.0 tanks are manually raked Volume of one tank < 4.0 Number of tanks installed $\geq$ 2
Primary treatment		
(a) Circular tanks	VOL = 0.25*DWF	Installed when DWF $\leq$ 40 Volume of one tank < 3.0 Wall depth $\leq$ 3.5 m Floor gradient 1:7 Diameter/wall depth $\geq$ 2.0 Number of tanks installed $\geq$ 2
(b) Rectangular tanks	VOL = 0.25*DWF	Installed when DWF > 4.0 Volume of one tank < 4.0 Number of tanks installed $\geq$ 2
Secondary treatment		
(a) Percolating filters	With recirculation loadings are:	Installed when DWF $\leq$ 10 Volume of one filter < 1.65 Number installed $\geq$ 2
(i) 30/20 standard	0.15 kg of BOD/d.m^3	
(ii) 10/10/10 standard	0.10 kg of BOD/d.m^3	
(b) Aeration		Installed when DWF > 10
(i) 30/20 standard	VOL = DWF*0.25 Loading = 1.4 kg of BOD/kWh	
(ii) 10/10/10 standard	VOL = DWF*0.42 Loading = 0.68 kg of BOD/kWh	
Secondary sedimentation		
(a) Humus tanks	VOL = DWF*0.17	Circular tanks installed - the constraints given in primary treatment are applicable
(b) Activated sludge tanks	VOL = DWF*0.19	
Tertiary treatment		
Rapid gravity sand filters for 10/10/10 standard only	AREA = 3*DWF/250	

Details of pumps for 30/20 and 10/10/10 standards	Head (m)	Flow (DWF)	Number installed
(a) Activated sludge plant			
(i) Wet well pumps	8	0.25	2
(ii) Storm pump	5	0.25	1
	7 (av.)	0.75	3
(b) Percolating filter plant			
(i) Wet well pumps	8	0.25	3
(ii) Storm pump	5	0.25	1
(iii) Recirculation pump	4	1.0	1
	5.6 (av.)	2.0	5
Details of pumps for 150/200 standard			
(i) Wet well pump	8	0.10	2
(ii) Storm pump	5	0.25	1
	6.3 (av.)	0.45	3

Note: The following units are used:-

MDF - '000 m^3/d
DWF - '000 m^3/d
AREA - '000 m^2
VOL - '000 m^3

B. The results - treatment costs excluding sludge

(i) Effluent standards 10/10/10 and 30/20

Table 13-12 presents the estimated capital costs of sewage treatment (excluding sludge) over a range of dry weather flows for the two river outfall effluent standards being considered. The table also shows the combination of component items assumed for each flow. In cases where there is no clear-cut choice of process units, alternative combinations have been included: these are indicated by (a) and (b) in the 'dry weather flow' column. At 10 000 m^3/d, for example, both activated sludge and percolating filters have been costed as alternative biological treatment processes.

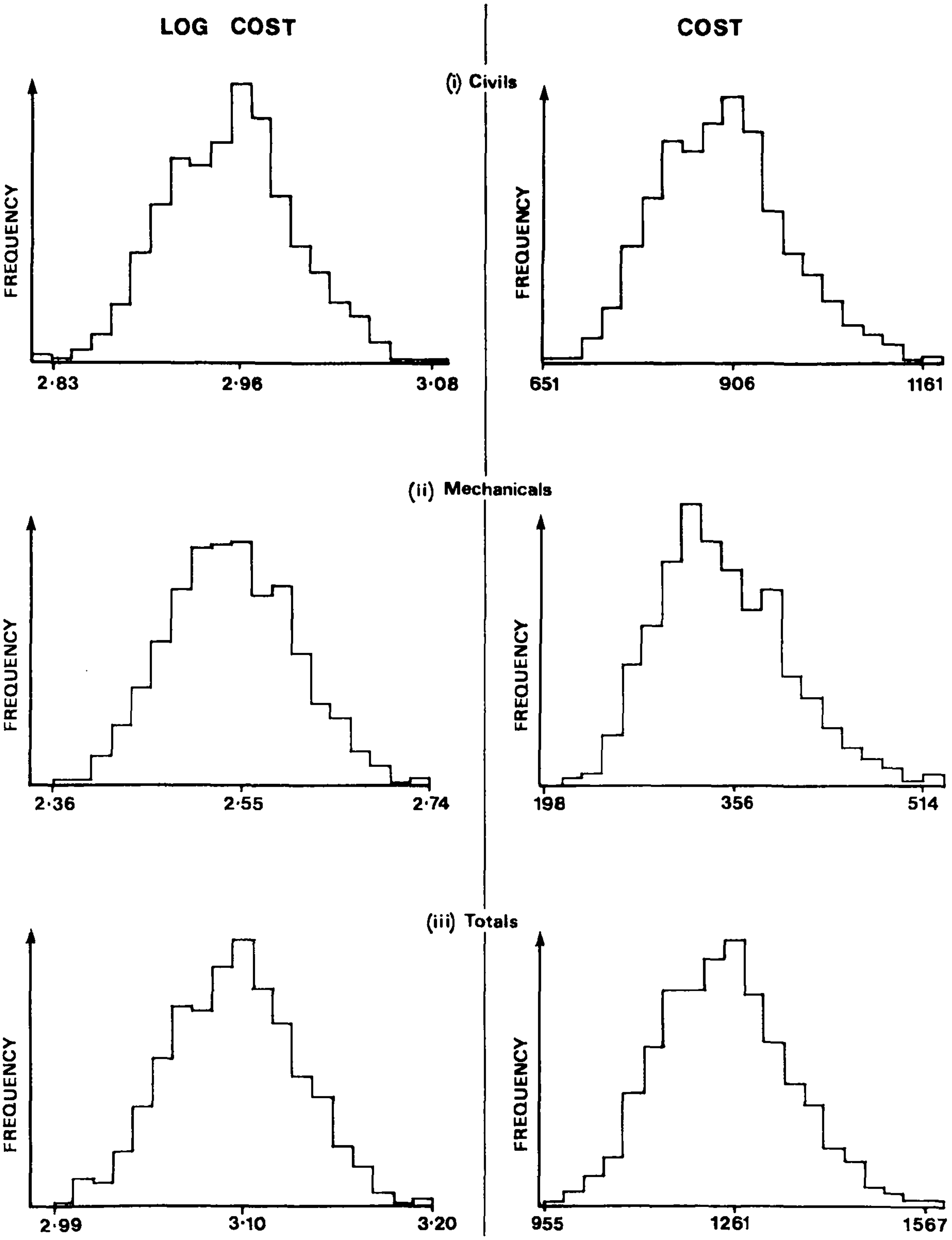
Every cost estimate in Table 13-12 is the mean of 1000 simulated 'worked examples', all containing different random errors in each cost component. To illustrate the spread of results obtained from the simulations, the distributions corresponding to the boxed figures in Table 13-12 are given in Figure 13-2, both for cost and for log cost. These show that, in each case, log cost can be closely approximated by a Normal distribution; and this was in fact a general conclusion over all the simulations. This means that the standard deviation of each log cost distribution can be used to form multiplicative 80 and 95% confidence intervals similar to those quoted for the individual cost functions throughout Part III. Furthermore, it was found that these standard deviations varied very little according to effluent standard or size of works. Consequently a single average value may be taken for each category of cost, and so the confidence interval multipliers corresponding to Table 13-12 are as follows:-

Confidence level	Civil cost		Mechanical cost		Total cost	
	Lower	Upper	Lower	Upper	Lower	Upper
80%	0.87	1.15	0.79	1.27	0.88	1.13
95%	0.81	1.24	0.69	1.44	0.83	1.21

Table 13-12. Capital costs of sewage treatment (excluding sludge) for two effluent standards

Dry weather flow ('000 m^3/d)	Description of works						Capital costs (£'000 1976 Q3)					
							Effluent standard					
							10/10/10			30/20		
	Preliminary treatment	Storm treatment	Primary treatment	Biological treatment	Secondary sedimentation	Tertiary treatment	Civil	Mech.	Total	Civil	Mech.	Total
2.5	Comminutors and manually raked grit channels	Manually raked rectangular tanks	Mechanically scraped circular tanks	Percolating filters	Mechanically scraped circular tanks	Sand filters for 10/10/10 standard only	446	110	556	345	65	410
5(a)							773	159	932	580	85	665
5(b)	Comminutors and mechanical detritors	Mechanically scraped rectangular tanks					773	193	966	580	119	699
10(a)							1 380	278	1 658	1 006	157	1 163
10(b)				Activated sludge			876	345	1 221 †	703	173	876
20							1 408	546	1 954	1 112	255	1 367
40(a)							2 370	918	3 290	1 868	425	2 290
40(b)			Mechanically scraped rectangular tanks				2 510	967	3 480	1 999	474	2 470
80							4 190	1 688	5 880	3 330	846	4 180
160							7 070	2 930	10 000	5 580	1 493	7 070

† Histograms of the simulation results for these costs are shown in Figure 13-2.



Note: 1. Each histogram is based on 1000 values, and the scale indicates the mean and ±3 standard deviations.
2. The costs refer to the boxed figures in Table 13.12.

Figure 13-2. Typical distributions of cost and log cost from the sewage treatment simulations

13.1.6. Total cost estimates for typical configurations

(ii) Effluent standard 150/200

The cost estimates and component processes for sewage treatment to estuarine discharge are displayed in Table 13-13 for a range of dry weather flows.

Table 13-13. Capital costs of sewage treatment (excluding sludge) for discharge to estuary

Dry weather flow ('000 m^3/d)	Description of works			Capital costs (£'000 1976 Q3)		
	Preliminary treatment	Storm treatment	Primary treatment	Effluent standard		
				150/200		
				Civil	Mech.	Total
5(a)	Comminutors and manually raked grit channels	Manually raked rectangular tanks	Mechanically scraped circular tanks	255	37	291
5(b)	Comminutors and mechanical detritors	Mechanically scraped rectangular tanks		255	71	326
10				399	87	486
20				635	108	743
40(a)				1076	161	1237
40(b)			Mechanically scraped rectangular tanks	1207	210	1417
80				1953	363	2320
160				3170	613	3790

The confidence interval multipliers corresponding to Table 13-13 are as follows:-

Confidence level	Civil cost		Mechanical cost		Total cost	
	Lower	Upper	Lower	Upper	Lower	Upper
80%	0.86	1.16	0.85	1.17	0.88	1.14
95%	0.80	1.25	0.79	1.27	0.82	1.22

C. The results - treatment costs including sludge

(i) Sludge treatment

The arbitrary assumption has been made that filter plate presses are used for sludge dewatering. Sludge holding tanks, with a capacity of five days' supply, are provided as a buffer in the event of a breakdown of the mechanical equipment. The factors governing operational practice and size of plant are discussed fully in Section 13.7.3; amongst these, the variables SPV (production rate of dry solids) and N, the pressing rate, are of major importance. These are related to the filtration area, A, and dry weather flow, DWF, by the following simplified formula:-

$$N*A = CONST*DWF*SPV.$$

For estuarine outfalls, where primary sludge only is produced, CONST takes the value 1.3 and SPV is typically about 0.32 kg/m^3 of DWF for domestic sewage. For river outfalls, CONST is 1.5 and SPV increases to about 0.5 kg/m^3. Using these values, the above formula can be used to establish the filtration area required for any given value of DWF and type of outfall, assuming that N lies in the normal operational range of 5 to 21 pressings per week. Sludge costs can then be estimated using the functions in Section 13.7.3, which relate civil and mechanical engineering costs to filtration area.

Sludge costs are shown for a number of combinations of N and A in Table 13-14. The table also indicates for each combination the corresponding DWF values for river and estuarine outfalls.

Table 13-14. Capital costs of filter plate presses for sludge treatment, for various values of N and A

N*A ('000 m^2/wk)	Number of pressings per press per week, N	Installed filtration area, A ('000 m^2)	Corresponding dry weather flow, DWF ('000 m^3/d)		Capital costs (£'000 1976 Q3)		
			River	Estuarine	Civil	Mech.	Total
2.5	5	0.5	3	6	110	150	260
5	5	1.0	7	12	180	280	460
5	10	0.5	7	12	110	150	260
10	10	1.0	13	24	180	280	460
20	10	2.0	27	48	300	510	810
20	15	1.33	27	48	220	360	580
50	15	3.33	67	120	440	800	1240
100	15	6.67	133	240	730	1460	2200
100	21	4.76	133	240	570	1090	1660
200	21	9.52	266	480	950	1990	2940

(ii) Effluent standards 10/10/10 and 30/20

Table 13-15 presents the total capital cost estimates of sewage and sludge treatment for the two river discharge standards. They have been obtained by calculating the sludge costs in the manner outlined in (i) above, and adding these to the results given in Table 13-12 for sewage treatment alone.

The confidence interval multipliers corresponding to Table 13-15 are as follows:-

Confidence level	Civil cost		Mechanical cost		Total cost	
	Lower	Upper	Lower	Upper	Lower	Upper
80%	0.89	1.12	0.84	1.19	0.91	1.10
95%	0.85	1.18	0.77	1.30	0.86	1.16

(iii) Effluent standard 150/200

The total capital cost estimates of sewage and sludge treatment for estuarine discharge are presented in Table 13-16. Like Table 13-15, this is formed by adding appropriate sludge treatment costs to the values in Table 13-13 for sewage treatment alone.

The confidence interval multipliers corresponding to Table 13-16 are as follows:-

Confidence level	Civil cost		Mechanical cost		Total cost	
	Lower	Upper	Lower	Upper	Lower	Upper
80%	0.88	1.14	0.83	1.20	0.90	1.11
95%	0.83	1.21	0.76	1.32	0.85	1.18

Table 13-15. Total capital costs of sewage treatment (including sludge) for two effluent standards

Dry weather flow ('000 m^3/d)	Description of works							Capital costs (£'000 1976 Q3)					
								Effluent standard					
								10/10/10			30/20		
	Preliminary treatment	Storm treatment	Primary treatment	Biological treatment	Secondary sedimentation	Tertiary treatment	Sludge treatment	Civil	Mech.	Total	Civil	Mech.	Total
2.5	Comminutors and manually raked grit channels	Manually raked rectangular tanks	Mechanically scraped circular tanks	Percolating filters	Mechanically scraped circular tanks	Sand filters for 10/10/10 standard only	Filter plate presses	552	229	781	452	184	636
5(a)								947	377	1 324	753	303	1 056
5(b)	Comminutors and mechanical detritors	Mechanically scraped rectangular tanks						947	411	1 358	753	337	1 090
10(a)								1 566	497	2 060	1 192	376	1 568
10(b)				Activated sludge				1 063	563	1 626	889	391	1 280
20								1 709	944	2 650	1 413	654	2 070
40(a)								2 760	1 430	4 190	2 250	937	3 190
40(b)			Mechanically scraped rectangular tanks					2 890	1 479	4 370	2 380	986	3 370
80								4 820	2 620	7 440	3 950	1 781	5 730
160								7 960	4 210	12 170	6 480	2 770	9 250

Table 13-16. Total capital costs of sewage treatment (including sludge) for discharge to estuary

Dry weather flow ('000 m^3/d)	Description of works				Capital costs (£'000 1976 Q3)		
					Effluent standard		
					150/200		
	Preliminary treatment	Storm treatment	Primary treatment	Sludge treatment	Civil	Mech.	Total
5(a)	Comminutors and manually raked grit channels	Manually raked rectangular tanks	Mechanically scraped circular tanks	Filter plate presses	371	169	540
5(b)	Comminutors and mechanical detritors	Mechanically scraped rectangular tanks			371	203	575
10					588	328	917
20					838	350	1188
40(a)					1405	604	2010
40(b)			Mechanically scraped rectangular tanks		1536	653	2190
80					2370	931	3300
160					3880	1650	5530

D. The results - sea outfall works

For this relatively simple case only two components are required: preliminary treatment, and the outfall pipe. For preliminary works (see Section 13. 2) L was taken as 4, representing comminutors and perhaps interconnecting channels. For the outfall pipe (see Section 13.4), a maximum velocity of 2 m/s was assumed. Table 13-17 presents the component and total costs estimated under these assumptions for a range of standard pipe diameters.

Table 13-17. Capital costs of sea outfall works

Bore of standard pipe (mm)	Max. design flow ('000 m^3/d)	Preliminary works costs (£'000 1976 Q3)			Cost of outfall (£'000 1976 Q3)	Total cost (£'000 1976 Q3)
		Civil	Mech.	Site-works		
444	27	20	9	3	460	490
597	48	30	10	5	710	760
746	76	39	12	7	1000	1060
998	140	57	14	10	1540	1620
1370	250	84	22	14	2480	2600

As the cost of preliminary works is insignificant in comparison with the outlet pipe cost, the confidence limits quoted in Section 13.4 can be used without modification. The multipliers for total cost are therefore:-

Confidence level	Lower	Upper
80%	0.67	1.49
95%	0.52	1.91

13.1.7. TOTAL COST ESTIMATES BASED ON CONSTRUCTED WORKS

A. The modelling approach

Data was obtained from 24 BoQs, covering the period 1966 to 1975, for sewage treatment works designed to treat to the 30/20 standard. The sample consisted of biological filter works using 'conventional' media, and activated sludge works, with associated sludge treatment and disposal. Most of the contracts for these types of works relate to extensions to existing installations, but only complete works were included in the sample.

The costs of civil engineering items were corrected for inflation using the New Construction Index, and mechanical engineering costs were deflated using the Engineering and Allied Industries Index. The costs exclude costs of piling, demolitions, and major access and stream diversion works.

Total civil and mechanical capital cost was related to the maximum design flowrate to full treatment. The scatter of the data about the function which was obtained is considerable. It was apparent from the detailed drawings for the works that substantial differences in civil work were demanded by different designers who were designing essentially similar structures. Far wider variations in sludge treatment equipment were found in the BoQs, ranging from virtually no equipment at all at some works to quite complex installations where sludge could be thickened, digested, chemically conditioned and dewatered mechanically prior to on-site storage awaiting transport to ultimate disposal site. The reasons for these differences could not be determined, and their effect has been to increase the variability in costs.

In view of the considerable unexplained scatter, the function should be used only as a preliminary guide to whole works capital costs, and certainly not in preference to estimates made using the component cost approach.

B. The results

(i) Data summary

Table 13-18. Whole treatment works data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total capital cost (corrected to 1976 Q3)	COST	£'000	16.0	9010	1120	1800
Maximum design flowrate to full treatment	MDF	'000 m^3/d	0.123	109	16.8	22.6

Note:
1. Number of cases: 24.
2. The New Construction Index was used to deflate civil engineering costs.
3. The Engineering and Allied Industries Index was used to deflate mechanical engineering costs.

(ii) The whole works total cost function

The function for whole works total cost is:-

$$\boxed{COST = 105*MDF^{0.82}}$$

The statistical details of the function are as follows:-

Number of observations	:	24
Correlation coefficient	:	0.96
Coefficient of determination (R^2)	:	93%
Standard error of residuals (in $\log_{10}$ model)	:	0.179

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.58	1.72
95%	0.43	2.35

C. Comparison between the whole works model and summation of the component cost models

For a range of works designed to treat to a 30/20 standard, two independent estimates of total cost have been made. Firstly, the whole works model estimates of total cost were evaluated for a number of flowrates using the function presented in part B above; these are tabulated below in Table 13-19. The assumption was made that MDF = 3*DWF for the works as a whole. Secondly, the corresponding cost estimates calculated by summing the estimates from the appropriate individual component cost models were obtained from Table 13-15; these also are given in Table 13-19.

In view of the wide scatter about the whole works model, there is reasonable agreement between the estimates for works with DWF of up to 10 000 m^3/d.

Table 13-19. Comparison of estimates for whole works designed to treat to a 30/20 standard

Dry weather flow ('000 m^3/d)	Whole works model estimate (£'000 1976 Q3)	Sum of component cost estimates (from Table 13-15) (£'000 1976 Q3)
2.5	548	636
5(a)	967	1060
5(b)	967	1090
10(a)	1710	1570
10(b)	1710	1280
20	3010	2070

13.2. PRELIMINARY PROCESSES

A. Introduction

Preliminary treatment is the first stage of treatment at sewage works and estuarine outfalls and is often the only stage at sea outfalls. The treatment consists of three separate processes: firstly, removal and disposal of screenings such as large, fibrous materials, rubber and plastic objects; secondly, removal and disposal of heavy particles which readily settle, such as detritus; and thirdly, regulation and volumetric measurement of the effluent stream(s).

At many installations not all of these processes are provided; for example, at sea outfalls and at small sewage works preliminary treatment may consist solely of screens comprising a grid of curved vertical steel bars. Usually the bars have a wedge-shaped cross-section with the apex pointing downstream, the upstream thickness of the bar and the width of the spaces between the bars being 13 mm and 19 mm respectively. The screens are cleaned by either manual or mechanical raking, the former being preferred at small works. The usual form of disposal is burial or tipping but at large works either a disintegrator or a press may be installed. After disintegration the screenings are returned to the sewage upstream of the screens, and where presses are installed these are used to dewater and solidify the screenings, thus simplifying tipping or burial.

At some works the actions of the screen and the disintegrator are combined by a single machine called a comminutor. This is essentially a vertically mounted cylindrical screen on which the retained solids are disintegrated by rotating teeth. Occasionally, coarse manually-raked screens are also installed, but this is not recommended by the manufacturer of the comminutor.

In the second of the preliminary treatment processes, particles which readily settle are removed either in constant velocity channels or in stilling basins. If allowed to pass to the primary sedimentation tanks the detritus may solidify the draw-off sludge and make removal difficult. The settled detritus in the channels or basins may be manually or mechanically discharged, the former being preferred at small works. The detritus is usually removed from site and tipped or buried.

The last link in the preliminary treatment chain is used to protect succeeding treatment from peak flows. Using an integral system of measuring/recording flumes and overflow weirs, the maximum flow to treatment is usually controlled at three times dry weather flow (DWF). The excess is diverted directly to the water course, or to storm tanks from which it is returned to the works when the rate of flow of the sewage influent has sufficiently decreased.

As preliminary treatment installations normally comprise a fairly complex civil engineering structure together with a variety of forms of mechanical equipment, a multi-purpose model has been developed for the civil works, and independent models have been developed for screens, comminutors and detritus removal equipment. A brief note is also included on the costs of flow recorders and disintegrators. Costs for screens have been correlated with submerged area which in turn is dependent on the maximum rate of flow or maximum design flow (MDF) for which the equipment is designed. In all other cases apart from flow recorders, costs have been correlated with MDF. Usually MDF was determined from the specifications given in documents such as Form Eng. 9 (Department of the Environment). However, for works in which extra capacity was built into the preliminary treatment works in anticipation of works extensions, the MDF was estimated from the capacity of the equipment installed. This value for the MDF was often a factor of two or more greater than the value found in Form Eng. 9. The MDF varied from approximately 4 to 20*DWF, according to the location of the works and the type of sewerage system. A MDF of 6*DWF is normally accepted as a typical value.

B. The results - civil engineering

(i) Detailed modelling approach

For the model representing civil engineering costs a treatment description variable, L, has been defined as the sum of the M values in Table 13-20 corresponding to those treatment processes present. Thus for each of the contracts the value of L depends upon the type and extent of the treatment installed. A typical value is 7, and so cost has been corrected by the factor (L/7) before being regressed against MDF.

Table 13-20. Value of M for each preliminary treatment process

Treatment process	Value of M
Screening	2
Comminution	3
Detritus removal	3
Measuring flumes and storm overflow	1
Distribution and inlet channels	1 (adjustable)

The M values were initially estimated from six contracts in which the sub-bill for preliminary treatment had been dissected to give the costs for the constituent process units. (In the remainder of the contracts only a global cost for preliminary treatment was given.) The values given in Table 13-20 are rounded figures designed to simplify the arithmetic in evaluating L for each contract.

The value of M for distribution and/or inlet channels can be adjusted in accordance with the engineer's judgement. In only one of the contracts were distribution channels included in the sub-bill for preliminary treatment and for this case a value of 1 for M was considered appropriate.

No attempt was made to derive a model in which the number and size of the individual units in each process were included as regression variables. Nor does the model differentiate between the alternative detritus removal processes. A more detailed analysis may ultimately lead to a more powerful model but the present data sample was not comprehensive enough for this to be carried out.

(ii) Data summary

Table 13-21. Preliminary treatment (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost for a standard composition of units (i.e. L=7) (corrected to 1976 Q3)	COST	£'000	3.81	301	74.6	86.1
Civil engineering cost (corrected to 1976 Q3)	CIVCOS	£'000	3.81	269	71.4	83.7
Treatment description variable	L	-	3	10	6.29	1.88
Maximum design flow	MDF	'000 m^3/d	0.674	409	97.0	136

Note: 1. Number of cases: 21.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-


COST


LOG COST


MDF

(iii) The recommended cost function

The recommended function for preliminary treatment civil engineering costs is:-

$$\boxed{CIVCOS = 4.50*(L/7)*MDF^{0.63}}$$

The statistical details of the function are as follows:-

Number of observations : 21
Correlation coefficient (R) : 0.97
Coefficient of determination (R^2) : 94%
Standard error of residuals (in $\log_{10}$ model) : 0.119

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
MDF	0.635	0.037	299	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.69	1.44
95%	0.56	1.77

Figures 13-3 and 13-4 show the five standard diagrams in support of the function.

(iv) <u>The data</u>

The civil engineering data is listed in Table A-36.

Figure 13-3. Preliminary treatment (civil engineering)

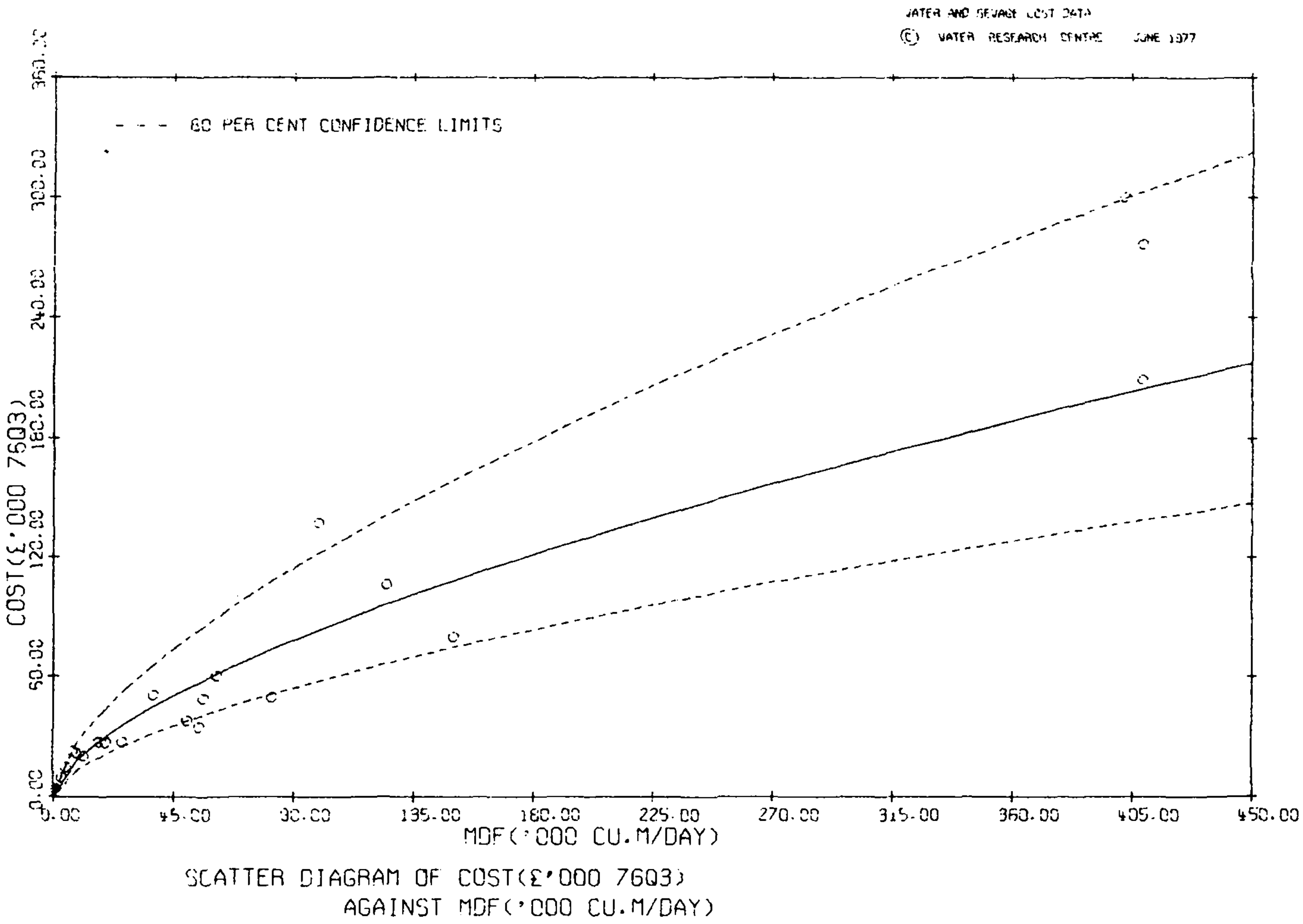
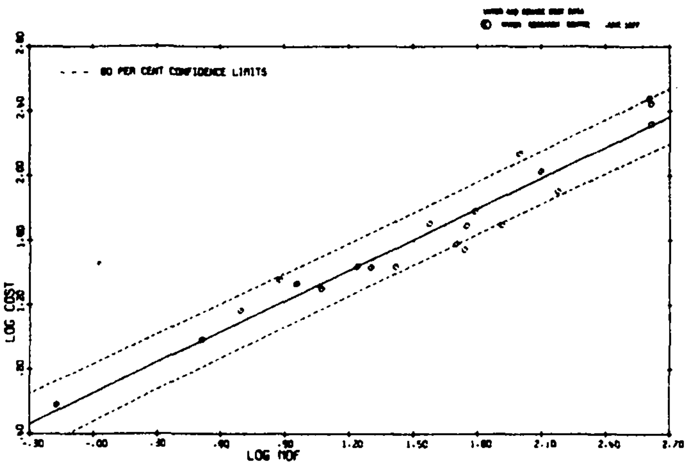
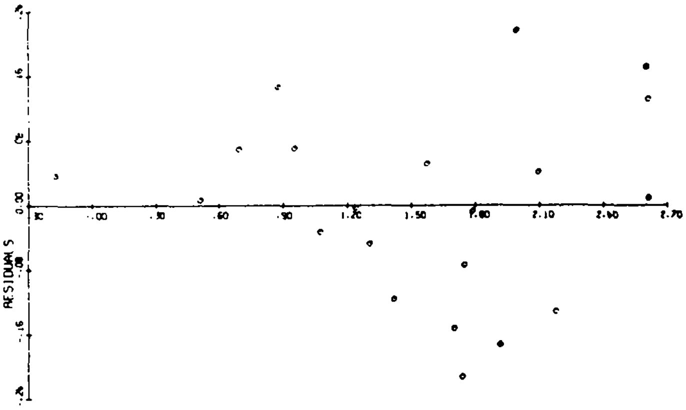


Figure 13-4. Preliminary treatment (civil engineering)

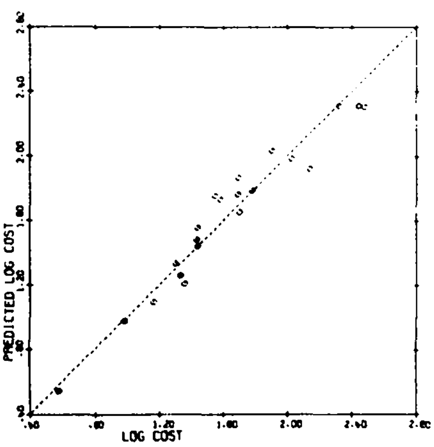


SCATTER DIAGRAM OF LOG COST
AGAINST LOG MOF



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG MOF

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - mechanically raked screens

(i) Detailed modelling approach

The submerged area of a conventional mechanically raked screen at maximum design flowrate (MDF) is a measure of the physical size of the equipment, and may also be related to MDF provided the superficial velocity of the sewage through the screens is known. Manufacturers recommend that, given normal operational conditions, the actual flow velocity through the voids be approximately 1 m/s. It is often assumed that the voidage of a fouled screen is about 50%, giving a superficial velocity of 0.5 m/s or 43 000 m/d. This is in close agreement with the average velocity of 39 000 m/d calculated from the contract data. Therefore, for average conditions:-

$$MDF = 40*AREA,$$

where MDF is maximum design flowrate ('000 m^3/d),
and AREA is submerged area at MDF (m^2).

Accordingly area was used as the main explanatory variable. The number of screens installed was also considered, but it was found that this did not significantly influence the cost per screen.

(ii) Data summary

Table 13-22. Mechanically raked screens data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost per screen (corrected to 1976 Q3)	COST/SC	£'000	3.82	17.6	9.94	3.84
Submerged area per screen at MDF	AREA	m^2	0.139	3.30	1.21	1.02

Note:
1. Number of cases: 11.
2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST/SC

LOG COST/SC

AREA

(iii) The recommended cost function

The recommended function for mechanically raked screens is:-

$$\boxed{\text{COST/SC} = 9.87*\text{AREA}^{0.39}}$$

The statistical details of the function are as follows:-

Number of observations : 11
Correlation coefficient (R) : 0.90
Coefficient of determination (R^2) : 80%
Standard error of residuals (in $\log_{10}$ model) : 0.085

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.387	0.064	36.5	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

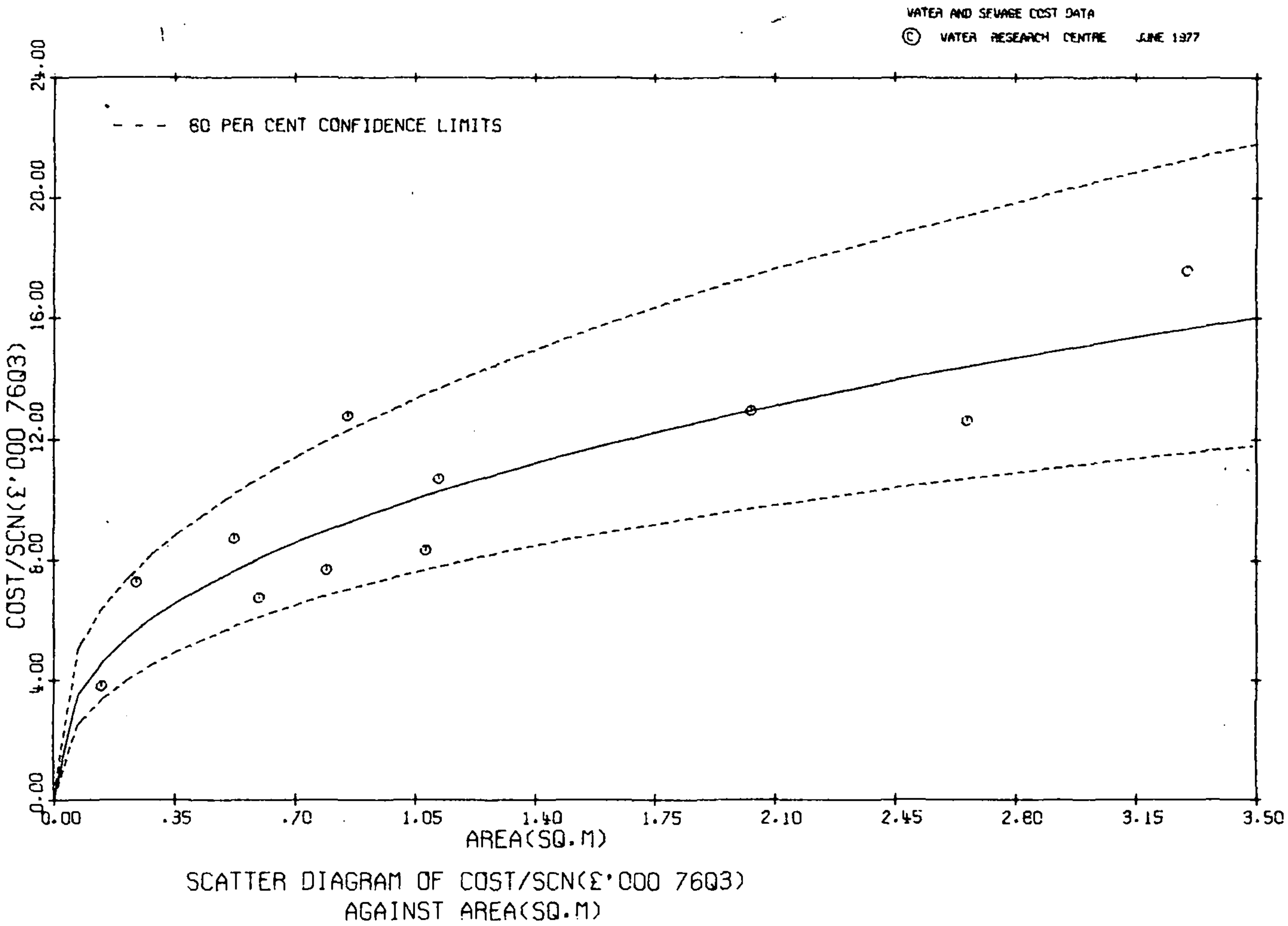
Confidence level	Lower	Upper
80%	0.76	1.31
95%	0.64	1.56

Figure 13-5 illustrates the recommended function.

(iv) The data

The mechanically raked screens data is listed in Table A-37.

Figure 13-5. Mechanically raked screens



WATER AND SEWAGE COST DATA

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SCATTER DIAGRAM OF COST/SCN(£'000 76Q3)
AGAINST AREA(SQ.M)

D. The results - comminutors

(i) Detailed modelling approach

Costs for comminutors have been related to MDF as recommended for the equipment by the manufacturer. Analysis of the data did not indicate any significant dependence on number of machines installed.

(ii) Data summary

Table 13-23. Comminutors data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost per machine (corrected to 1976 Q3)	COST/MAC	£'000	3.56	8.61	5.42	1.90
Maximum design flow per machine	MDF	'000 m^3/d	4.09	90.9	37.7	34.1

Note: 1. Number of cases: 9.

2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-


COST/MAC


LOG COST/MAC


MDF

(iii) The recommended cost function

The recommended function for comminutors is:-

$$\boxed{COST/MAC = 2.22*MDF^{0.27}}$$

The statistical details of the function are as follows:-

Number of observations	:	9
Correlation coefficient (R)	:	0.90
Coefficient of determination (R^2)	:	81%
Standard error of residuals (in $\log_{10}$ model)	:	0.069

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
MDF	0.268	0.049	29.5	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.80	1.25
95%	0.69	1.46

Figure 13-6 illustrates the recommended function.

(iv) The data

The comminutors data is listed in Table A-38.

Figure 13-6. Comminutors

WATER AND SEWAGE COST DATA

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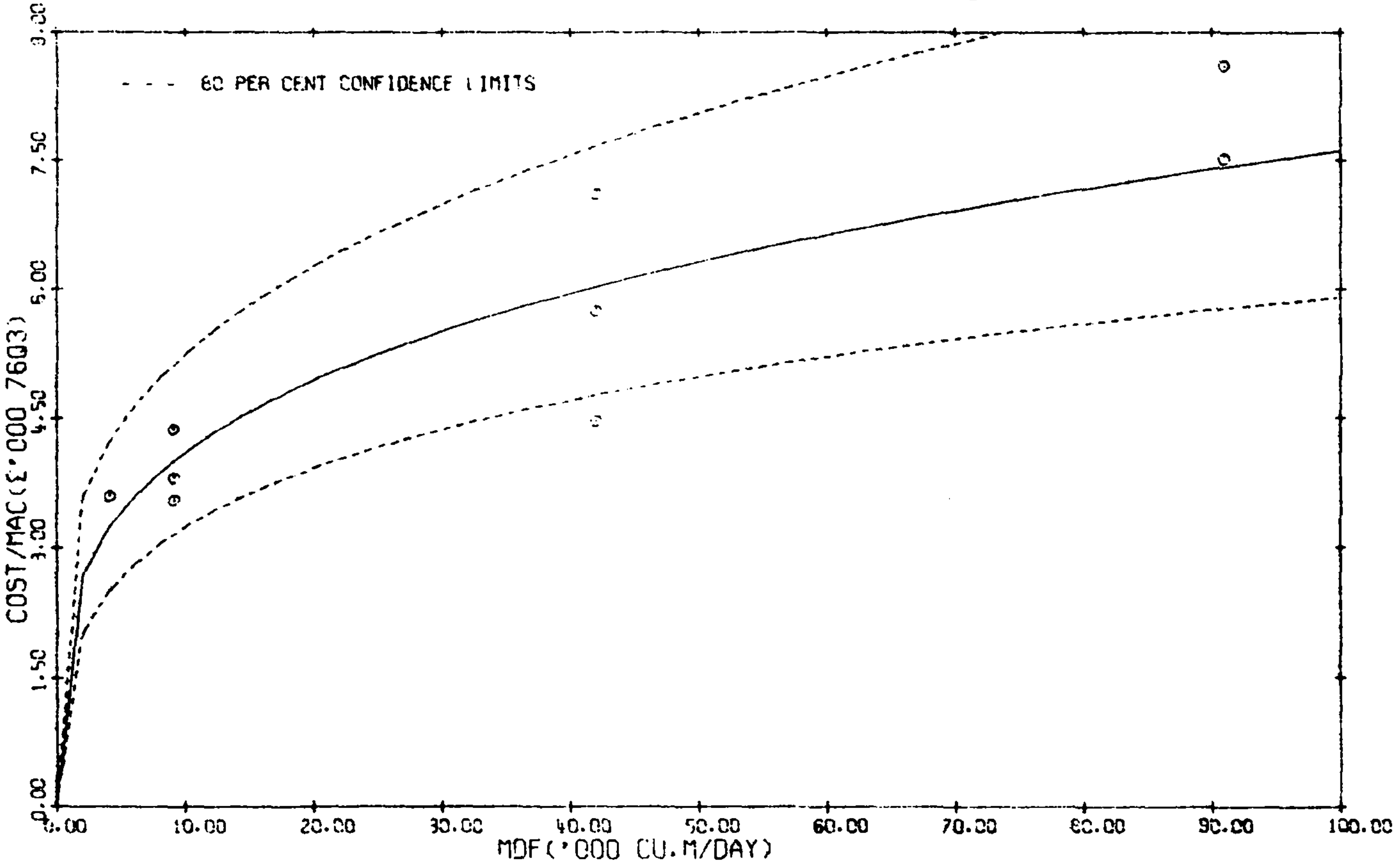


SCATTER DIAGRAM OF COST/MAC(£'000 76Q3)
AGAINST MDF('000 CU.M/DAY)

E. The results - detritus removal

(i) Detailed modelling approach

MDF was calculated from the number and cross-section of the basins installed in accordance with British Standard Code of Practice 2005, 1968. This recommends that, for the removal of siliceous particles greater than 0.2 mm in diameter, 1 m^2 of cross-section area should be provided for each 1600 m/d of MDF. Cost was then related to MDF, number of detritors installed, and capacity of the individual machines. Only MDF was found to be significant, whereas an examination of budget costs shows that for a given total capacity the installation of large machines is substantially more economic than the installation of a larger number of machines of reduced capacity. This limitation was forced on the model by the limited sample size and the scatter in the data.

(ii) Data summary

Table 13-24. Detritus removal equipment data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	COST	£'000	18.9	69.2	41.6	17.8
Maximum design flow	MDF	'000 m^3 /d	57.7	390	162	117

Note: 1. Number of observations: 8.

2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST

LOG COST

MDF

(iii) The recommended cost function

The recommended function for detritus removal equipment is:-

$$\boxed{COST = 2.57*MDF^{0.56}}$$

The statistical details of the function are as follows:-

Number of observations : 8
Correlation coefficient (R) : 0.91
Coefficient of determination (R^2) : 82%
Standard error of residuals (in $\log_{10}$ model) : 0.086

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
MDF	0.556	0.105	27.9	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

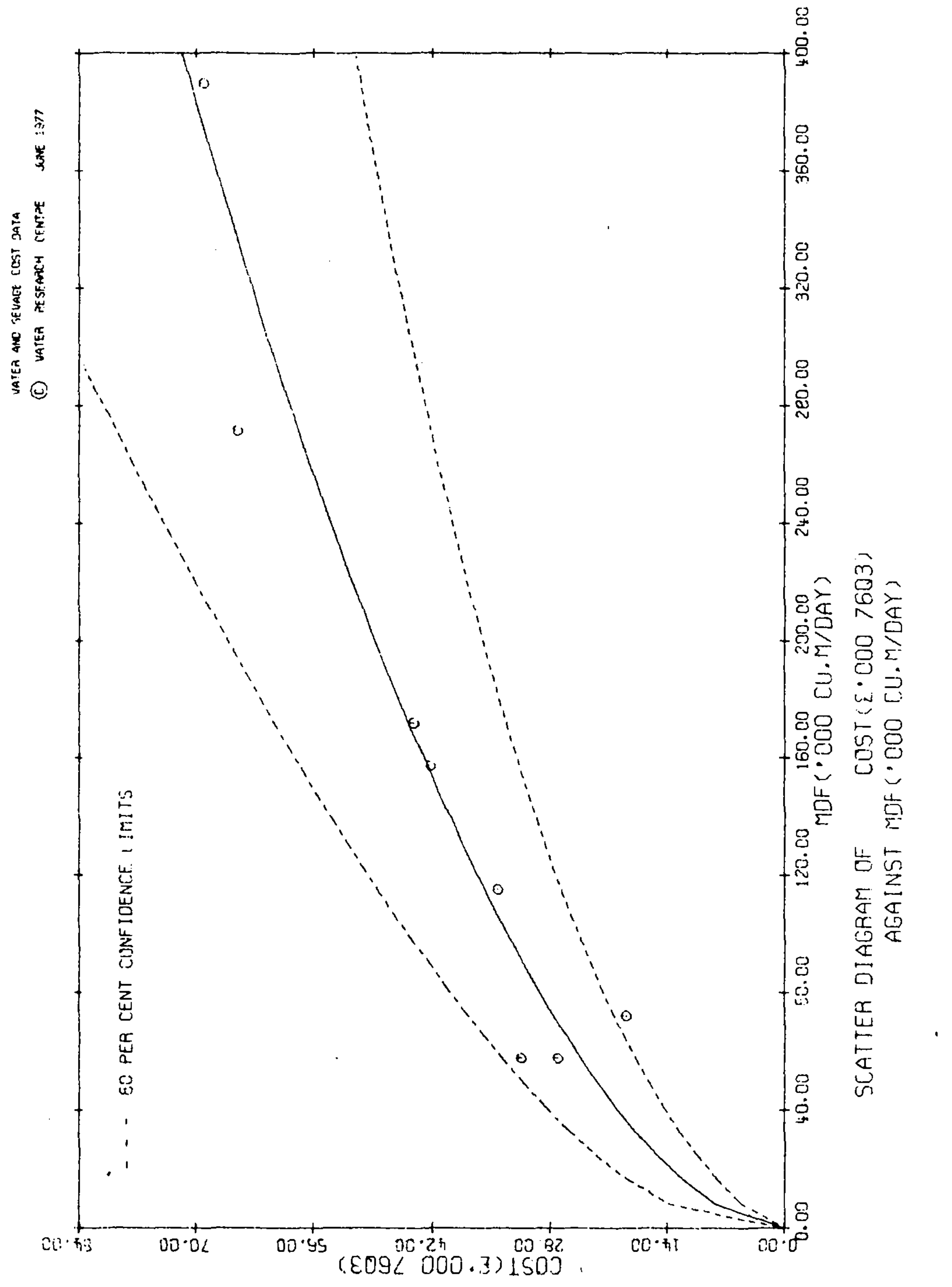
Confidence level	Lower	Upper
80%	0.75	1.33
95%	0.62	1.62

Figure 13-7 illustrates the recommended function.

(iv) The data

The detritus removal equipment data is listed in Table A-39.

Figure 13-7. Detritus removal equipment



F. The results - flow recorders

Costs for flow recorders account for only a very small proportion of the total cost for a treatment works. The number of flow recorders installed at any given works largely depends upon local requirements. At large and moderately sized works employing peak flow control there is a minimum requirement of two recorders. At small works the installation of one recorder is usually sufficient. The cost of a recorder/integrator varies from approximately £600 to £1000 and is insensitive to the maximum flow to be measured. The provision of a control panel and alarm will increase the cost to approximately £3000.

G. The results - disintegrators

Disintegrators, like flow recorders, account for only a small proportion of the cost for a treatment works. They are manufactured in a range of sizes capable of handling screenings at works where the MDF is within the range from 70 to 180 '000 m^3/d of sewage containing an average concentration of screenings. No contract prices have been collected, but budget costs for supply of equipment and spares, delivery and erection suggest a price range from £4700 to £6000, depending upon the size. These costs do not cover the additional civil engineering work such as a bedding plinth, but this is expected to be a small item.

13.3. PRIMARY SEDIMENTATION

13.3.1. CIRCULAR SEDIMENTATION TANKS

A. The modelling approach

Circular sedimentation tanks consist of a structure which is predominantly a civil engineering item, and a scraper assembly which is usually supplied by a firm of mechanical engineers. Separate models were therefore developed for civil and mechanical engineering. All the tanks for which data was available were constructed with inclined floors having gradients less than 1:7 converging to central sludge hoppers. For the civil engineering cost model, wetted surface area proved a more satisfactory explanatory variable than either nominal tank capacity or plan area, the two usual design variables. Wetted surface area cannot be calculated easily from plan area and nominal volume, and so Table 13-25, which applies to sedimentation tanks with a typical geometry, has been provided.

Table 13-25. Wetted areas corresponding to a range of design variables, for typical sedimentation tanks

Nominal volume (m^3)	Plan area (m^2)	Wetted area (m^2)
100	40	95
200	75	155
300	105	205
400	130	245
600	185	325
1000	280	470
1500	390	630
2000	500	775
2500	610	855
3000	715	1045

Capital costs for mechanical and electrical engineering associated with the scrapers were related to tank diameter. There was slight evidence that scrapers fitted to primary circular sedimentation tanks are more expensive than those used in secondary tanks, but the effect was small in comparison with the variation between contracts and so only one function was derived.

B. The results - civil engineering

(i) Data summary

Table 13-26. Circular sedimentation tanks (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Civil engineering cost of tank (corrected to 1976 Q3)	CIVCOS	£'000	9.36	81.2	31.2	18.0
Wetted surface area of tank	AREA	'000 m^2	0.133	1.07	0.417	0.233

Note: 1. Number of cases: 21.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

CIVCOS

LOG CIVCOS

AREA

(ii) The recommended cost function

The recommended function for circular sedimentation tanks civil engineering is:-

$$\boxed{\mathrm{CIVCOS} = 73.0*\mathrm{AREA}^{0.99}}$$

The value of AREA exponent is so close to unity that a simpler relationship can be used with little loss in precision:-

$$\boxed{\mathrm{CIVCOS} = 74.2*\mathrm{AREA}}$$

Note that CIVCOS and AREA relate to single tanks, not complete installations.

The statistical details of the model are as follows:-

Number of observations : 21
Correlation coefficient (R) : 0.98
Coefficient of determination (R^2) : 97%
Standard error of residuals (in $\log_{10}$ model) : 0.049

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.990	0.043	528	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.86	1.16
95%	0.64	1.56

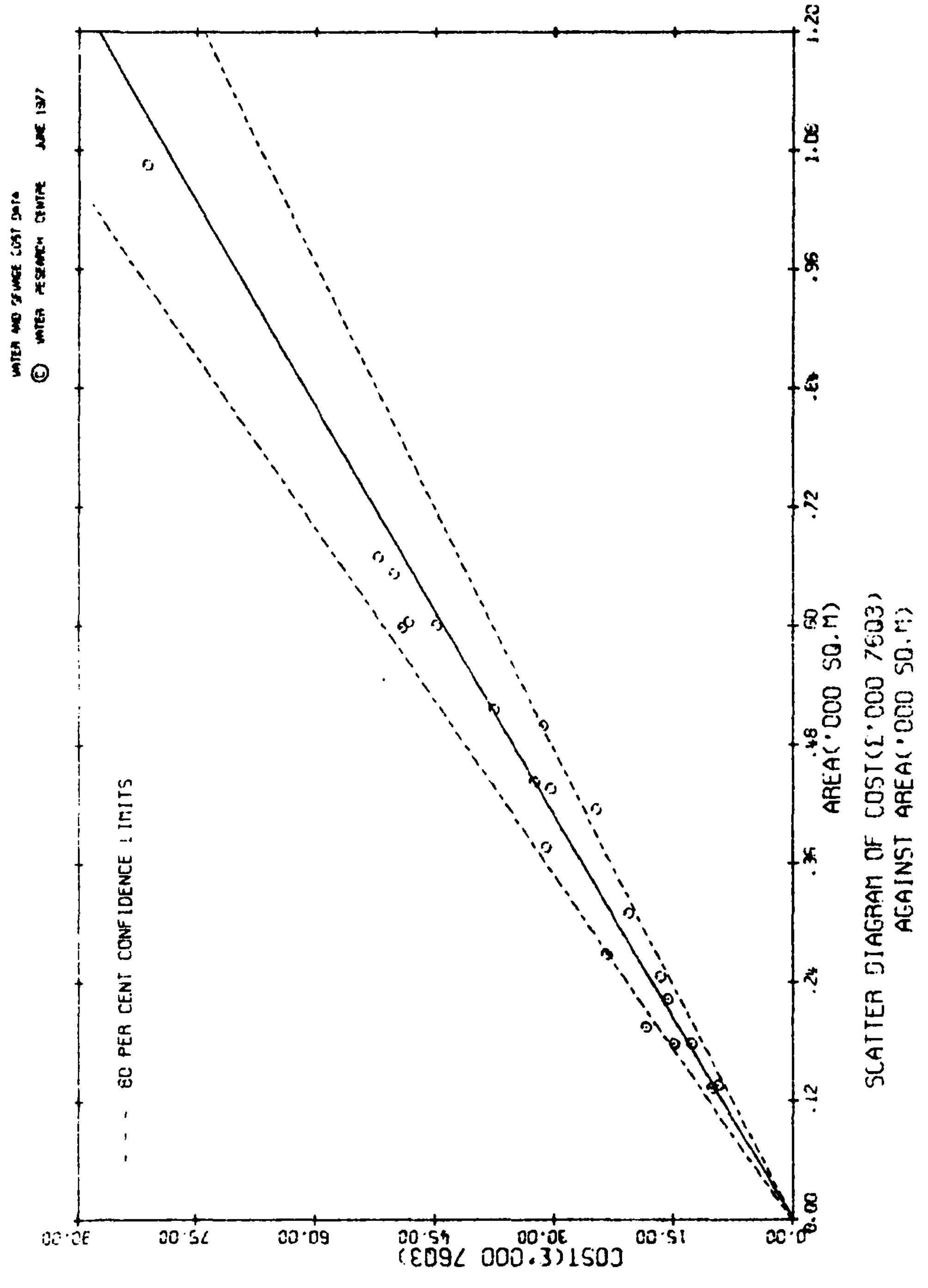
Figures 13-8 and 13-9 show the five standard diagrams in support of the function.

(iii) <u>The data</u>

The civil engineering data is listed in Table A-40.

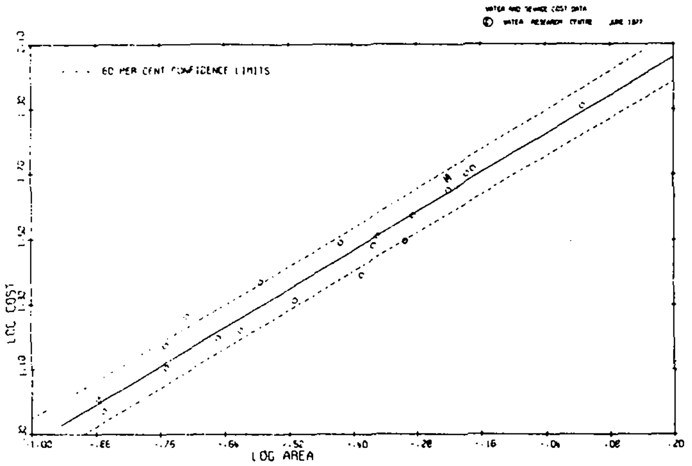
13.3.1. Circular sedimentation tanks

Figure 13-8. Circular sedimentation tanks (civil engineering)

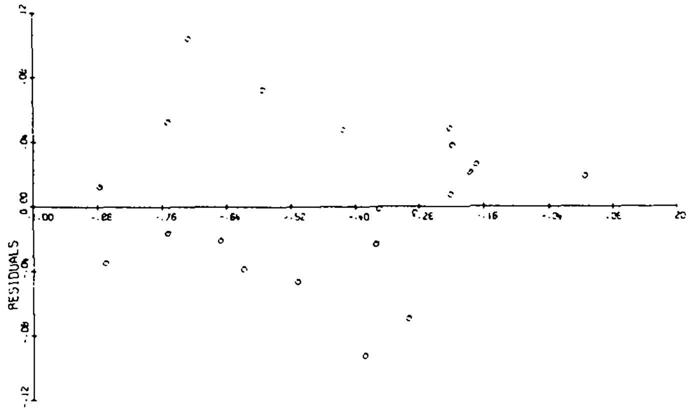


13.3.1. Circular sedimentation tanks

Figure 13-9. Circular sedimentation tanks (civil engineering)

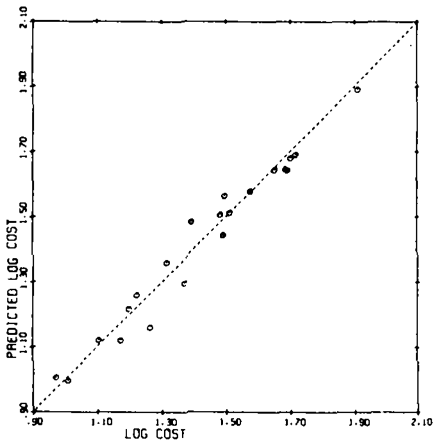


SCATTER DIAGRAM OF LOG COST
AGAINST LOG AREA



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG AREA

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - mechanical engineering

(i) Data summary

Table 13-27. Circular sedimentation tanks (mechanical engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost of scraper (corrected to 1976 Q3)	COST/MAC	£'000	4.70	10.3	6.82	1.81
Diameter of tank	DIAM	m	12.0	27.3	20.2	5.72

Note:
1. Number of cases: 18.
2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST/MAC

LOG COST/MAC

DIAM

(ii) The recommended cost function

The recommended function for circular sedimentation tanks mechanical engineering is:-

$$\boxed{COST/MAC = 1.45*DIAM^{0.51}}$$

The statistical details of the model are as follows:-

Number of observations	:	18
Correlation coefficient (R)	:	0.61
Coefficient of determination (R^2)	:	37%
Standard error of residuals (in $\log_{10}$ model)	:	0.091

13.3.1. Circular sedimentation tanks

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DIAM	0.511	0.165	9.57	<1.0%

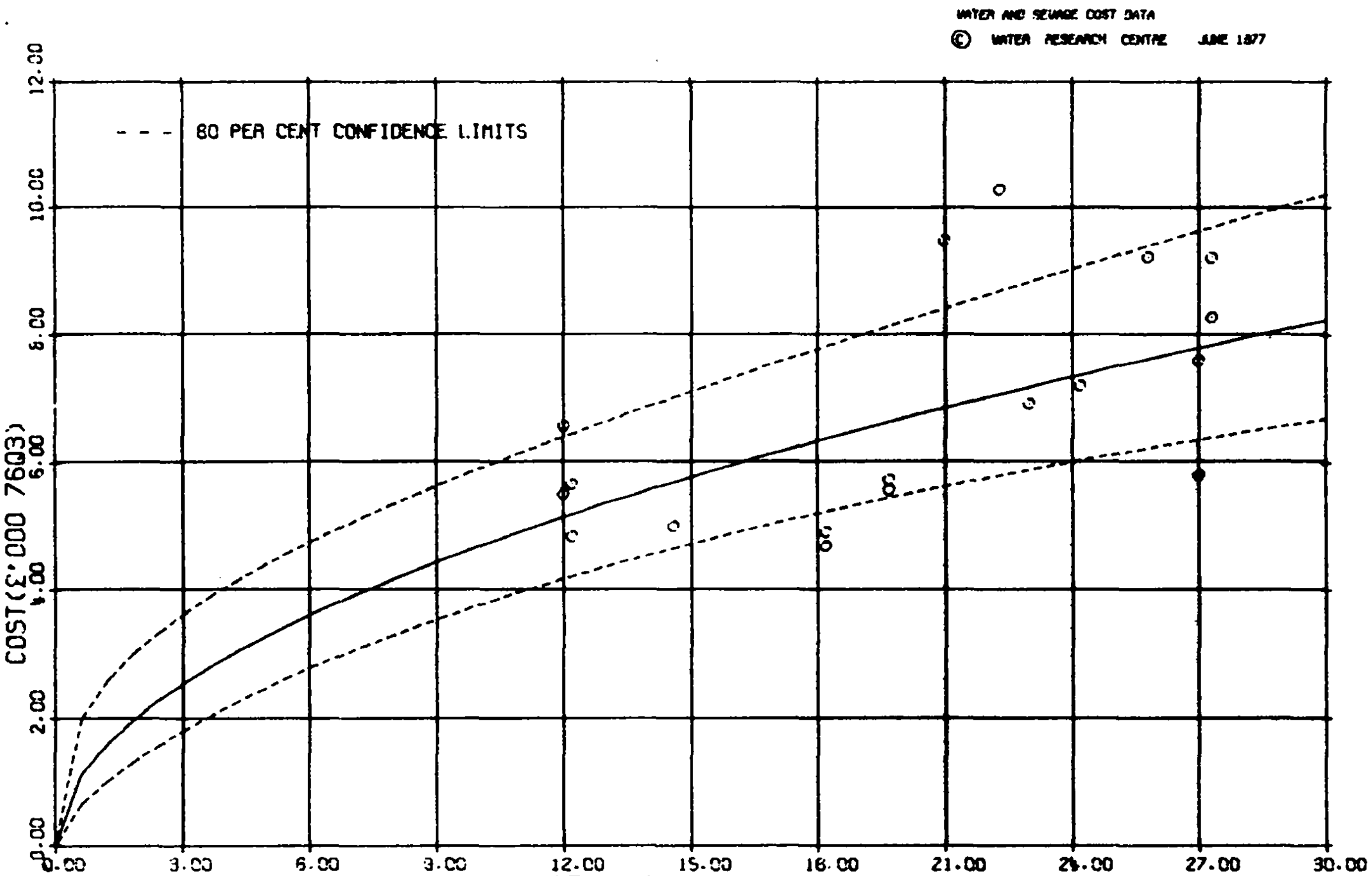
Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.76	1.32
95%	0.64	1.56

Figures 13-10 and 13-11 show the five standard diagrams in support of the function.

(iii) The data

The mechanical engineering data is listed in Table A-41.

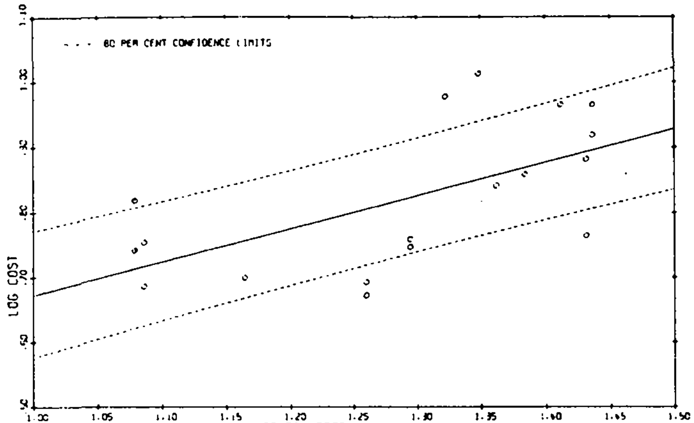


SCATTER DIAGRAM OF COST(£'000 7603)
AGAINST DIAMETER(M)

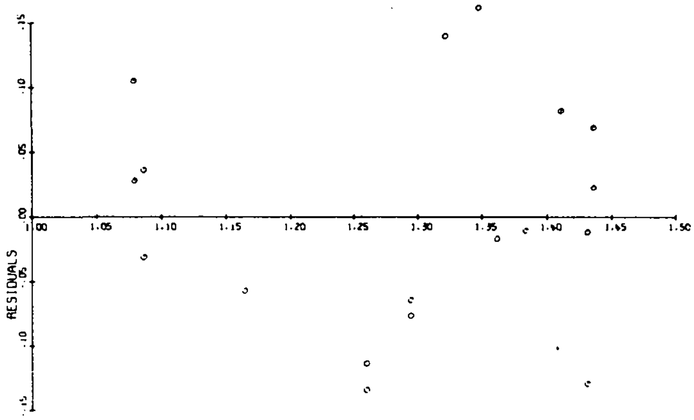
Figure 13-10. Circular sedimentation tanks (mechanical engineering)

13.3.1. Circular sedimentation tanks

Figure 13-11. Circular sedimentation tanks (mechanical engineering)

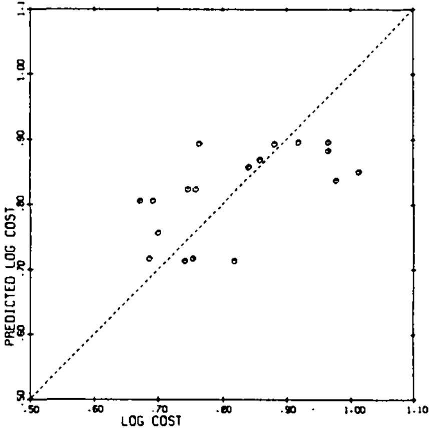


SCATTER DIAGRAM OF LOG COST
AGAINST LOG DIAMETER



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG DIAMETER

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

13.3.2. RECTANGULAR TANKS

A. The modelling approach

Civil engineering cost data was collected for eight storm and sedimentation tanks, six diffused air tanks and eleven surface aeration tanks. Small variations in the design of these types of tanks were evident, particularly in the floor geometry, but as the tanks were all essentially rectangular a comprehensive model could be developed. Volume of tanks and number constructed were examined as explanatory variables, but only volume was significant.

Mechanical equipment consists of either scrapers for use in storm or sedimentation tanks, or aeration equipment. A model for scrapers is presented here. Aeration equipment, which can account for a substantial proportion of the total mechanical and operating costs of a works, is treated separately in Section 13.5.2.

Data was collected for two scraper types: the 'motorized bridge', normally used in primary settlement tanks, and a type of rope hauled device normally used intermittently in storm tanks. Both types span the width of the tank and traverse the length, but differ in the method of traction used. It was necessary to develop separate models as there were evident differences in costs between the two types.

The length, width, and number of tanks installed were examined as explanatory variables. However, none of these was found to be significant in either case, partly because of the very limited amount of data. The cost functions therefore take the form COST/SCRAPER = constant. It should be noted that additive rather than multiplicative confidence intervals are given with the functions.

13.3.2. Rectangular tanks

B. The results - civil engineering

(i) Data summary

Table 13-28. Rectangular tanks (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total civil engineering cost (corrected to 1976 Q3)	CIVCOS	£'000	8.28	1150	236	291
Total volume of tanks	VOL	'000 m^3	0.072	38.0	6.69	10.3
Number of tanks installed	NTANK	-	1	34	7.12	8.23

Note: 1. Number of cases: 25.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

CIVCOS

LOG CIVCOS

VOL

(ii) The recommended cost function

The recommended function for rectangular tanks civil engineering is:-

$$\boxed{CIVCOS = 68.4*VOL^{0.73}}$$

Note that CIVCOS and VOL relate to total installations, not individual tanks.

The statistical details of the function are as follows:-

Number of observations : 25

Correlation coefficient (R) : 0.99

Coefficient of determination (R^2) : 98%

Standard error of residuals (in $\log_{10}$ model) : 0.075

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.734	0.023	1050	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.80	1.25
95%	0.70	1.43

Figures 13-12 and 13-13 show the five standard diagrams in support of the function.

(iii) The data

The civil engineering data is listed in Table A-42.

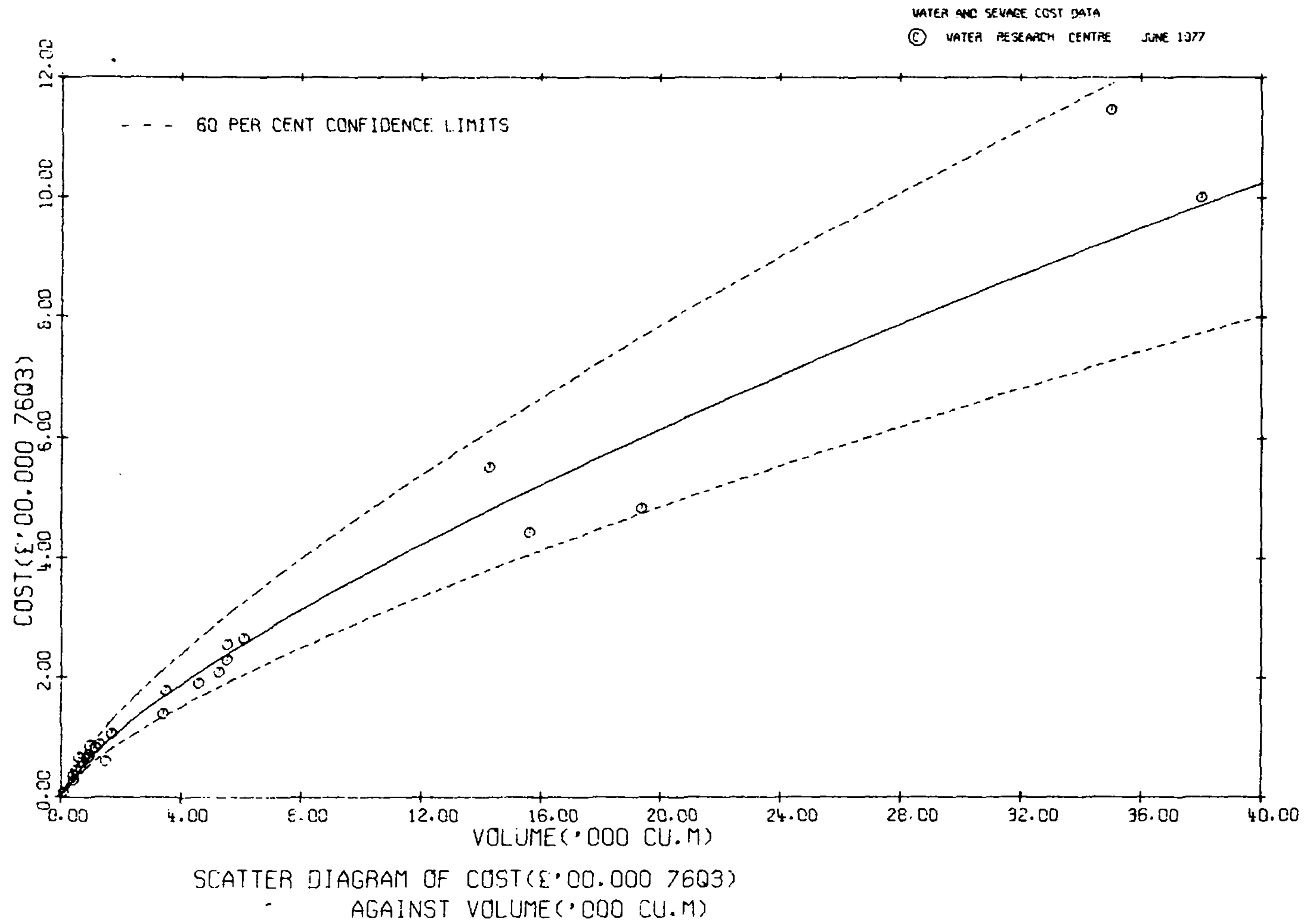
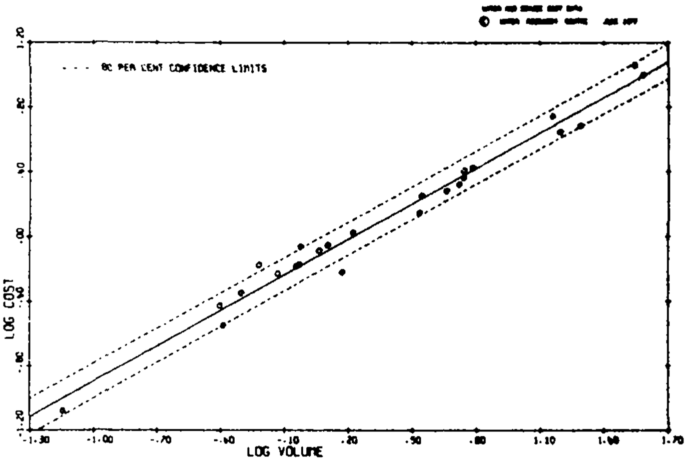


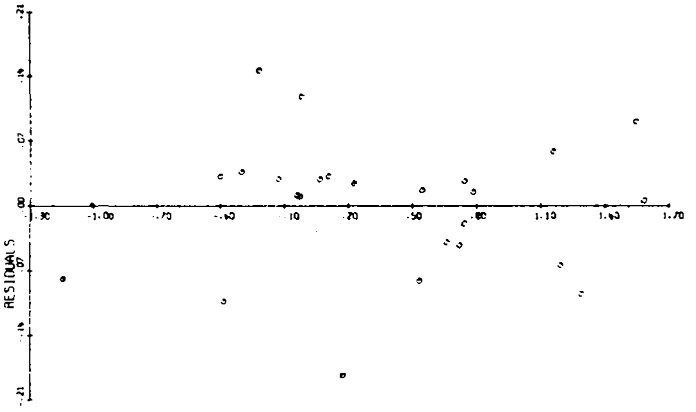
Figure 13-12. Rectangular tanks (civil engineering)

13.3.2. Rectangular tanks

Figure 13-13. Rectangular tanks (civil engineering)

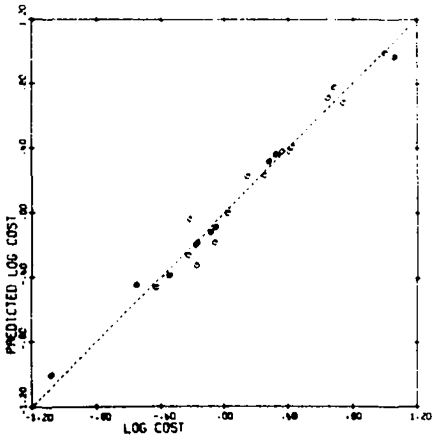


SCATTER DIAGRAM OF LOG COST
AGAINST LOG VOLUME



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG VOLUME

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - rectangular scrapers

(i) Data summary

Table 13-29. Rectangular scrapers data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Motorized bridge type (6 cases)						
Cost per scraper (corrected to 1976 Q3)	COST/SC	£'000	21.0	36.9	25.4	3.84
Width	WIDTH	m	14.5	20.0	16.6	2.08
Length	LEN	m	31.0	69.0	54.1	14.4
Number installed	NUM	-	1.0	4.0	3.17	1.05
Rope hauled type (4 cases)						
Cost per scraper (corrected to 1976 Q3)	COST/SC	£'000	4.57	7.56	6.64	1.13
Width	WIDTH	m	10.0	17.9	15.6	2.92
Length	LEN	m	20.0	58.0	43.4	16.3
Number installed	NUM	-	2.0	10.0	4.75	3.59

Note: The Engineering and Allied Industries Index was used for deflation.

(ii) The recommended cost function - motorized bridge type

The recommended function for motorized bridge type (for primary settlement tanks) is:-

$$\boxed{COST/SC = 25.4}$$

The statistical details of the function are as follows:-

Number of observations : 6
Standard error of residuals : 3.84

Approximate additive confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	19.7	31.1
95%	15.5	35.3

(iii) The recommended cost function - rope hauled type

The recommended function for rope hauled type (for storm tanks) is:-

$$\boxed{COST/SC = 6.64}$$

The statistical details of the function are as follows:-

Number of observations : 4
Standard error of residuals : 1.13

Approximate additive confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	4.79	8.49
95%	3.04	10.24

(iv) The data

The data is presented below in Table 13-30.

13.3.2. Rectangular tanks

Table 13-30. Rectangular scrapers data listing

Total raw cost (£'000)	Deflation factor	Length per scraper (m)	Width per scraper (m)	No. of scrapers	Type of scraper
6.70	2.05	20	10	3	Rope hauled
11.8	2.04	29	15	4	
40.0	1.89	58	17.9	10	
6.78	1.89	34.5	14	2	
26.6	2.04	45	15	2	Motorized bridge
18.8	1.97	45	16	1	
38.4	2.19	69	17.5	4	
45.3	2.08	31	14.5	4†	
58.4	1.95	61	20	4	
45.0	2.19	62	15.5	4	

† At this works four tanks were scraped by two scrapers spanning two tanks each.

13.3.3. PYRAMIDAL TANKS

A. The modelling approach

At one time, pyramidal tanks were specified for use in the majority of small rural works, both for primary sedimentation and as final separating or humus tanks. Recently, however, they have given way to scraped circular tanks.

Pyramidal tanks employed as primary sedimentation tanks may be designed with a maximum upward flow velocity of 1.2 m/h at 3 DWF (see Table 13.5). Somewhat higher loadings can be employed in final separating tanks, though the effluent is likely to deteriorate if loadings of greater than 1.5 m/h are employed (at 3 DWF).

Data was obtained from 10 BoQs for 14 installations of pyramidal tanks used for either primary or humus settlement. A preliminary examination of the data showed that the sample could be split into two groups. The smaller group (Type 2) consisted of cheaper tanks with the hoppers constructed with mesh reinforcement and constant thickness of concrete. The larger and more expensive group (Type 1) had the hopper walls constructed with bar reinforcement with a stepped profile.

Five explanatory variables for total cost were considered:-

(i) total plan area;
(ii) total volume available;
(iii) depth of vertical wall immediately above hopper;
(iv) the number of tanks constructed;
(v) the type of the tank(s).

The recommended cost function is based on total plan area and the type of tank. The New Construction Index was found more suitable for deflation than the DQSD, the Basic Weekly Wage Rate and the Construction Materials Indices.

13.3.3. Pyramidal tanks

B. The results

(i) Data summary

Table 13-31. Pyramidal tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total construction cost (corrected to 1976 Q3)	COST	£'000	5.88	27.1	15.6	7.14
Total plan area of tanks	AREA	m^2	13.3	67.2	38.7	15.6
Total volume of tanks	VOL	m^3	27.0	171	88.3	44.6
Type of tank	TYPE	-	1	2	1.29	0.469
Number of tanks	NTANK	-	1	2	1.71	0.469

Note:
1. Number of cases: 14.
2. The New Construction Index was used for deflation.
3. TYPE is 1 for cases where the hopper walls were constructed with bar reinforcement with stepped profile, and
   2 for cases where the hopper walls were constructed with mesh reinforcement and constant thickness of concrete.

(ii) The recommended cost function

The recommended function for pyramidal tanks is:-

$$\boxed{\text{COST} = 2.01*\text{AREA}^{0.61}*\text{TYPE}^{-1.19}}$$

The statistical details of the function are as follows:-

Number of observations : 14
Multiple correlation coefficient (R) : 0.96
Coefficient of determination (R^2) : 93%
Standard error of residuals (in $\log_{10}$ model) : 0.065

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.608	0.088	47.7	≪0.1%
TYPE	-1.19	0.128	85.9	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.82	1.23
95%	0.72	1.39

This model was developed at too late a stage for figures or a data listing to be included in the report.

13.3.4. HOLDING TANKS

A. The modelling approach

The sample of 18 circular tanks is split evenly between digesters and an assortment of tanks for storage, mixing and conditioning. All the tanks were without roofs and had low gradient floors. Only the cost of the civil engineering structure has been included. With the exception of stirrers, which vary from about 15 to 25% of the civil engineering cost depending upon the size of the tank, mechanical equipment is not normally installed.

Volume per tank and number of tanks constructed were included as explanatory variables; however, only volume was found to be significant.

B. The results

(i) Data summary

Table 13-32. Holding tanks data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Civil engineering cost per tank (corrected to 1976 Q3)	COST/TK	£'000	5.82	117	26.6	25.1
Volume per tank	VOL	'000 m^3	0.053	5.80	0.976	1.37
Number of tanks installed	NTANK	-	1	8	2.28	1.67

Note: 1. Number of cases: 18.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST/TK

LOG COST/TK

VOL

(ii) The recommended cost function

The recommended function for holding tanks (civil engineering) is:-

$$\boxed{COST/TK = 29.9*VOL^{0.52}}$$

The statistical details of the function are as follows:-

Number of observations	:	18
Correlation coefficient (R)	:	0.93
Coefficient of determination (R^2)	:	86%
Standard error of residuals	:	0.118

13.3.4. Holding tanks

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.521	0.052	98.7	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.70	1.44
95%	0.56	1.78

Figure 13-14 illustrates the recommended function.

(iii) The data

The holding tanks data is listed in Table A-43.

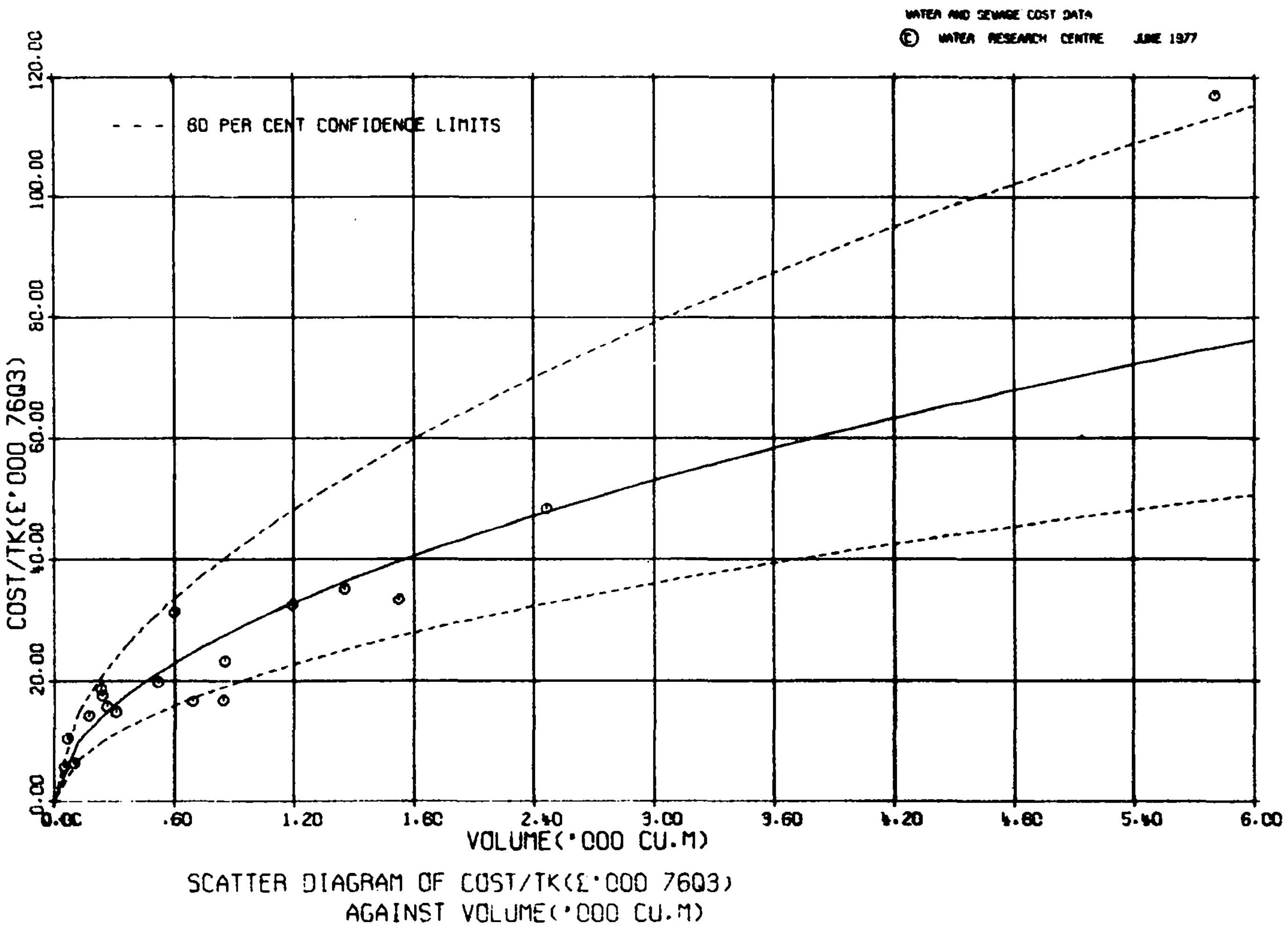


Figure 13-14. Holding tanks (civil engineering)

13.4. SEA OUTFALLS

A. The modelling approach

The sample of long sea outfalls consists of eleven constructed using the bottom towed pipe method and two using tunnel construction. At ten of the pipe outfalls, steel coated in a protective layer of reinforced concrete was used as the material of construction; the one exception used high density polythene. At one of the tunnel outfalls the sewage flowed through twin concrete pipes placed inside the tunnel and terminating at different offshore distances. At the other tunnel outfall this method of construction was used to circumvent the problems associated with high cliffs and deep water. Only the towed pipe data was used in developing the cost function.

The total cost of a scheme covers the insurance, supply of plant and materials, installation and reinstatement of the assembly area, but excludes the pipeline survey. A cost function was developed for the towed pipe outfalls with length and internal diameter of the structural pipe as explanatory variables. There was some evidence to suggest that costs were also affected by the conditions in the assembly area and by the availability of equipment, but these could not be incorporated in the model.

The cost of the twin pipe tunnel outfall was found to lie within the upper 80% confidence limit on the estimate made using the towed pipe model. The cost of the other tunnel outfall, however, was significantly higher than the corresponding towed pipe estimate.

The flow velocity in a sea outfall is limited both in its maximum and its minimum value. It is common practice to design for a maximum velocity of about 2 m/s, but smaller velocities may be necessary if the pressure head at the inlet is limiting. Table 13-33 shows the maximum design velocity and the estimated head loss for a number of existing outfalls, some of which are included in the data sample. The limitation on the minimum flow is controlled by the onset of particulate deposition at approximately 0.3 m/s. Should deposition occur, cleansing is possible in practice by the shearing action at a high velocity.

The length of an outfall is determined by the local marine conditions causing dispersion, and by the volumetric flowrate of sewage.

Table 13-33. Flow and head loss in long sea outfalls

Internal diam. of structural pipe (mm)	Length of outfall (km)	Maximum flow ('000 m^3/d)	Velocity at maximum flow (m/s)	Estimated head loss at max. flow (m)
426	1.43	15.4	1.25	7.5
686	2.88	34.4	1.08	7.3
762	1.26	49.2	1.25	3.8
686	0.828	66.0	2.07	7.8
900	4.95	95.0	1.73	23.2
1035	2.75	112	1.54	8.5
1067	3.35	136	1.76	12.9
1090	0.671	171	2.12	3.8
1500	1.15	187	1.22	1.5
2130†	1.83	340	1.10	1.3

Note:
1. Head loss includes both frictional and kinetic components, calculated assuming a wall roughness of 3 mm.
2. The largest outfall (†) is of tunnel construction.

B. The results

(i) Data summary

Table 13-34. Sea outfall data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost (corrected to 1976 Q3)	COST	£'000	185	2720	1210	869
Internal diameter of structural pipe	DIAM	mm	610	1090	815	191
Length of outfall	LEN	km	0.494	4.95	2.00	1.39
Omnibus 19 (see Section 8.3.3)	Z19	-	0.298	5.86	2.19	1.97

Note: 1. Number of cases: 11.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

COST

LOG COST

DIAM

LEN

(ii) The recommended cost function

The recommended function for sea outfalls is:-

$$\boxed{COST = 0.0272*DIAM^{1.50}*LEN^{0.86}}$$

The statistical details of the function are as follows:-

Number of observations : 11
Multiple correlation coefficient (R) : 0.95
Coefficient of determination (R^2) : 91%
Standard error of residuals (in $\log_{10}$ model) : 0.126

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DIAM	1.50	0.404	13.8	<1.0%
LEN	0.864	0.127	46.3	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.67	1.50
95%	0.51	1.95

The omnibus variable is given by:-

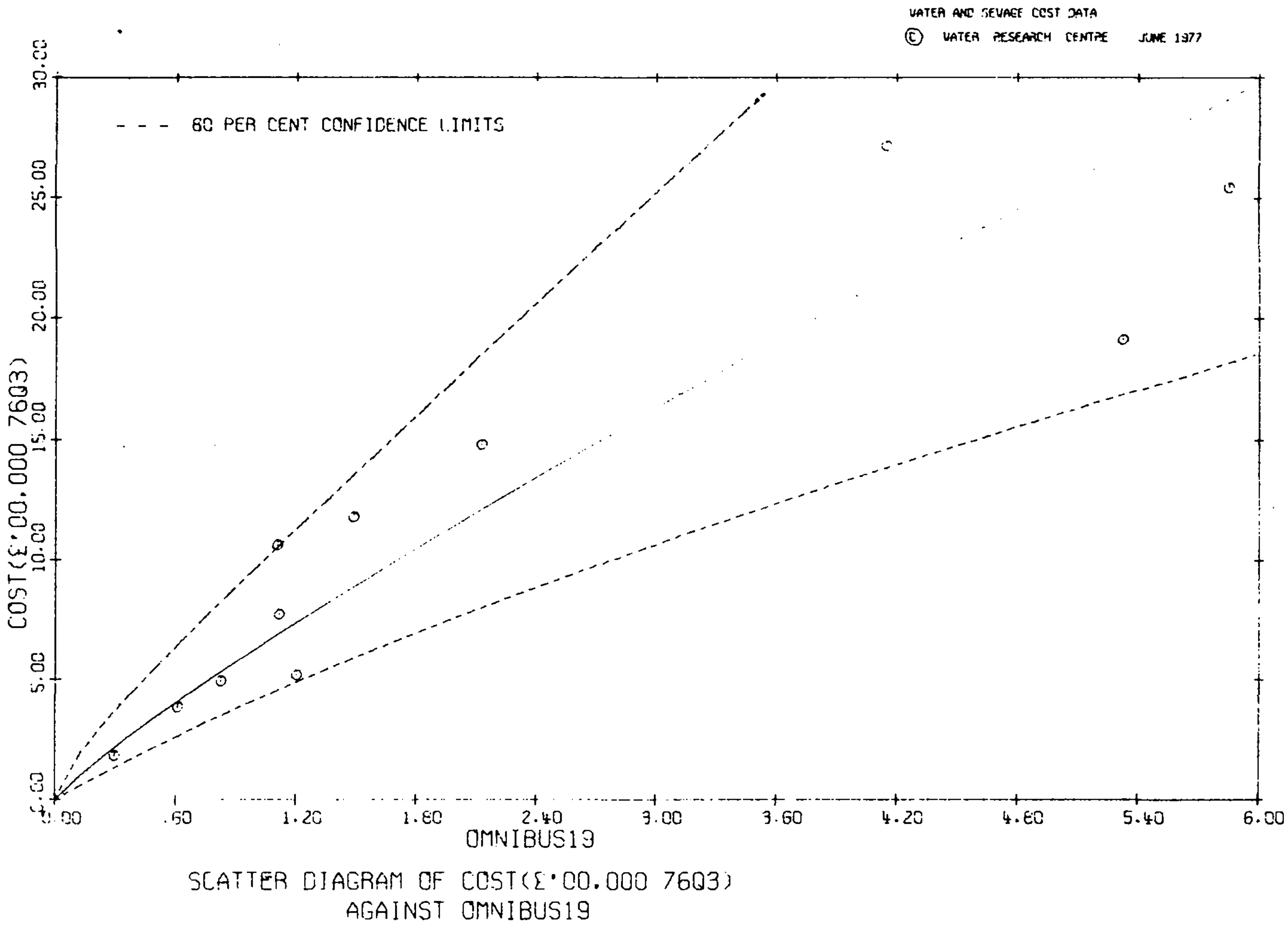
$$Z19 = 0.00000880*LEN*DIAM^{1.74}.$$

Figure 13-15 illustrates the recommended function.

(iii) The data

The sea outfalls data is listed in Table A-44.

Figure 13-15. Sea outfalls



13.5. SECONDARY BIOLOGICAL TREATMENT

The two conventional forms of secondary biological treatment are considered: biological filters, and activated sludge. Both systems can be designed and operated to produce effluents of various standards after subsequent treatment, for example 30/20 to 10/10/10 or even better. However, as the design criteria for nitrifying biological filters are not well established the performance relationships given for these systems have been restricted to the 30/20 standard. Simplified performance criteria for nitrifying and non-nitrifying activated sludge plants receiving balanced and non-balanced flow are also given.

13.5.1. BIOLOGICAL FILTERS

A. The modelling approach

In a conventional biological filter, settled sewage is uniformly distributed over the surface of a bed of filter media. This is contained within a retaining structure and supported on a floor which drains the media and also provides ventilation. For filters up to 30 m diameter distributors are normally of the type known as full bridge, in which four tubular radial arms each with jets are supported at a central pivot and suspended by a pyramid of guy wires. The reaction of settled sewage discharged at the jets provides motive power. Larger distributors (up to 50 m diameter) often consist of only one radial arm, termed a half bridge. The arm in this case is supported at a central pivot and on a peripheral rail or coping; propulsion is often provided by a motor drive.

Three models have been developed: one for civil engineering (including both the floor and the walls), one for mechanical engineering associated with the distributor, and one for the filter media. The civil and mechanical models are for cost per filter; the media model is in terms of cost per cubic metre of media. All the data relates to circular filters as no information was collected on rectangular filters in the survey.

For the civil engineering model two explanatory variables were considered: volume contained by the structure, and number of filters installed at each site. It was found that cost per filter was unrelated to number of filters (i.e. there is no economy of scale).

The sample for the distributors model covered only full bridge distributors. Diameter and number of units were taken as explanatory variables; again, number of units was insignificant.

Three factors might be expected to influence media cost per unit volume: the volume of media supplied, the type (crushed rock, stone, blast furnace slag, etc.), and the delivery distance from supplier to site. Of these, however, only volume was available from the BoQs and this was found not to influence cost significantly. The media model is therefore simply an average cost per m^3.

B. The results - civil engineering

(i) Data summary

Table 13-35. Biological filters (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Civil engineering cost per filter (corrected to 1976 Q3)	CIVCOS/ FIL	£'000	3.00	44.0	20.5	11.6
Mean diameter of filters in structure	DIAM	m	7.00	39.0	24.4	8.20
Mean volume of filters in structure	VOL	'000 m^3	0.070	2.19	0.949	0.559
Number of filters installed at site	NFIL	-	1	8	3.56	2.22

Note: 1. Number of cases: 25.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-

CIVCOS/FIL

LOG CIVCOS/FIL

VOL

(ii) The recommended cost function

The recommended function for biological filters civil engineering is:-

$$\boxed{CIVCOS/FIL = 21.1*VOL^{0.73}}$$

The statistical details of the function are as follows:-

Number of observations	:	25
Correlation coefficient (R)	:	0.91
Coefficient of determination (R^2)	:	83%
Standard error of residuals (in $\log_{10}$ model)	:	0.124

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
VOL	0.729	0.070	110	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.69	1.46
95%	0.55	1.81

Figures 13-16 and 13-17 show the five standard diagrams in support of the function.

(iii) The data

The civil engineering data is listed in Table A-45.

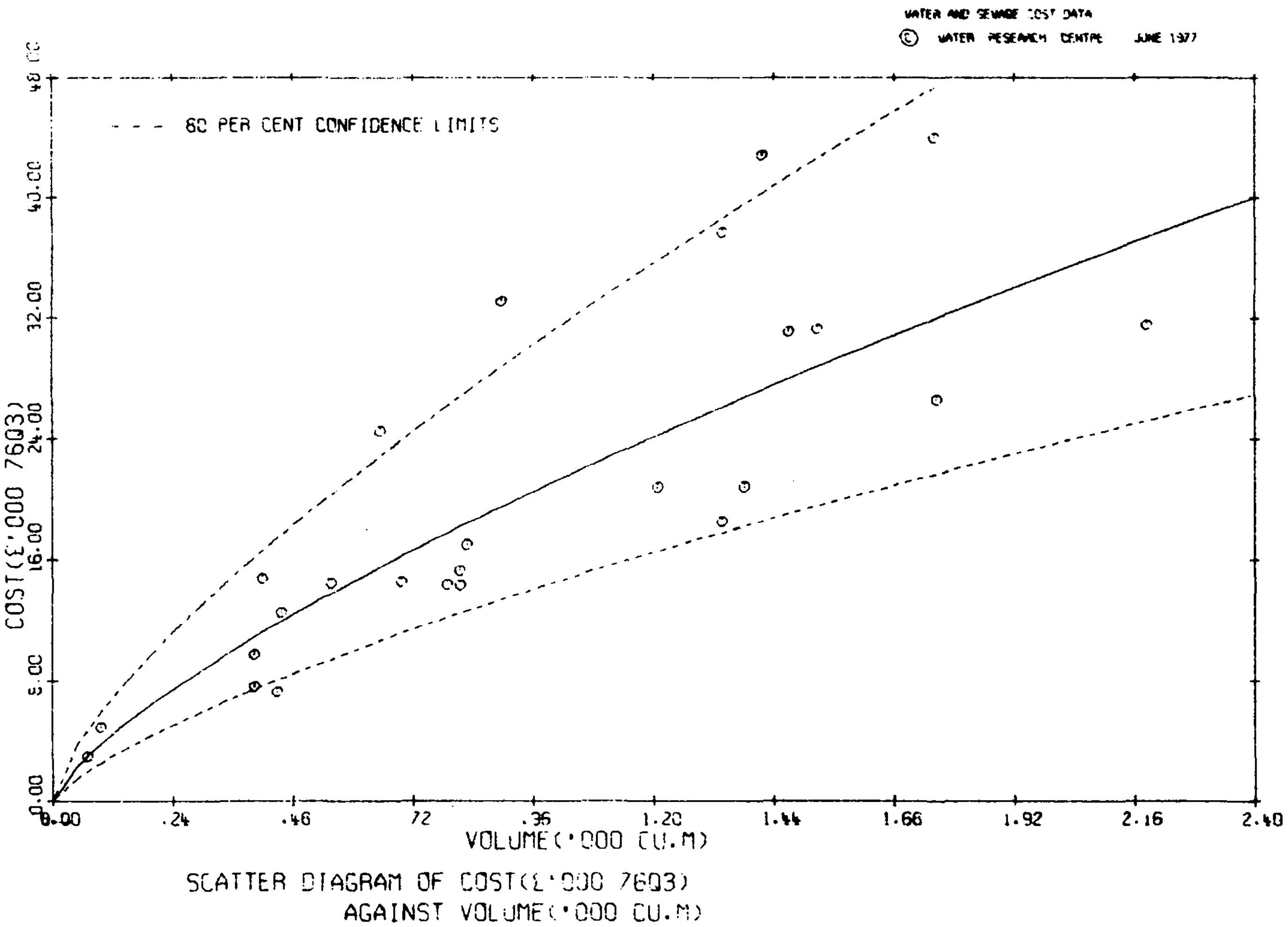
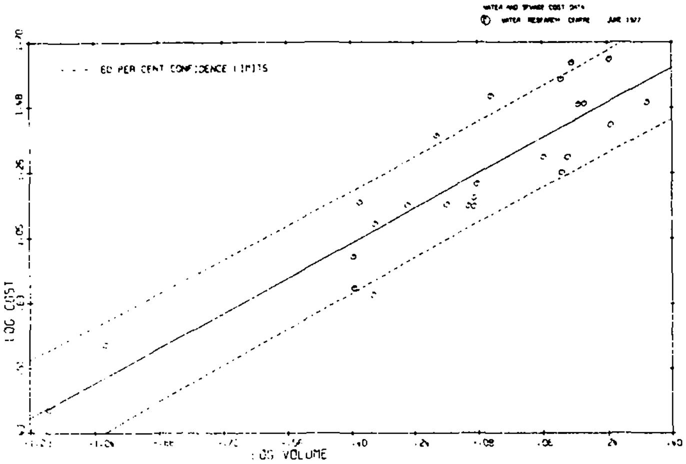


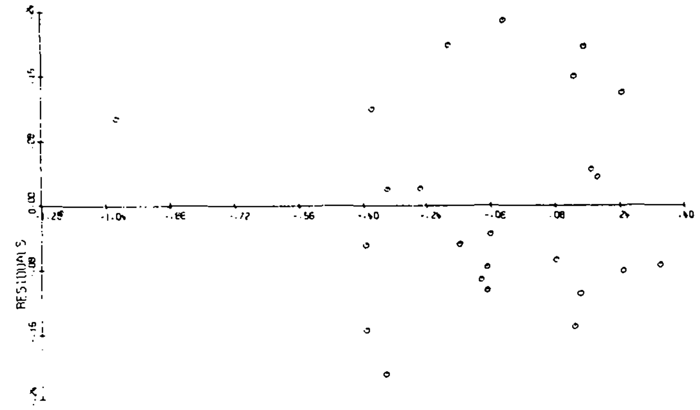
Figure 13-16. Biological filters (civil engineering)

13.5.1. Biological filters

Figure 13-17. Biological filters (civil engineering)

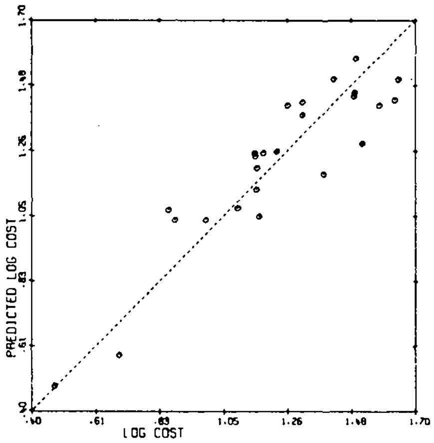


SCATTER DIAGRAM OF LOG COST
AGAINST LOG VOLUME



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG VOLUME

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - full bridge distributors

(i) Data summary

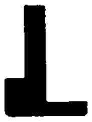
Table 13-36. Full bridge distributors data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost per distributor (corrected to 1976 Q3)	COST/DIS	£'000	1.27	5.40	2.92	1.05
Mean diameter of filters in structure	DIAM	m	8.20	34.9	21.2	7.53
Number of units installed	NDIS	-	1	8	3.00	1.96

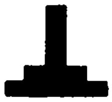
Note: 1. Number of cases: 13.

2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-



COST/DIS



LOG COST/DIS

DIAM

(ii) The recommended cost function

The recommended function for full bridge distributors is:-

$$\boxed{\mathrm{COST/DIS} = 0.235*\mathrm{DIAM}^{0.82}}$$

The statistical details of the function are as follows:-

Number of observations : 13

Correlation coefficient (R) : 0.90

Coefficient of determination (R^2) : 81%

Standard error of residuals (in $\log_{10}$ model) : 0.072

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DIAM	0.823	0.12	47.6	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.80	1.25
95%	0.69	1.44

Figure 13-18 illustrates the recommended function.

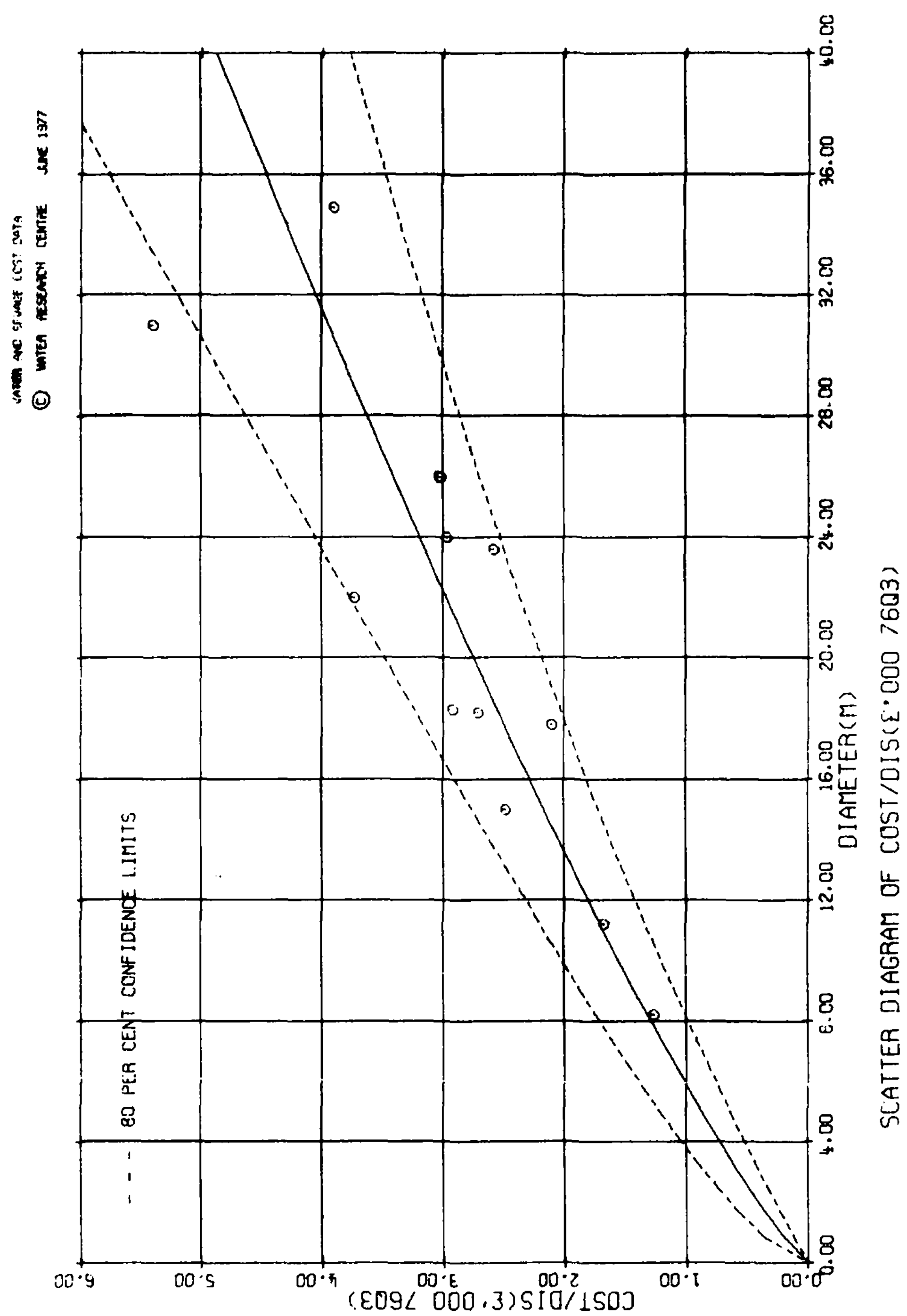
For some purposes it will be convenient for the cost of distributors to be expressed in terms of filter volume rather than diameter, and as most conventional filters are 1.83 m deep (i.e. six feet), the recommended cost function may be rewritten:-

$$\boxed{\mathrm{COST/DIS} = 0.202 * \mathrm{VOL}^{0.41}}$$

(iii) <u>The data</u>

The full bridge distributor data is listed in Table A-46.

Figure 13-18. Full bridge distributors



D. The results - biological filter media

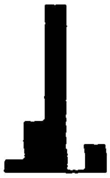
(i) Data summary

Table 13-37. Biological filter media data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost per m^3 of filter media (corrected to 1976 Q3)	COST/ VOL	£/m^3	7.83	19.2	12.4	2.71
Volume of media	VOL	m^3	77	17 000	4400	4560

Note:
1. Number of cases: 20.
2. The Engineering and Allied Industries Index was used for deflation.
3. Because of wastage, VOL is sometimes as much as 10% greater than total filter volume.

Mini-histogram:-



COST/VOL

(ii) The recommended cost function

The recommended function for biological filter media is:-

$$\boxed{COST/VOL = 12.4}$$

The statistical details of the function are as follows:-

Number of observations : 20

Standard error of residuals : 2.71

Approximate additive confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	8.80	16.00
95%	6.73	18.07

(iii) The data

The biological filter media data is listed in Table A-47.

13.5.2. ACTIVATED SLUDGE

A. The modelling approach

The civil engineering costs for mixed liquor aeration tanks do not differ substantially from those for other rectangular tanks, namely storm sewage tanks and primary sedimentation tanks, and the cost function developed in Section 13.3.2 is suitable for all three types of rectangular tank. This section is concerned solely with the mechanical equipment used for contacting settled sewage with activated sludge in the presence of dissolved oxygen transferred from the atmosphere. Of the many commercial designs available the present data sample is limited to:-

(i) the fine bubble diffused air (FBDA) system, in which air is injected into the liquor through porous diffusers;

(ii) the cone surface aeration system, in which the liquor is agitated at the surface.

These two systems are the most common in use and are probably representative both in cost and performance.

The FBDA systems studied consisted of aeration tank floor equipment, air main and blower house equipment. For works with an installed duty power greater than 100 kW, automatic control was installed consisting of either positive displacement blowers with DC motors or variable vane compressors with induction motors and dissolved oxygen measuring and recording equipment. Standby compression capacity was also installed; this varied from 33 to 100% of the duty capacity, depending upon the size of the works.

The surface aeration systems consisted of cones with supports, motors and gearboxes. At the works with an installed power less than 130 kW, the power consumption was controlled by manually adjustable weir plates located at the outlets of the aeration tanks. At the largest works the weir plates were automatically adjusted.

For both systems, cost covers the supply, erection and wiring of complete aeration plant, and the return sludge screw pumps.

At works which employ the activated sludge process, the major proportion of the total energy requirement is consumed by the aeration equipment. Where this power is taken from the grid supply it represents a large fraction of the operating costs for the works. It is therefore important to discuss the performance relationships and the method of specifying the size of the mechanical equipment in some detail.

The performance of aeration equipment may be characterized by the oxygenation capacity, this being the rate of oxygen transferred per unit volume (of aeration tank), and by the oxygenation efficiency, which is the rate transferred per unit power. In this study the oxygenation capacity has a sufficiently high value for most conventional equipment operating under normal conditions, and so needs no further consideration. The value of the oxygen efficiency can be highly sensitive to the presence of detergents or other surface active agents in the liquid. It is therefore common practice to make measurements in clean de-oxygenated water and in mixed liquor or its equivalent. These values are compared for the two aeration systems in Table 13-38 below.

Table 13-38. Typical oxygenation efficiency values for two aeration systems

Aeration system	Oxygenation efficiency in clean de-oxygenated water (kg of O_2/kWh)		Variation in value of α† over aeration channels	Oxygenation efficiency in mixed liquor (kg of O_2/kWh)	
	Absorbed energy	Line energy (at max. design load)		Optimum conditions	Practical conditions
Fine bubble diffused air (FBDA)	5.5	4.0	0.3 - 0.8	2.2	1.8 - 2.0
Cone aerators	-	2.0	1.1 - 1.2	2.2	1.8 - 2.0

† α = ratio of efficiencies in clean water and mixed liquor.

The comparison shows that the high clean water efficiency of the FBDA system is not realized in practice owing to the low value of α. Under optimum practical operating conditions the oxygenation efficiency for both systems is about 2.2 kg of O_2/kWh, but through general deterioration and possibly non-optimum tank design, the value attained at many works is about 1.8 to 2.0 kg of O_2/kWh.

13.5.2. Activated sludge

The power of the aeration equipment may be related to the BOD removal rate, given the ratio between oxygen consumed and BOD removed. This ratio is controlled by the biological reaction, and typical values for conventional sludge loading rates are given in Table 13-39 for works with and without nitrification and flow balancing. However, these values are not applicable for non-conventional treatment such as extended and high-rate aeration, when the ratio must be determined from the plant operating conditions. For works without diurnal flow balancing, the installed power must be able to cope with the maximum aeration demand (usually occurring in mid-afternoon) and so its value will be greater than the daily average requirement. Table 13-39 shows that the installed duty power per kg of BOD removed per hour, calculated at the average daily BOD loading, varies depending upon the uniformity of the BOD loading from 0.55 to 0.76 kW for non-nitrifying works, and from 1.2 to 1.6 kW for nitrifying works. In practice, installed power will sometimes fall outside these limits because of special operating conditions such as high or low sludge loadings, or to provide capacity for future extensions.

Table 13-39. Installed power required for BOD removal and nitrification

		Type of works			
		Conventional, with no flow balancing		With flow balancing	
		Non-nitrifying	Nitrifying	Non-nitrifying	Nitrifying
	Average sludge loading (kg/kg of MLSS.d)	0.25	0.15	0.25	0.15
	Maximum BOD removal rate divided by average removal rate	1.3 - 2.0	1.1 - 1.7	1.0	1.0
Estimated at maximum loading	Mass of oxygen consumed in BOD removal (kg of O_2/kg of BOD)	0.9 - 0.7	1.4 - 1.0	1.1	1.5
	Mass of oxygen consumed in ammoniacal nitrogen oxidization (kg of O_2/kg of N_2)	0	4.3	0	4.3
	Total mass of oxygen consumed per unit mass of BOD removed (kg of O_2/kg of BOD)†	0.9 - 0.7	1.9 - 1.6	1.1	2.0
	Average dissolved oxygen concentration (% of saturation)	0	10	0	10
	Installed duty power per unit mass of BOD removed (kW/(kg of BOD removed per h))††	0.47 - 0.38	1.1 - 0.92	0.55	1.2
	Installed duty power per unit mass of BOD removed at average daily loading (kW/(kg of BOD removed per h))	0.61 - 0.76	1.2 - 1.6	0.55	1.2

† Assuming concentration reduction of BOD = 200 mg/l,
concentration reduction of ammoniacal nitrogen = 25 mg/l.

†† Oxygenation efficiency = 1.9 kg of O_2/kWh.

B. The results

(i) Data summary

Table 13-40. Aeration equipment data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Cost (corrected to 1976 Q3)	COST	£'000	32.8	1150	266	304
Installed duty power for both types of equipment	POWER	kW	30.0	1080	266	339
Installed power for surface aeration equipment (9 cases)	-	kW	30.0	480	107	144
Installed duty power for diffused air aeration equipment (7 cases)	-	kW	90.0	1080	469	386
Type of aeration equipment	TYPE	-	1	2	1.44	0.512

Note:
1. Number of cases: 16.
2. The Engineering and Allied Industries Index was used for deflation.
3. TYPE is 1 for surface aeration equipment, and
   2 for diffused air aeration equipment.

Mini-histograms for the main variables of interest:-

COST

LOG COST

POWER

(ii) The recommended cost function

The recommended function for aeration equipment is:-

$$\boxed{\mathrm{COST} = 2.21*\mathrm{POWER}^{0.87}}$$

The statistical details of the function are as follows:-

Number of observations	:	16
Correlation coefficient (R)	:	0.96
Coefficient of determination (R^2)	:	93%
Standard error of residuals (in $\log_{10}$ model)	:	0.128

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
POWER	0.868	0.063	188	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

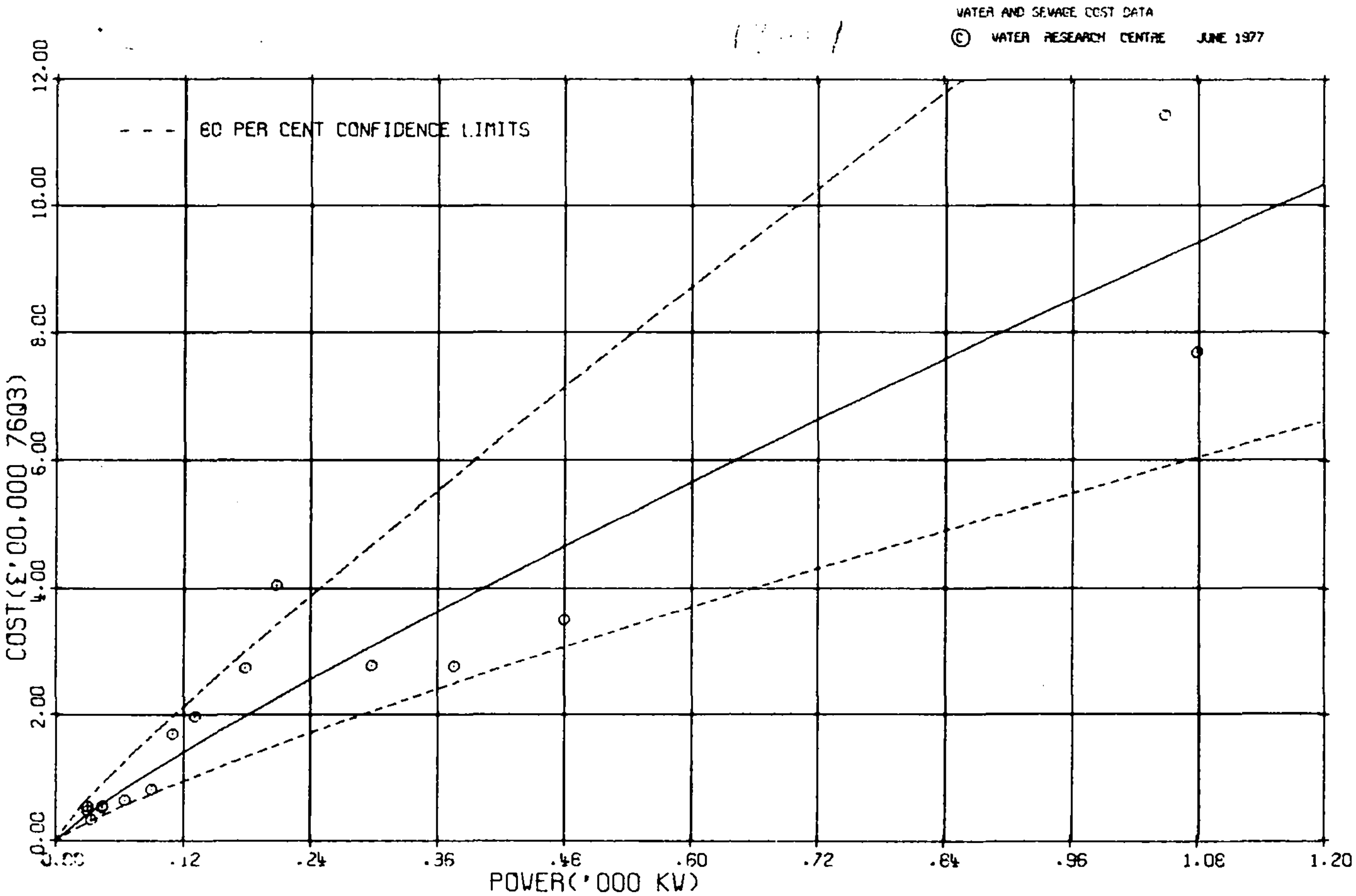
Confidence level	Lower	Upper
80%	0.67	1.49
95%	0.53	1.88

Figure 13-19 illustrates the recommended function.

(iii) The data

The aeration equipment data is listed in Table A-48.

Figure 13-19. Aeration equipment



SCATTER DIAGRAM OF COST(£'00.000 76Q3)
AGAINST POWER('000 KW)

13.6. TERTIARY TREATMENT

Several tertiary treatment processes may be used for improving the quality of settled effluent following secondary biological treatment, for example lagoons, microstrainers, pebble bed clarifiers, rapid sand filters and slow sand filters. Pebble bed clarifiers are often specified for small rural works and microstrainers for medium sized plants, but where tertiary treatment is required in large works the current practice is to employ either rapid gravity flow or upflow sand filters.

Only a minority of sewage treatment works are equipped with tertiary treatment plant; consequently very little data could be collected. However, rapid sand filters and microstrainers are frequently used in water treatment, and the cost information given in the sections concerned with intake plant (12.2.2) and gravity filtration (12.3.3) may be used.

13.7. SLUDGE PROCESSES

13.7.1. LAGOONS

Lagoons can be used for sludge treatment or storage. The treatment process consists of anaerobic digestion for at least two years, during which time the destruction of up to 35% of the total solids occurs. In the initial period the sludge thickens so that substantial quantities of supernatant liquor can be removed. Data for only a few sludge treatment lagoons was available, but the information given in Section 12.5.2 may be used for cost estimating.

13.7.2. MESOPHILIC DIGESTION

A. The modelling approach

The total cost of digestion was subdivided into civil engineering and mechanical engineering. Further subdivisions could have been defined, but it would not have been possible to develop useful models for these categories from the limited data available.

Total cost, civil engineering cost and mechanical engineering cost were obtained for 26 cases covering the period 1962 to 1975. All cases were mesophilic digesters, and none was insulated by earth banks. Both fixed and floating roof digesters were represented in the sample.

The civil engineering costs include all primary digestion tanks (walls, floors, foundations and roof if this is fixed), heater/pumphouse, pipework associated with these units, and drains. Costs do not include allowance for general siteworks, clearance and levelling, construction of roads, paths, fences, administration, laboratory and workshop buildings. The costs should be viewed as those of a mesophilic digestion plant in isolation on a good site. The New Construction Index was used for deflation.

The mechanical engineering costs include pumps, heat exchangers, boilers, floating roofs or surplus gas holder and burner and all control gear. The Engineering and Allied Industries Index was used for deflation.

Each scheme was characterized by:-

(i) the volume of each individual tank;
(ii) the number of tanks in the complex;
(iii) the type of digester - fixed or floating roof.

Models were developed separately for total, civil and mechanical cost using the above explanatory variables. It was found that digester type was not significant.

B. The results - mesophilic digesters (total cost)

(i) Data summary

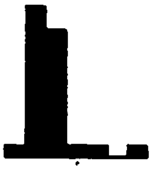
Table 13-41. Mesophilic digesters data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total cost (corrected to 1976 Q3)	TOTCOS	£'000	51.5	1060	298	213
Omnibus 20†	Z20	-	0.255	18.8	2.32	3.68
Civil engineering cost (corrected to 1976 Q3)	CIVCOS	£'000	31.1	456	142	91.6
Omnibus 22†	Z22	-	0.303	14.5	2.10	2.83
Mechanical engineering cost (corrected to 1976 Q3)	MECCOS	£'000	20.4	599	156	127
Omnibus 21†	Z21	-	0.205	26.3	2.70	5.13
Volume of each tank	VOL	'000 m^3	0.495	5.15	1.70	1.07
Number of tanks in the facility	NTANK	-	1	4	1.73	0.78

† See Section 8.3.3.

Note:
1. Number of cases: 26.
2. The New Construction Index was used for deflating civil engineering costs.
3. The Engineering and Allied Industries Index was used for deflating mechanical engineering costs.

Mini-histograms for the main variables of interest:-

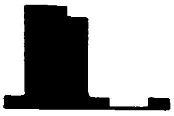


TOTCOS

LOG TOTCOS

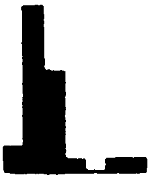
VOL

NTANK



CIVCOS

LOG CIVCOS



MECCOS

LOG MECCOS

(ii) The recommended cost function

The recommended function for mesophilic digesters total cost is:-

$$\boxed{TOTCOS = 131*VOL^{0.58}*NTANK^{0.89}}$$

The statistical details of the function are as follows:-

Number of observations : 26
Multiple correlation coefficient (R) : 0.93
Coefficient of determination (R^2) : 86%
Standard error of residuals (in $\log_{10}$ model) : 0.112

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
NTANK	0.895	0.132	45.8	<<0.1%
VOL	0.579	0.095	37.0	<<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.71	1.40
95%	0.59	1.70

The omnibus variable is defined as:-

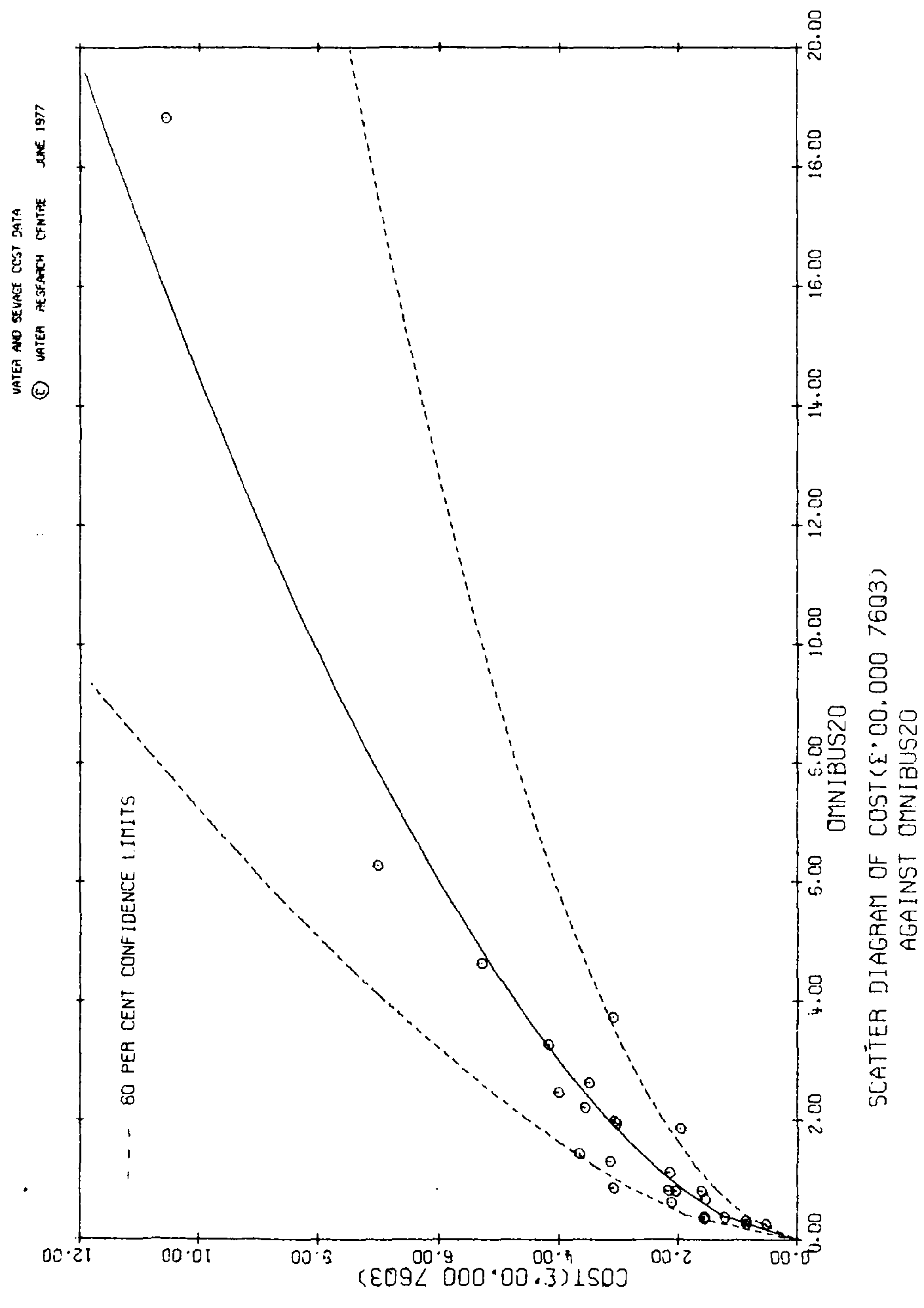
$$Z20 = 0.429*VOL*NTANK^{1.55}.$$

Figures 13-20 and 13-21 show the five standard diagrams in support of the function.

(iii) The data

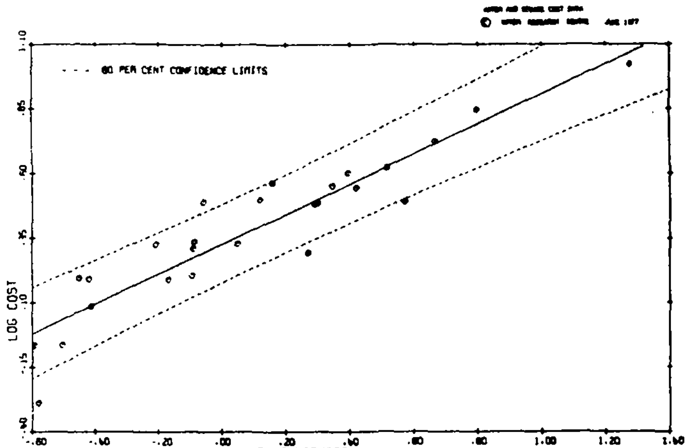
The mesophilic digesters total cost data is listed in Table A-49.

Figure 13-20. Mesophilic digesters (total cost)

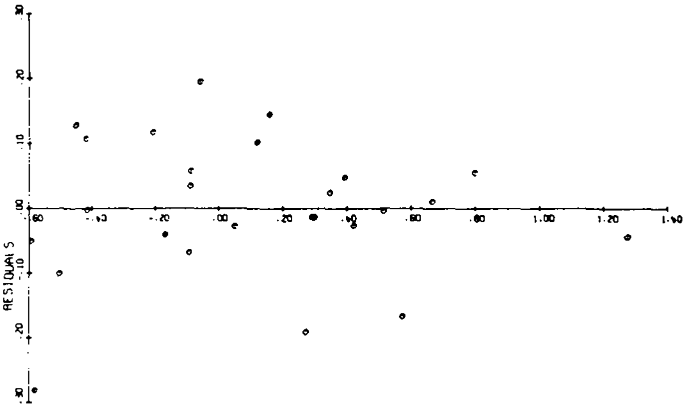


13.7.2. Mesophilic digestion

Figure 13-21. Mesophilic digesters (total cost)

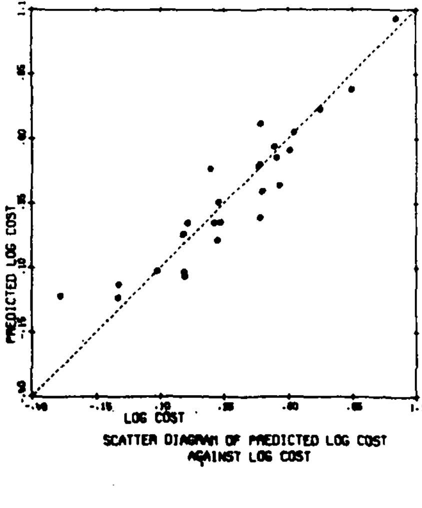


SCATTER DIAGRAM OF LOG COST
AGAINST LOG OMNIBUS20



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG OMNIBUS20

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

13.7.2. Mesophilic digestion

C. The results - mesophilic digesters (civil engineering)

(i) Data summary

See Table 13-41.

(ii) The recommended cost function

The recommended function for mesophilic digesters civil engineering cost is:-

$$\boxed{CIVCOS = 65.7*VOL^{0.63}*NTANK^{0.77}}$$

The statistical details of the function are as follows:-

Number of observations	:	26
Multiple correlation coefficient (R)	:	0.91
Coefficient of determination (R^2)	:	82%
Standard error of residuals (in $\log_{10}$ model)	:	0.127

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
NTANK	0.770	0.150	26.5	≪0.1%
VOL	0.625	0.108	33.7	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.68	1.47
95%	0.55	1.83

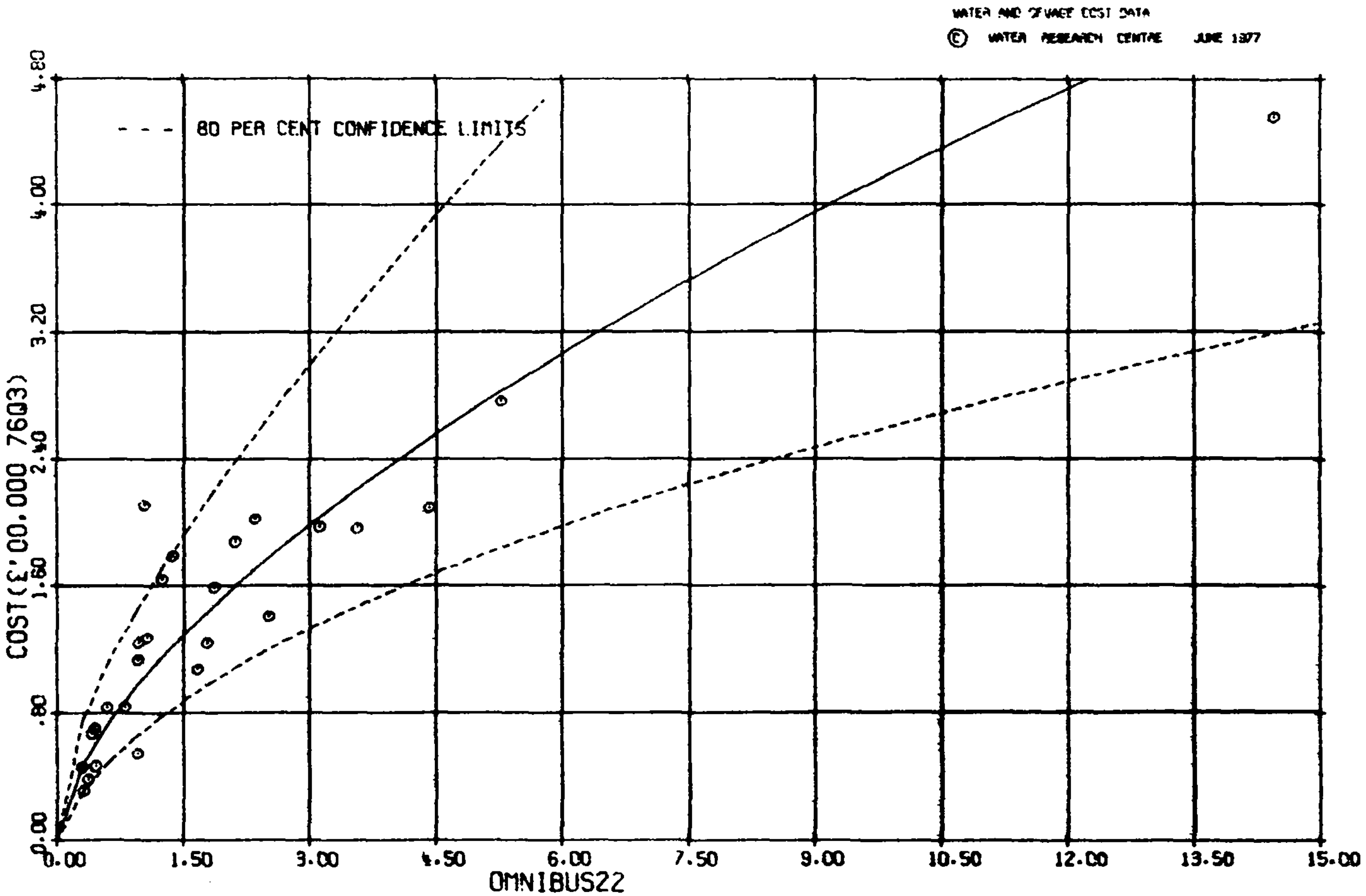
The omnibus variable is defined as:-

$$Z22 = 0.509*VOL*NTANK^{1.23}.$$

Figure 13-22 illustrates the recommended function.

(iii) The data

The mesophilic digester civil engineering data is listed in Table A-50.



SCATTER DIAGRAM OF COST(£'00,000 7603)
AGAINST OMNIBUS22

Figure 13-22. Mesophilic digesters (civil engineering)

D. The results - mesophilic digesters (mechanical engineering)

(i) Data summary

See Table 13-41.

(ii) The recommended cost function

The recommended function for mesophilic digesters mechanical engineering cost is:-

$$\boxed{MECCOS = 62.6*VOL^{0.53}*NTANK^{1.03}}$$

The statistical details of the function are as follows:-

Number of observations	:	26
Multiple correlation coefficient (R)	:	0.88
Coefficient of determination (R^2)	:	78%
Standard error of residuals (in $\log_{10}$ model)	:	0.154

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
NTANK	1.03	0.181	32.0	≪0.1%
VOL	0.527	0.131	16.3	<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.63	1.59
95%	0.48	2.08

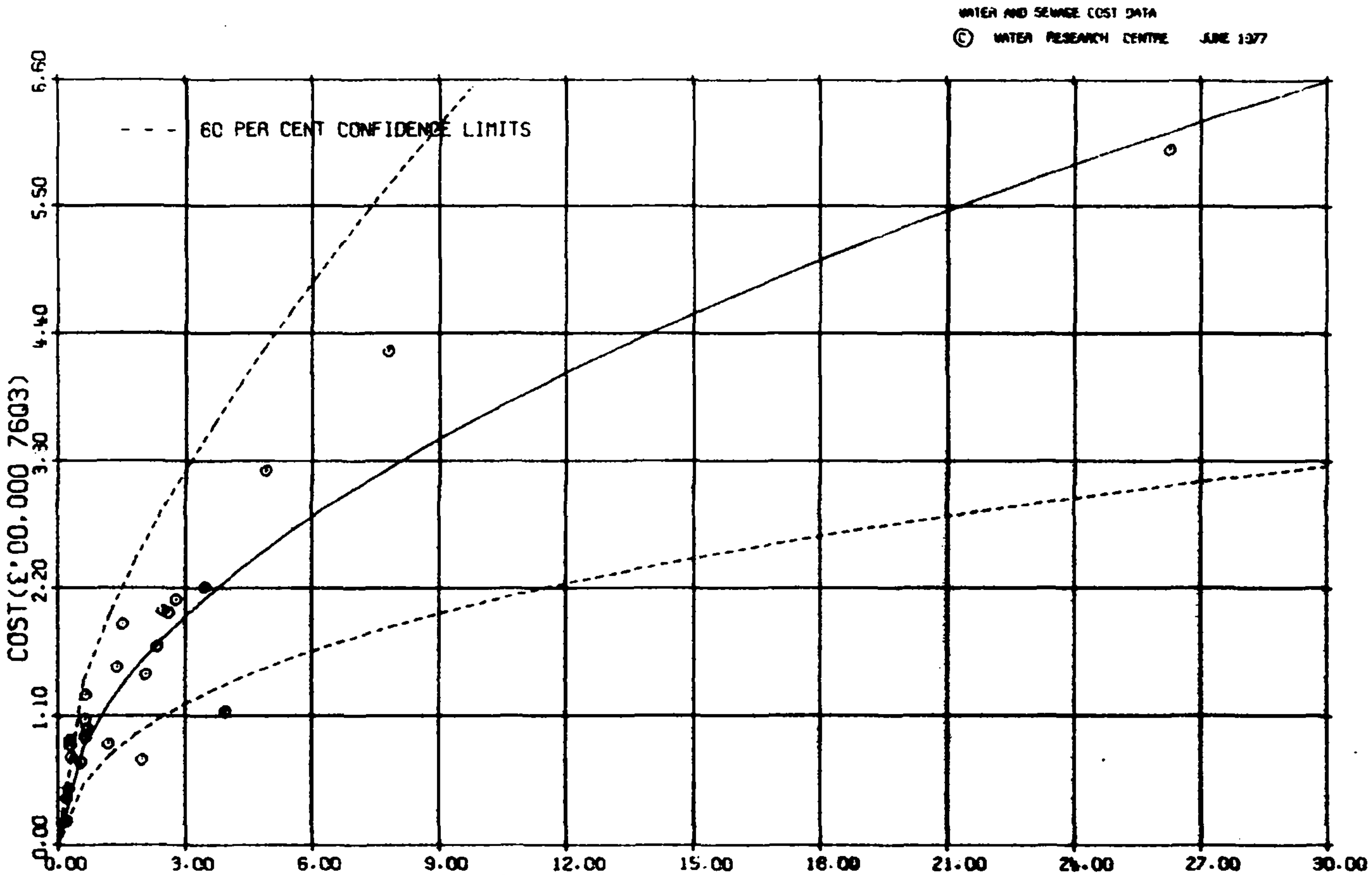
The omnibus variable is defined as:-

$$Z21 = 0.344*VOL*NTANK^{1.95}.$$

Figure 13-23 illustrates the recommended function.

(iii) The data

The mesophilic digesters mechanical engineering data is listed in Table A-51.



SCATTER DIAGRAM OF COST(£'00.000 76Q3)
AGAINST OMNIBUS21

Figure 13-23. Mesophilic digestors (mechanical engineering)

13.7.3. FILTER PLATE PRESSES

A. General

For filter plate press installations comprising the presses with associated mechanical equipment and a protective housing, two cost functions have been developed: one for civil plant, and one for mechanical equipment. In both cases, costs have been related to filtration area.

The area of filter surface required at a particular works depends on a variety of factors, some of which are influenced by conditions peculiar to the works in question. A simplified model of the performance relationship for filter plate presses is given below. This relates the capacity of a press installation measured in terms of the population, P ('000), to the filtration area, A ('000 m^2), as follows:-

$$P*k = \frac{A*t*\rho*(W/100)*N*Y*(1 - D/100)}{2*S(1 + C/100)} ,$$

where k = ratio of the actual production of dry solids to the production from the domestic population,

t = width of press chambers (m),

ρ = density of cake (Mg/m^3),

W = weight % of solids in cake,

C = % ratio of conditioner to dry solids,

N = number of pressings per week per press,

Y = working weeks per year,

D = downtime (%),

and S = annual production of dry solids per capita for a domestic population (Mg/(year)(head)).

Evaluation of this equation is not straightforward owing to the considerable variability of some of the components of the equation. The value for W is usually in the range 30 to 35%, at which concentration the cake is both dimensionally stable (essential if tipping is used as the disposal method) and probably autothermic (desirable for incineration). The dosage of conditioner can vary from approximately 0.1 to 50% depending upon its type and the performance required. Recent trends have favoured the use of polyelectrolyte and aluminium chlorohydrate for which the dosage is usually less than 2% - a negligible addition to the solids loading. At most installations the width of the press chamber is 0.032 m, although 0.025 m chambers are in use, especially where a high cake solids is required or where the sludge is difficult to condition.

The values of the variables given in Table 13-42 represent the performance that should be attainable at most installations treating both primary and secondary sludges. For these values the performance relationship simplifies to:-

$$P*k = 1890*A/N.$$

For a purely domestic population the value of k would be unity, but commonly it is approximately equal to two, and may be as high as five in industrialised areas.

Table 13-42. Values assumed in the filter plate press performance relationship

t (m)	ρ (Mg/m^3)	W %	C %	Y (weeks per year)	D %	S† (Mg/(year)(head))
0.032	1.1	32.5	2	52	15	0.03

† This is the nationally accepted value for primary and secondary sludge (0.018 Mg/(year)(head) primary and 0.012 Mg/(year)(head) secondary).

Alternatively the performance relationship can be expressed in terms of the dry weather flow, DWF ('000 m^3/d), as follows:-

$$DWF*SPV = (A/14)*t*\rho*(W/100)*N*(Y/52)*(1 - D/100)$$

where SPV is the solids production (kg per m^3 of DWF).

Partially substituting the recommended values for some of the variables in the above relationship gives:-

$$A = 1.5*DWF*SPV/N.$$

According to economic considerations and the availability of labour the value of the pressing rate, N, varies in practice from 5 to 10 pressings per week at a small installation working day shifts, and from 15 to 28 per week at a large installation employing a continuous operation for five or seven days per week. The value of SPV is also variable (depending on the industrial contribution to the sewage) but is typically 0.51 kg of solids per m^3 of DWF for a combination of primary and secondary sludges from a domestic sewage. Values of A corresponding to various values of N and SPV are tabulated in Table 13-43. A dash indicates that a plant would not normally be constructed to operate under the given conditions.

13.7.3. Filter plate presses

Table 13-43. Typical filtration areas for a range of values of sludge solids, DWF and pressing rate, for small additions of conditioner

SPV (kg/m^3)	DWF ('000 m^3/d)	Filtration area ('000 m^2)			
		Maximum number of pressings per press per week, N			
		5	10	15	28
0.26	5	0.38	-	-	-
	10	0.77	-	-	-
	20	1.5	0.77	-	-
	50	-	1.9	-	-
	100	-	3.8	2.6	-
	200	-	-	5.1	2.7
0.51	5	0.77	-	-	-
	10	1.5	0.77	-	-
	20	-	1.5	-	-
	50	-	3.8	2.6	-
	100	-	-	5.1	2.7
	200	-	-	10.2	5.5
0.77	5	1.15	0.57	-	-
	10	-	1.15	-	-
	20	-	2.3	1.5	-
	50	-	-	3.8	-
	100	-	-	7.6	4.1
	200	-	-	15.0	8.2

† If lime and copperas are used, values for filtration area should be increased by up to 40%.

B. The results - filter plate presses (civil engineering)

(i) Detailed modelling approach

Included in the civil engineering work are the treatment building, the lime and copperas (conditioning) tanks, and a cake discharge area. Items not included are sludge storage tanks, roads and paths, landscaping and inter-process pipework.

Because the treatment buildings accounted for most of the expenditure their construction was examined in the BoQs. Most were two-storey buildings of reinforced concrete framed construction. The only exception, the largest installation, had a building of three storeys. Variation in the design was caused by the wall construction, which ranged from cavity brick to asbestos cladding, and one of the buildings had a prefabricated upper storey. The sizes of the buildings were partly dependent on the positioning of the conditioning tanks and the provision of ancillary facilities such as workshops and mess rooms.

The major factor affecting the size of the treatment building was its maximum design capacity. Usually, to simplify projected extensions, spare capacity in the form of extended or empty press stands was incorporated in the building at the design stage. At one installation this practice more than doubled the size of the building.

(ii) Data summary

Table 13-44. Filter plate presses (civil engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Civil engineering cost (corrected to 1976 Q3)	CIVCOS	£'000	100	965	300	282
Filtration area	AREA	'000 m^2	0.579	8.09	2.20	2.53

Note: 1. Number of cases: 10.
2. The New Construction Index was used for deflation.
3. CIVCOS excludes the part-fabricated building cost.

13.7.3. Filter plate presses

Mini-histograms for the main variables of interest:-

CIVCOS

LOG CIVCOS

AREA

(iii) The recommended cost function

The recommended function for filter plate presses civil engineering cost is:-

$$\boxed{\text{CIVCOS} = 177*\text{AREA}^{0.74}}$$

The statistical details of the function are as follows:-

Number of observations : 10
Correlation coefficient (R) : 0.97
Coefficient of determination (R^2) : 94%
Standard error of residuals (in $\log_{10}$ model) : 0.084

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.744	0.07	118	<<0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.76	1.31
95%	0.64	1.56

Figure 13-24 illustrates the recommended function.

(iv) The data

The filter plate presses civil engineering data is listed in Table A-52.

13.7.3. Filter plate presses

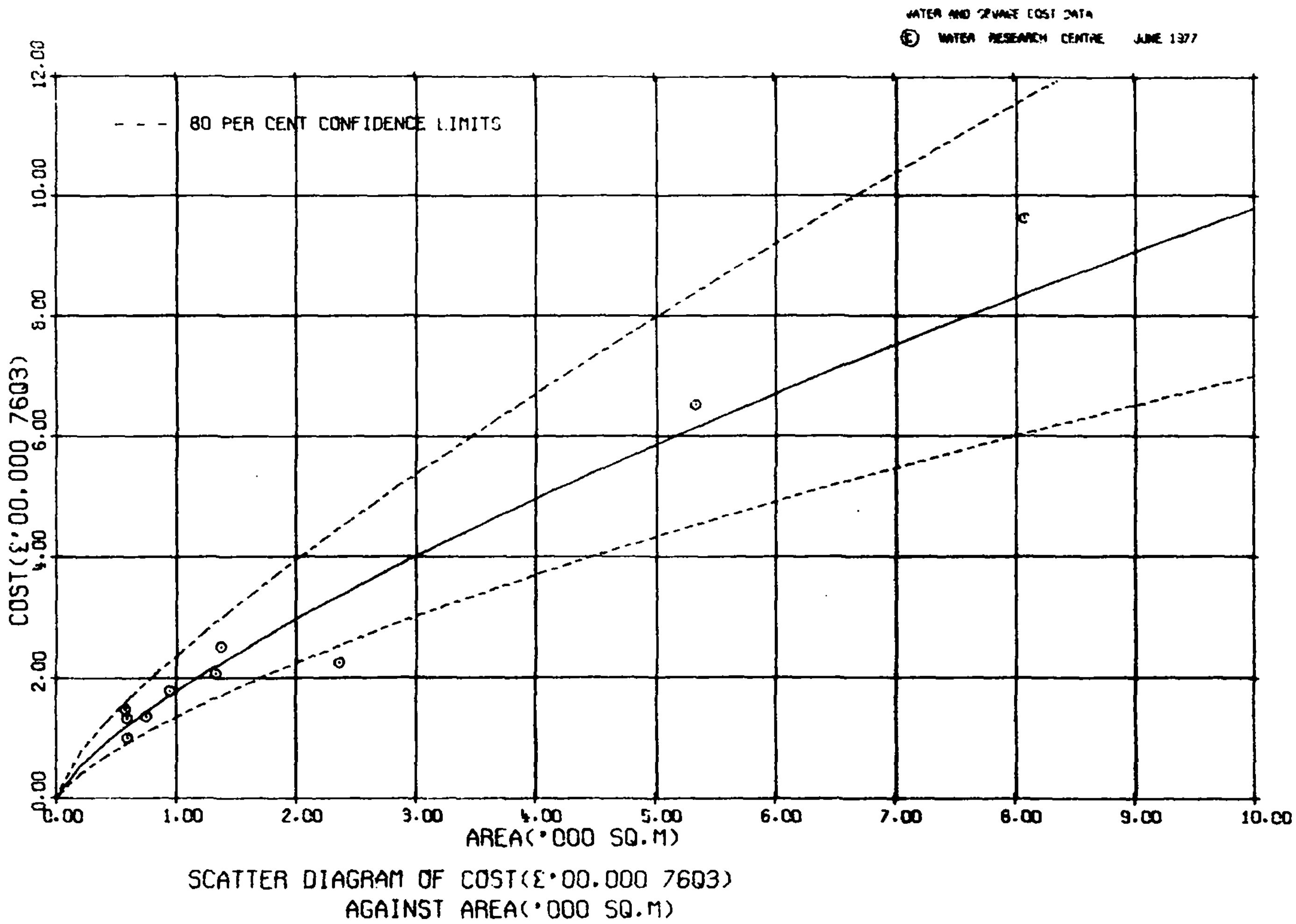


Figure 13-24. Filter plate presses (civil engineering)

13.7.3. Filter plate presses

C. The results - filter plate presses (mechanical engineering)

(i) Detailed modelling approach

The mechanical and associated electrical equipment consists of the presses and ancillary equipment such as feed pumps, pressure vessel (when required), conveyors for cake discharge, measuring instruments, control panel, gantry crane and conditioning tank stirrers. In most of the installations the press plates were 1.22 m square and of steel construction. At one installation rubber-backed plates (1.22X1.83 m) were installed. As a proportion of the total cost of the mechanical and electrical equipment, the cost of the presses increased from approximately 0.3 at the small works to 0.7 at the largest works.

Data from one works where abnormally complex mechanical handling equipment had been installed was discarded.

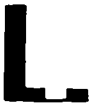
(ii) Data summary

Table 13-45. Filter plate presses (mechanical engineering) data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Mechanical engineering cost (corrected to 1976 Q3)	MECCOS	£'000	121	2350	491	721
Filtration area	AREA	'000 m^2	0.30	8.09	1.85	2.55

Note:
1. Number of cases: 9.
2. The Engineering and Allied Industries Index was used for deflation.

Mini-histograms for the main variables of interest:-


MECCOS


LOG MECCOS


AREA

(iii) The recommended cost function

The recommended function for filter plate presses mechanical engineering cost is:-

$$\boxed{\text{MECCOS} = 282*\text{AREA}^{0.87}}$$

The statistical details of the function are as follows:-

Number of observations	:	9
Correlation coefficient (R)	:	0.98
Coefficient of determination (R^2)	:	96%
Standard error of residuals (in $\log_{10}$ model)	:	0.094

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.872	0.071	152	$\ll$0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.74	1.36
95%	0.60	1.67

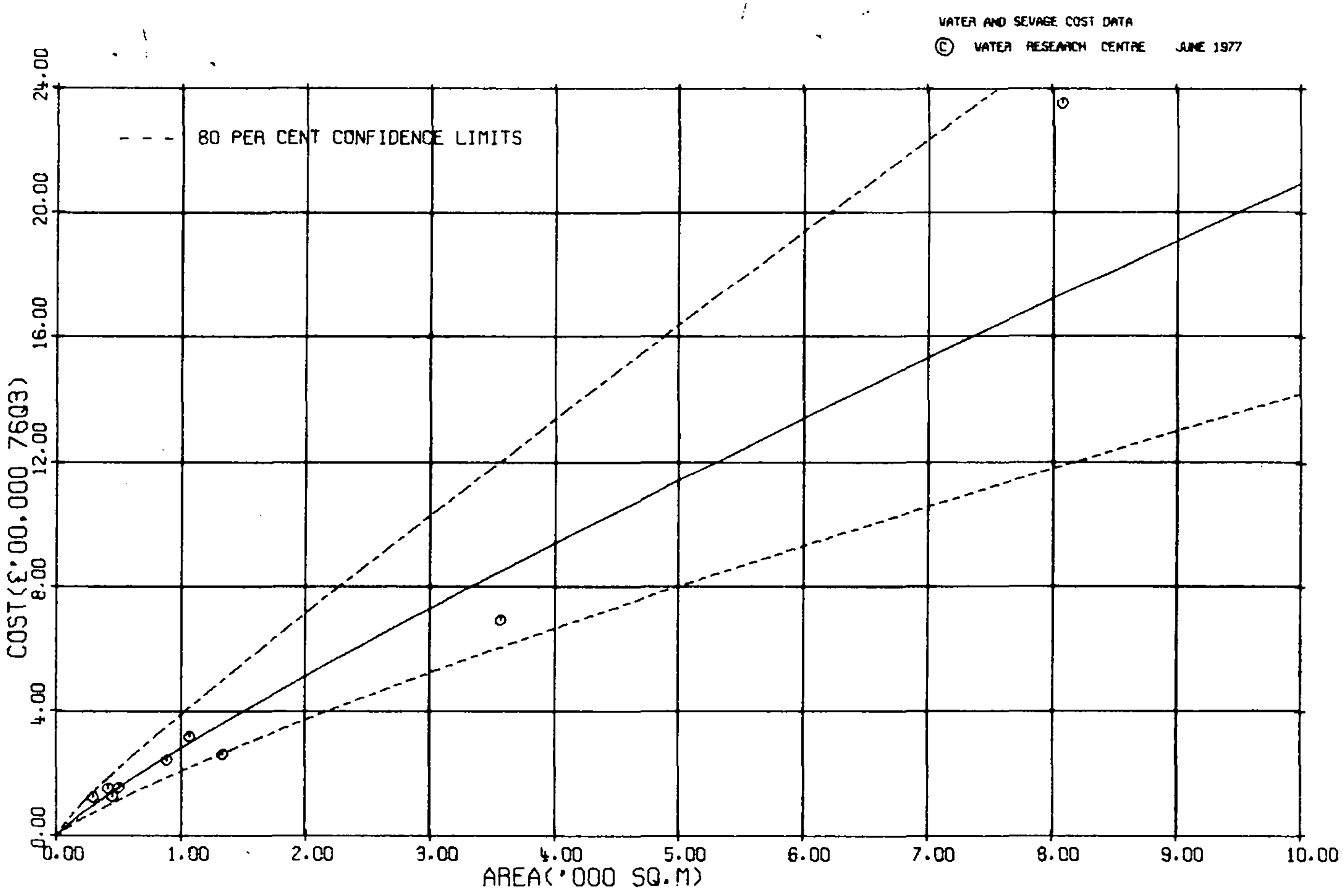
Figure 13-25 illustrates the recommended function.

(iv) The data

The filter plate presses mechanical engineering data is listed in Table A-53.

13.7.3. Filter plate presses

Figure 13-25. Filter plate presses (mechanical engineering)



SCATTER DIAGRAM OF COST(£'00.000 76Q3)
AGAINST AREA('000 SQ.M)

13.7.4. FILTER BELT PRESSES

The filter belt press is a fairly recent development; indeed, major changes in design are apparent in the 'second generation' of equipment. Consequently very little data could be collected from these recent installations, and so this section is based largely on figures provided by manufacturers. In these machines, sludge follows a convoluted path between the filter belts. The performance of belt presses is often expressed in terms of throughput per unit width of belt (see Section 13.1.4 (f)(iii)); for this reason capital costs have been related to belt width.

Capital and operating costs for a range of sizes of installations are presented in Table 13-46 for the treatment of a combination of primary and secondary sludges.

Table 13-46. Costs for belt press installations suitable for dewatering thickened co-settled primary and secondary sludges

DSP (mg/d)	Population equivalent	Working week (h)	Sludge to be handled per h (kg/h)	Effective belt width† (m)	Number of machines	Total belt width (m)	Capital costs (1976 Q3)		Operating costs (1976 Q3)		
							Mechanical engineering (£)	Civil engineering†† (£)	Electricity§ (£/yr)	Conditioner (£/yr)	Total (£/yr)
2	24 000	40	351	2.0	1	2.2	65 000	32 000	270	3 960	4 230
10	120 000	120	585	3.4	2	3.8	90 000	41 000	1 400	19 600	21 000
20	240 000	120	1 170	6.9	3	7.5	150 000	63 000	2 600	39 000	41 600
100	1 000 000	120	5 850	34.4	15	37.4	870 000	90 000	13 000	196 000	209 000

† Includes an allowance for 15% downtime.

†† Calculated from cost function in Section 14.2.

§ Cost of electricity assumed to be 1.6 p/kWh.

13.7.5. INCINERATION

A. General

Incineration is one of the more expensive processes currently used in sludge disposal, and its use is normally restricted to those works where, for various reasons, no other form of sludge disposal can be carried out. Consequently very few installations exist in the UK, and little data on costs and performance has been published. However, the process is widely used in the USA, and data collected from these installations by Unterberg et al (22) has been used to derive the performance relationships presented below.

The performance of multiple hearth incinerators is summarized in (23), where capital and operating costs are derived for incinerators capable of burning a variety of sludges of different calorific values. The present study considers only the incineration of an autothermic sludge; this might contain about 32% DS - a value that could easily be achieved in filter plate presses and perhaps by some belt presses. It is assumed that incinerators would burn sludge 24 hours per day on five days each week. At weekends a standby temperature within the incinerator would be maintained by burning fuel oil.

B. Performance data

(i) Loading = 30 kg of cake/h m^2 of hearth area.

(ii) Electricity consumption = $50*A^{-0.3}$ kVAh/Mg of cake, where A is total hearth area (m^2).

(iii) Supplementary heat. This is generated by the combustion of fuel for standby at weekends and reheating after shutdown periods, and is a function of hearth area as shown in Table 13-47.

Table 13-47. Supplementary heat required by multiple hearth incinerators

Hearth area (m^2)	Heat required for one reheat (10^9 Joules)	Standby heat required at weekends (10^9 Joules/wk)
50	19	11
100	49	23
150	110	39
300	440	104

Each incinerator is assumed to shut down on three occasions every year, and to burn light fuel oil.

(iv) Downtime planned = 3 wk/yr;
unplanned = 5 wk/yr.

(v) Maintenance costs depend upon the operational practice, and have been estimated at 3% of mechanical capital cost per year.

C. Capital cost data

Because few incinerators have been installed in this country insufficient data has been collected to allow a cost relationship to be developed for contract prices. However, the following relationship has been derived from budget prices (supplied by a manufacturer) for the erection of an incinerator, conveyor, ash cooler and gas scrubbing equipment:-

$$\boxed{\text{COST} = 22 * A^{0.67}}$$

where COST is the cost of an individual incinerator (£'000 1976 Q3),
and A is total hearth area (m^2).

The cost of an installation with multiple units may be taken as the cost of the equivalent number of individual units.

The small amount of data available on contract prices suggests that the civil engineering costs are about two-thirds of the incinerator cost (mechanical engineering alone).

D. Derived costs

From the above assumptions, capital and operating costs have been estimated for values of the dry solids production rate (DSP) ranging from 20 to 160 Mg/d. These are presented in Table 13-48 below.

Table 13-48. Derivation of capital and operating costs of multiple hearth incinerators

DSP (Mg/d)	Cake† (Mg/h)	Area of furnaces†† (m^2)	Number of furnaces	Area per furnace (m^2)	Capital costs (£'000 1976 Q3)		Operating data (1976 Q3)									Total operating cost/yr
							Labour		Electricity		Reheat fuel		Standby fuel at weekend			
					Mechanical	Civil	No. of men/shift	Cost (£'000/yr)	kVAh*10^6/yr	Cost (£'000/yr)	10^9 Joules/yr	Cost (£'000/yr)	10^9 Joules/yr	Cost (£'000/yr)	Maintenance (£'000/yr)	
20	2.56	138	1	138	600	400	2	25.9	0.256	4.1	290	0.5	1 670	2.7	18	51
40	5.13	277	1	277	950	640	2	25.9	0.416	7.1	1 140	1.8	3 960	6.4	29	70
80	10.3	554	2	277	1 900	1 300	3	38.8	0.831	14.0	2 280	3.7	7 920	13.0	57	126
160	20.5	1 110	3	369	3 500	2 300	3	38.8	1.53	26.0	5 400	8.7	18 500	30.0	105	208

† Cake solids = 32.5%.

†† Downtime = 15%;
operational week = 116 hours.

13.7.6. Drying beds

13.7.6. DRYING BEDS

Sludge drying beds are seldom specified at present except for small rural treatment works, and very little data was collected for beds designed for sewage sludge. Consequently a composite cost function was derived using drying beds data relating both to sewage treatment works and to water treatment plants. This is described in Section 12. 5. 2.

13.8. OTHER WORKS ITEMS

13.8.1. SITEWORKS AND PIPEWORKS, OVERHEADS AND BUILDINGS

(a) General

The costs discussed in this section represent a very substantial proportion of the total cost of a treatment works. They have been handled in a uniform way throughout the sewage treatment area and so it is convenient to consider them collectively. When estimating the cost of a completely new large treatment works or a big extension to an existing plant, all four categories of cost will normally be incurred. On the other hand, when a small extension to an existing works is under consideration relatively low costs may be incurred for siteworks, as items such as roads, fences and pathways may already be in place. Similarly, no new buildings may be necessary. However, costs for inter-process pipework and contractors' overheads will still be incurred. Thus, by listing these four classes of costs separately the data may be used in a wider variety of cases than had it simply been distributed in an arbitrary fashion amongst the civil engineering capital costs for process units.

Allowances are made for these cost items by adding appropriate increments to the sum of the capital costs for civil engineering directly associated with process plant, i.e. process civil engineering costs (PCEC). The magnitudes of these costs and their incremental values are discussed below. It should be noted that the approach taken is slightly different from that adopted in Chapter 12 for sewage treatment.

(b) Inter-process pipework

Inter-process pipework costs for 47 works were examined (35 were green field sites). Although these costs vary from 4% to over 50% of the PCEC, a more usual figure is between 15 and 20%. The proportion is apparently not related to size of contract. It is likely to be influenced by site topography and ground conditions, but these factors could not be quantified. The results are illustrated in histogram form in Figure 13-26(i).

13.8.1. Siteworks and pipeworks, overheads and buildings

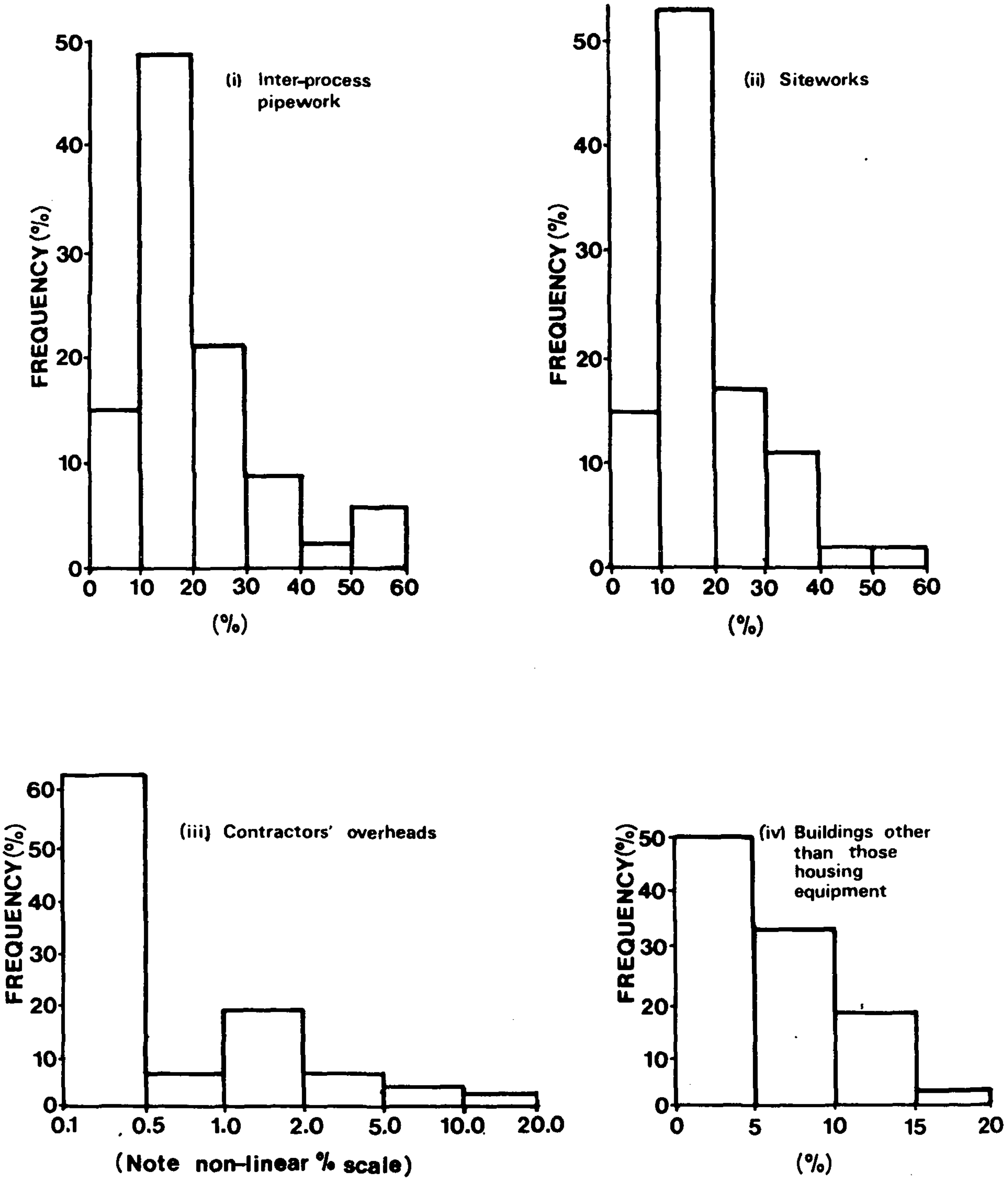


Figure 13-26. Histograms for cost of other works items as percentages of process civil engineering capital cost

(c) Siteworks

Costs for siteworks in 47 BoQs were examined. They vary between 4 and 51% of the PCEC, but a typical figure is about 14%. The results are illustrated in histogram form in Figure 13-26(ii).

(d) Contractors' overheads

For the 36 BoQs studied, contractors' overheads ranged from 0.1 to 15% of the PCEC. In a minority of BoQs it was not possible to identify the costs which normally constitute contractors' overheads, and in these instances the contractor presumably recovered the cost by increasing other costs within the bill. It is considered that any errors resulting from this uncertainty are unlikely to be significant. The results are illustrated in histogram form in Figure 13-26(iii).

(e) Buildings other than those housing equipment

Administrative buildings, laboratories, canteens, mess rooms and other staff amenity buildings are included under this heading. At only 18 works from a total of 47 were any buildings of these types included, and within this group the costs for the buildings did not appear to be related to the size of the works. This is not altogether surprising as the availability of laboratory and other facilities at adjacent existing works may influence what is built at many small- and medium-sized works. Further investigation of the consequence of managerial factors such as these lay beyond the scope of the present study. The distribution of these costs is shown in histogram form in Figure 13-26(iv). The values range from 3 to 14% of PCEC, with a typical value of about 4.5%.

(f) Summary

When the process civil engineering costs have been estimated four increments must be added. In the absence of more specialized information, typical values may be used of 16% for inter-process pipework, 14% for siteworks, 4% for contractors' overheads and 4.5% for buildings other than those housing equipment.

13.8.2. ADDITIONAL ITEMS

This section discusses such costs as demolition, piling, major access works and major diversions. These costs are only encountered at a minority of works. For example, at the 36 complete works built on green field sites for which data was available, piling was required at only four sites and major stream or road diversions at only three. However, the costs involved at these few works were very substantial, with piling costing up to 50% of the sum of the process civil engineering capital costs (PCEC) and diversions up to 59%.

The highly erratic nature of these costs makes averages largely meaningless. Nevertheless, they are of some value in national planning provided it is recognized that they can be no more than a very rough approximation, even when considering a large number of works. When estimating these additional costs for an individual works, there should be sufficient local information available relating to site conditions either to ignore them completely or to include more realistic estimates of those items likely to be undertaken.

The costs do not appear to be related to contract size, although with the very small sample sizes available such a conclusion is unsurprising. Nevertheless, it is noteworthy that the works where the cost of a major diversion to a stream amounted to 59% of the process civil engineering costs was a small installation designed to treat a maximum flow of under 10 Ml/d (population probably less than 5000 persons); it seems highly unlikely that a medium- or large-sized treatment works would be built on a site which necessitated a major diversion for which the costs amounted to such a high proportion of the process civil engineering costs.

For national planning purposes a single increment for all additional costs of 9% of PCEC has been determined, although for the reasons given above this could be as high as 24%. Whenever possible, local information on site conditions should be sought so that rather more realistic values for incremental costs may be employed when it has been established that demolitions, piling or major access roads are required. The four cost categories are summarized in Table 13-49. In the case of major diversions of roads and streams, the three available values were so scattered that no average figure has been offered.

Table 13-49. Summary of additional costs for demolition, piling, major access roads and major diversions incurred at 36 treatment works constructed on green field sites

	Additional costs resulting from:-			
	Demolitions	Piling	Major access roads	Major diversions of streams and roads
Number out of the 36 sites at which this additional cost was incurred†	8	4	8	3
Additional costs expressed as percentage of sum of capital costs for civil engineering associated with process plant:				
minimum	1	15	1	5
maximum	6	50	14	59
mean	4.4	33	7	-††

† It should be stressed that these additional costs occurred only in these few cases out of the sample of 36 complete works (see discussion above).

†† As only three values have been found, covering a very wide range, no mean has been calculated.

13.9. OPERATING COSTS

The main components of operating cost for a sewage treatment plant are:-

(i) power (electricity);
(ii) materials;
(iii) labour and maintenance.

In principle, models could be developed for these categories in the same way that capital cost functions have been derived from data contained in BoQs. However, it was found that no corresponding source of comprehensive information on operating costs was available. Consequently, it was necessary to generate 'synthetic' cost functions from the knowledge and experience that was available. In this way, tentative estimates were made of power consumption for all major process areas, and these are presented in Section 13.9.1.

The major consumption of materials in sewage treatment is in the use of chemical coagulants in the conditioning of sludge at works where mechanical dewatering processes are used. Information was obtained from a variety of sources on the rates of consumption and the costs for these materials. A list of typical values for use in cost estimating is given in Section 13.9.2.

The general problem of estimating labour and maintenance requirements has not been resolved.

Despite the shortage of appropriate data, it did prove possible to collect figures for total operating cost and throughput for a small number of works. These are discussed in Section 13.9.3.

13.9.1. POWER CONSUMPTION

(a) Preliminary treatment

No allowance is made for head losses; if pumping is required to lift sewage from the sewer, this should be calculated in the light of local knowledge. Manufacturers' data from power consumption for comminutors and detritus removal plants has been collected, and this is summarized in Table 13-50.

Table 13-50. Power consumption in comminution and detritus removal plant

Maximum flow rate (Ml/d)	Comminutor motor power (kW)	Detritor scraper motor power (kW)
0.35 - 1.35	0.18	-
1.35 - 4.25	0.38	-
4.25 - 9.25	0.55	-
9.25 - 15	1.2	-
15 - 33	1.2	0.18
33 - 41	1.2	0.18
41 - 90	1.5	0.55
90 - 118	1.5	0.55
118 - 236	-	0.75

Equipment for conveying detritus tends to be operated intermittently, and as the power involved is small these units are not considered further. The annual power consumption, E(kWh/yr), may be calculated from

$$E = P*0.75*24*365,$$

where P is the installed power (kW).
The plant is assumed to be in operation for 0.75 of the working day.

13.9.1. Power consumption

(b) Primary treatment

Many sedimentation tanks have scrapers fitted with motor drives using 1 kW motors. Using this figure, the annual power consumption, E(kWh/yr), is

$$E = P*0.75*24*365,$$

where P is the installed power (kW).
It should be noted that some scrapers can be transferred from one tank to another, and under these circumstances the number of scrapers will be less than the number of tanks.

(c) Secondary treatment (biological filters)

At a few works where topography allows for gravity flow from primary tanks to the filter distributors, no pumping will be required. In the majority of works, however, settled sewage must be pumped from the outlet channels in the primary tanks to the filter distributors. The annual energy consumption, E(kWh/yr), is

$$E = F*10^3*h*9.81*365/(3.6*10^6*e),$$

where F is the average daily flow (m^3/d),
h is the head loss through filters (m),
and e is the effective motor efficiency.

A value of 3.5 m may be used for the head loss and a value of 0.5 for motor efficiency.

(d) Secondary treatment - activated sludge

Operating costs for conventional activated sludge plants consist of the costs for driving the aeration equipment and the return sludge pumps. Costs for the aeration plant depend on the oxygen requirements and the effective aeration efficiency. For non-nitrifying works the rate of oxygen consumption is 0.7 to 0.9 times the rate of BOD removal, but rises to 1.6 to 1.9 times the BOD removal for nitrifying plants. Aeration efficiencies as high as 1.9 kg O_2/kWh may be recorded in plant operating at or close to the optimum design loading, but for practical purposes this figure should be reduced by about 15%.

The annual power consumption, E(kWh/yr), may then be calculated as

$$E = F*\Delta BOD*R*365/(0.85*1.9),$$

where F is the average daily flow (m^3/d),
ΔBOD is the change in five-day biochemical oxygen demand (g/m^3),
and R is the ratio of oxygen required to BOD removed.

The power consumed in returned sludge pumping, E(kWh/yr), can be estimated directly from the equation

$$E = 10^3*F*h*9.81*365/(3.6*10^6*e),$$

where F is the average daily flow (m^3/d),
h is the head against which flow is pumped (m),
and e is the pump efficiency.

A value of 2.5 m may be used for the head, and the pump efficiency can be taken as 0.5.

(e) Final separating tanks

For each tank scraper a 1 kW motor is likely to be used. Using this figure, the annual power consumption, E(kWh/yr), will be

$$E = P*0.75*24*365,$$

where P is the installed power (kW).

(f) Tertiary treatment - rapid gravity sand filters

Pumping will normally be required as there is a head loss of several metres through rapid gravity sand filters. The annual power consumption, E(kWh/yr), is

$$E = F*10^3*h*9.81*365/(3.6*10^6*e),$$

where F is the average daily flow (m^3/d),
h is the head loss through filters (m),
and e is the pump efficiency.

A value of 4.0 m may be used for h, and for the motor efficiency a value of 0.5 is assumed.

(g) Sludge dewatering

Power is consumed in pressurizing the sludge feed and also in driving the ancillary equipment, e.g. chemical mixers, storage tanks, ventilator fans and chemical feed pumps. The energy required to drive the sludge feed pumps can easily be estimated, but it is more difficult to determine the power used for driving ancillary equipment. In some installations the sludge feed pumps appear to consume the major proportion of the total power, but in other installations the total power consumed is ten times that used for the sludge feed pumps.

Supposing that feed sludge contains 4.5% DS, the volume of wet sludge containing 1 tonne DS is 22 m^3. The energy then required to elevate the pressure to 100 psi (70 m head) with a pump having an overall efficiency of 33% is

$$22*10^3*70*9.81/(3.6*10^6*0.33)$$
$$= 13 \text{ kVAh/tonne DS.}$$

Assuming that ancillary plant consumes six to seven times as much power as the sludge feed pumps, the total power is 100 kVAh/tonne DS.

(h) Sludge transportation

The total costs for a seven tonne tipper truck amount to £0.26/mile. For cake containing 30% DS this is equivalent to £0.12/mile-dry tonne. The costs for loading and unloading are equivalent to an additional £0.47/dry tonne. '

Typical round trip distances vary from under five miles for small rural works to 20 miles or more for large urban works.

13.9.2. MATERIALS

In sewage treatment, the only major cost for materials is incurred at works where sludge is conditioned prior to dewatering, with the aid of chemical coagulants. Costs for coagulants in common use, and figures representing typical dose rates, are shown in Table 13-51.

Table 13-51. Typical ranges of coagulant dose rates and costs

Chemical coagulant	Range of dose rates (% of DS)	Cost (1976 Q3)
Aluminium chlorohydrate (containing solution 15% Al_2O_3)	1 - 5% Al_2O_3	£90/tonne of solution
Slaked lime	20 - 50% $Ca(OH)_2$	£22/tonne $Ca(OH)_2$
Copperas ($FeSO_4 7H_2O$)	10 - 40%	£15/tonne $FeSO_4 7H_2O$
Polyelectrolyte (liquid 15% active)	1 - 7% of liquid	£220/tonne of liquid
Polyelectrolyte (solid)	0.15 - 0.7%	£1800/tonne of solid

Note:

1. Slaked lime and copperas are often used in combination, typical doses being 25% lime and 15% copperas; the cost per tonne of sludge dry solids would in this case be £7.75.
2. Costs for these chemicals will normally be proportional to the quantity of sludge which is dewatered mechanically (see worked example in Section 13.1.5 and also Sections 13.7.3 and 13.7.4).

13.9.3. TOTAL OPERATING COSTS FOR WHOLE WORKS

A limited amount of operating cost data was collected for whole works; this is listed in Table 13-52. Figure 13-27 provides evidence of an underlying relationship between annual operating cost and design DWF, although the data shows a substantial scatter. Much of this arises because of the marked differences in the processes used for treating and disposing of sludge at the various works. However, it was not possible to break the costs down because only in one case could individual process costs for electricity and maintenance be identified.

At several of the small works, sludge was transported to a larger works (Works E in Table 13-52) for digestion and subsequent transport to land. This accounts for why point E in Figure 13-27 is relatively high. Another irregularity in Figure 13-27 can be explained by noting that Works A is highly automated, and so its annual operating cost would be expected to fall well below that for a conventionally controlled works such as Works B.

Because of these identifiable causes of variation within the data it was not thought worthwhile to attempt to estimate a cost function. Nevertheless, Figure 13-27 provides an indication of how operating cost varies with size of works which may be taken as a useful rough guide. It should, however, be noted that the log-log scale which it was necessary to adopt conceals the full extent of the variability. For example, the operating cost for Works E is nearly three times that for Works F, although the two works have similar dry weather flows.

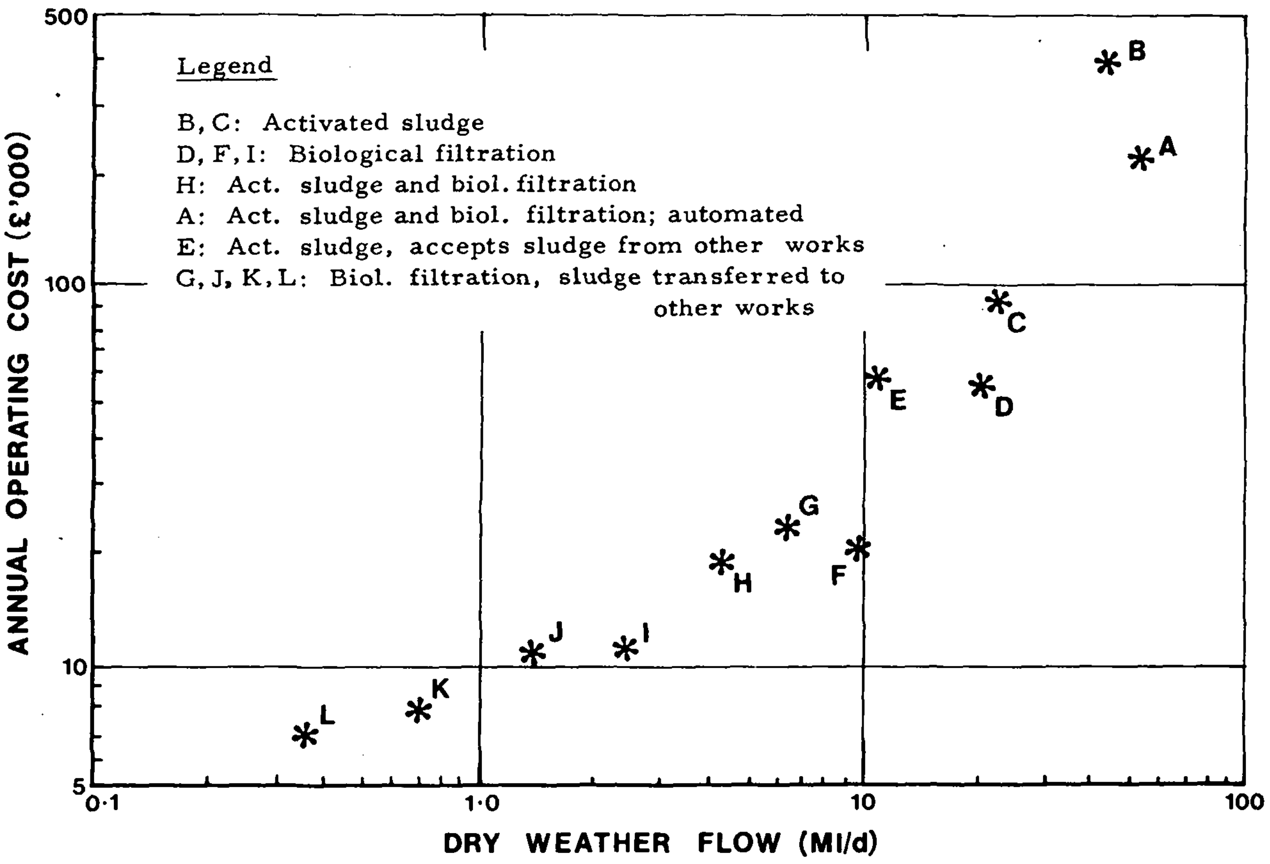
13.9.3. Total operating costs for whole works

Table 13-52. Annual operating costs for 12 sewage treatment works

Works	Design DWF (Ml/d)	Population ('000)	Type of secondary treatment	Type of sludge treatment and disposal	Annual operating cost (£'000 1975/76)
A	55	200	Activated sludge and biological filters	Primary sludge de-watered in press plate, secondary sludge digested	220
B	45	125	Activated sludge	Digestion, major prop. as liquid to land, vacuum filters	390
C	23	85	Activated sludge	Thickened, digestion, tankered to land	96
D	21	121	Biological filters	Digestion, major prop. as liquid to land	55.6
E	11	14.5	Activated sludge	Accepts sludge from other works for digestion	57.7
F	10	25	Biological filter treating to 10/10/5 standard	Digestion, centrifuge, tip	20.7
G	6.5	24	Biological filters	Thickened and tankered to other works	23.1
H	4.2	18	Activated sludge (package plant) and biological filters	Cold digestion, drying beds	19.2
I	2.4	16	Biological filters	Cold digestion, drying beds	11.0
J	1.4	7.7		Thickened and tankered to other works	11.1
K	0.72	3.8			8.00
L	0.36	2.0			6.84

Note:

1. These works were designed to produce effluents to a standard not worse than 30/20 (SS/BOD), with the exception of Works F, which was designed to 10/10/5 (SS/BOD/ammoniacal N).
2. Works A was fully automated.
3. Operating costs include labour, supervision, supplies, maintenance, transport and electricity.
4. Local authority rates were excluded because they were widely different from one works to another: at one works their inclusion would have increased annual charges by 50%, but at another by only 2%.



Note: 1. See Table 13-52 for a more detailed description of the 12 works.

2. Costs include labour, supervision, scientific services, electricity, maintenance and supplies.

3. Local authority rates are not included.

Figure 13-27. Annual operating cost (1975/76) plotted against DWF for 12 sewage treatment works designed to produce a 30/20 final effluent

14. BUILDINGS

The cost of the buildings which house electrical or mechanical equipment has been included in some of the cost functions presented in Chapters 12 and 13, such as the sewage sludge filter plate presses and the global treatment works models. However, for many areas the cost of the associated buildings has not been included. In such cases, the cost of buildings can be estimated using one of the cost functions given in this chapter, and then combined with the other costs to obtain the total cost.

Data was obtained from tender BoQs for four types of building:-

(i) water treatment works;
(ii) water works pumphouses;
(iii) sewage sludge treatment buildings;
(iv) sewage pumping stations.

The functions which were developed referred only to the construction costs, so they excluded costs for electrical and mechanical engineering items such as tanks, filters, pumps and generators.

Initially, functions were obtained for each type of building relating cost to total floor area, this being the only physical dimension for which details were consistently available. The functions were very similar for both types of water treatment buildings, so a recommended model is given in Section 14.1 based upon the combination of both samples of data. However, the functions for sewage sludge treatment buildings and for sewage pumping stations were considerably different both from those for water treatment and from each other. They are presented in Sections 14.2 and 14.3 respectively.

The cost functions demonstrated that sewage works buildings generally cost less than water works buildings or water pumphouses of the same floor area. A reason for this is that traditionally water works have been constructed to a higher level of architectural detail, both internally and externally, than sewage works. In particular, whereas the internal walls of sewage works are often of bare brick or concrete, the internal finishing of water treatment works is of necessity less spartan. It is possible, however, that these differences will lessen in the future as a result of the rationalization within the Water Industry.

Sewage pumping stations usually consist of underground sumps, the vast majority of which are constructed of reinforced concrete or pre-cast units, and have superstructures of varying degrees of sophistication. The floor area is usually much less than it is in other buildings. Because of these differences from the other three types of building, the main function recommended in Section 14.3 for sewage pumping stations uses design capacity and number of pumps in preference to area.

14.1. WATER WORKS AND WATER PUMPHOUSES

A. The modelling approach

Details of tender costs, total floor area and the number of storeys (when available) were extracted from BoQs for 42 buildings. Of these, 15 cases were of water pumphouses and the other 27 were of water treatment works.

Cost was defined as total construction cost including the cost of site works and pipe works in the immediate vicinity but excluding cost of cranes. The total floor area consisted of all working area, including sumps, platforms, galleries and basements but excluding sump platforms which were counted as roofing. The number of storeys was not available in many cases, and as it did not significantly influence the cost of those buildings for which it was available it was discarded as an explanatory variable.

Total floor area, the only remaining explanatory variable for this sample of buildings, ranged from 70 to 3440 m^2 for water pumphouses and from 57 to 2980 m^2 for water works. The functions relating cost to total floor area were very similar both for water treatment works and for water pumphouses. The two data samples were therefore combined to produce one function valid for both types of building; this is described in part B. The New Construction Index was chosen for deflation of costs in preference to the DQSD, Construction Materials and Basic Weekly Wage Rate Indices.

At broad planning levels, total floor area for pumphouses and other buildings is not known. One approach is to estimate area from design throughput and other information of that sort. This can be done for water treatment works using the function given in Section 12.2.3, which relates chemical equipment floor area to throughput. However, a more satisfactory approach is to relate cost directly to these planning variables, and so efforts were made to obtain a sample of water pumphouses for which this could be done. This resulted in details of the following explanatory variables being obtained for 11 cases:-

(i) design throughput;
(ii) design total number of pumps;
(iii) whether pumps were vertical or horizontal;
(iv) whether a screen chamber was included or not;
(v) whether the servicing facilities were provided or not.

14.1. Water works and pumphouses

Costs were taken from tender documents at date of contract. The DQSD Index was chosen to deflate the costs in preference to the Construction Materials, New Construction and Basic Weekly Wage Rate Indices. Only design throughput was found to be significant; the function is detailed in part C of this section.

B. The results - water works and water pumphouse buildings

(i) Data summary

Table 14-1. Water works and water pumphouse buildings data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total construction cost (corrected to 1976 Q3)	WATCOS	£'000	21.2	1300	201	261
Total floor area	AREA	'000 m^2	0.0570	3.44	0.704	0.773

Note:
1. Number of cases: 42.
2. The New Construction Index was used for deflation.
3. If floor area of a pumphouse has to be estimated from throughput, it is better to use the function following in part C.

Mini-histograms for the main variables of interest:-

WATCOS

LOG WATCOS

AREA

(ii) The recommended cost function

The recommended function for water works and water pumphouse buildings is:-

$$\boxed{WATCOS = 248*AREA^{0.94}}$$

The statistical details of the function are as follows:-

Number of observations : 42

Correlation coefficient (R) : 0.89

Coefficient of determination (R^2) : 78%

Standard error of residuals (in $\log_{10}$ model) : 0.213

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.935	0.078	145	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.53	1.89
95%	0.37	2.69

Figures 14-1 and 14-2 show the five standard diagrams in support of the function.

(iii) The data

The water works and water pumphouse buildings data is listed in Table A-54.

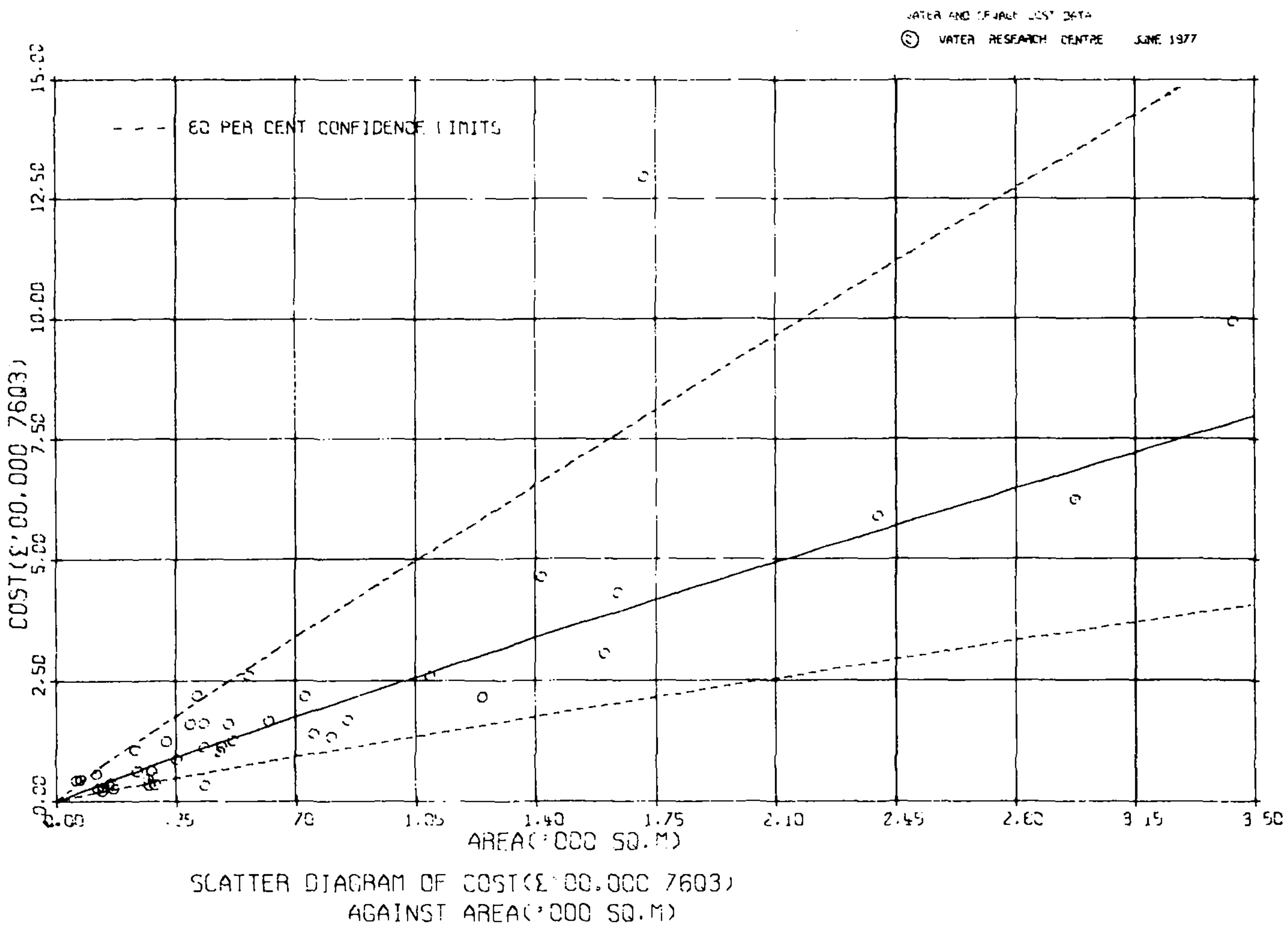
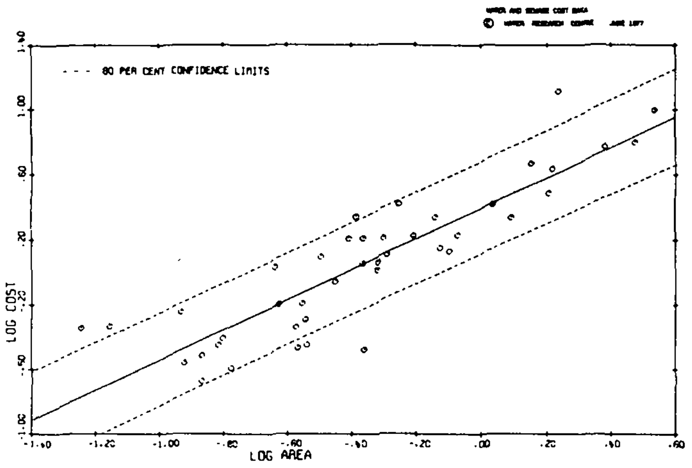


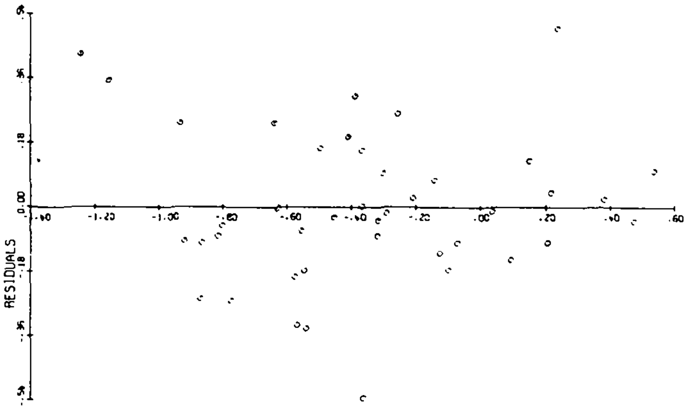
Figure 14-1. Buildings—water general

14.1. Water works and pumphouses

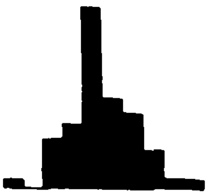
Figure 14-2. Buildings—water general



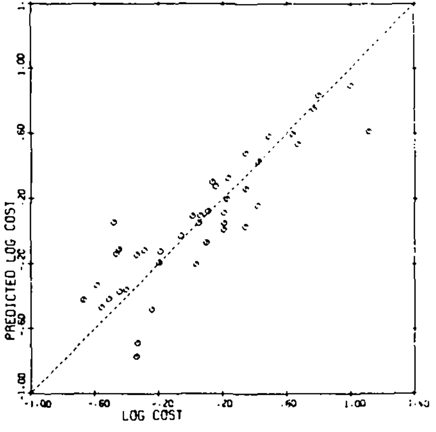
SCATTER DIAGRAM OF LOG COST
AGAINST LOG AREA



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG AREA



HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

C. The results - water pumphouses

(i) Summary of data

Table 14-2. Water pumphouse data summary

Variable	Label	Unit	Min.	Max.	Mean	St.dev.
Total construction cost (corrected to 1976 Q3)	WATPUMP-COS	£'000	49.2	874	248	279
Design throughput	THRUPUT	'000 m³/d	15	680	165	191

Note: 1. Number of cases: 11.

2. The DQSD Index was used for deflation.

Mini-histograms for the main variables of interest:-

WATPUMPCOS

LOG WATPUMPCOS

THRUPUT

(ii) The recommended cost function

The recommended function for water pumphouses is:-

$$\boxed{WATPUMPCOS = 4.00 * THRUPUT^{0.79}}$$

The statistical details of the function are as follows:-

Number of observations	:	11
Correlation coefficient (R)	:	0.86
Coefficient of determination (R^2)	:	74%
Standard error of residuals (in $\log_{10}$ model)	:	0.227

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
THRUPUT	0.792	0.155	26.0	≪0.1%

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.49	2.06
95%	0.31	3.26

Figure 14-3 illustrates the recommended function.

(iii) The data

The water pumphouse data is listed in Table A-55.

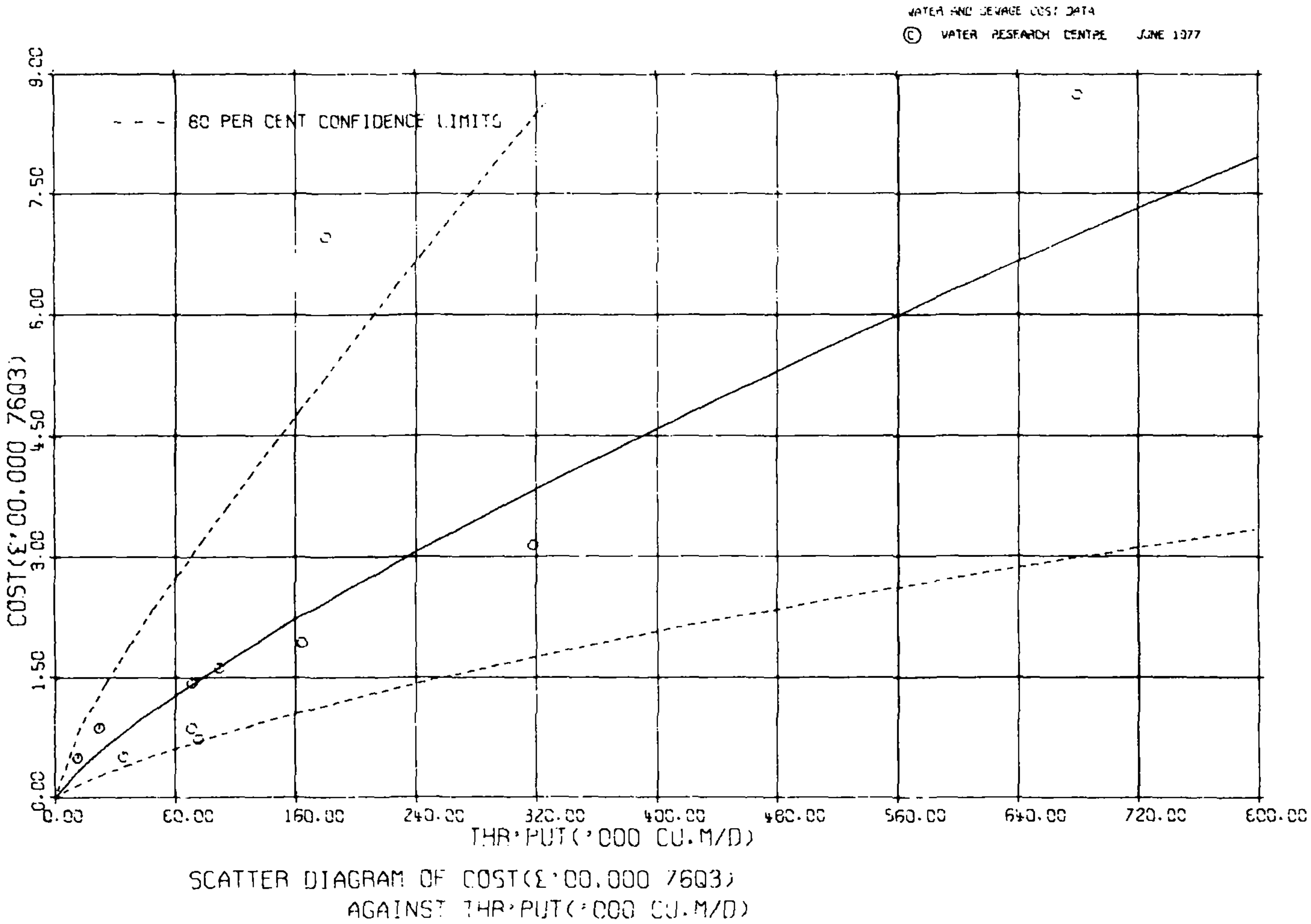


Figure 14.3. Buildings—water pumphouses

14.2. SEWAGE SLUDGE TREATMENT BUILDINGS

A. The modelling approach

The tender price for construction was obtained for 13 sewage sludge treatment buildings. The cost of all associated conditioning tanks and holding tanks and cost of paths and roadways were excluded from the construction cost. Most of the buildings in the sample had reinforced concrete framework with either red-brick or corrugated steel cladding. The sample included examples of treatment buildings for filter presses and vacuum filters. The largest building in the sample housed filter presses and had three storeys.

Two explanatory variables were considered: total floor area (including all suspended floors), and number of storeys. The number of storeys, which varied between one and three, was not significant.

The New Construction Index was chosen for deflation of costs in preference to the DQSD, Construction Materials and Basic Weekly Wage Rate Indices.

B. The results

(i) Data summary

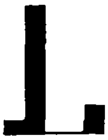
Table 14-3. Sewage sludge treatment buildings data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total construction cost (corrected to 1976 Q3)	SEWCOS	£'000	38.6	597	190	177
Total floor area	AREA	'000 m^2	0.243	4.72	1.14	1.30
Number of storeys	NSTORY	-	1	3	1.92	0.49

Note: 1. Number of cases: 13.

2. The New Construction Index was used for deflation.

Mini-histograms for the main variables of interest:-



SEWCOS

LOG SEWCOS

AREA

(ii) The recommended cost function

The recommended function for sewage sludge treatment buildings is:-

$$\boxed{\text{SEWCOS} = 180 * \text{AREA}^{0.83}}$$

The statistical details of the function are as follows:-

Number of observations	:	13
Correlation coefficient (R)	:	0.96
Coefficient of determination (R^2)	:	93%
Standard error of residuals (in $\log_{10}$ model)	:	0.094

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
AREA	0.827	0.070	141	$\ll 0.1\%$

Approximate multipliers for confidence intervals about a prediction:-

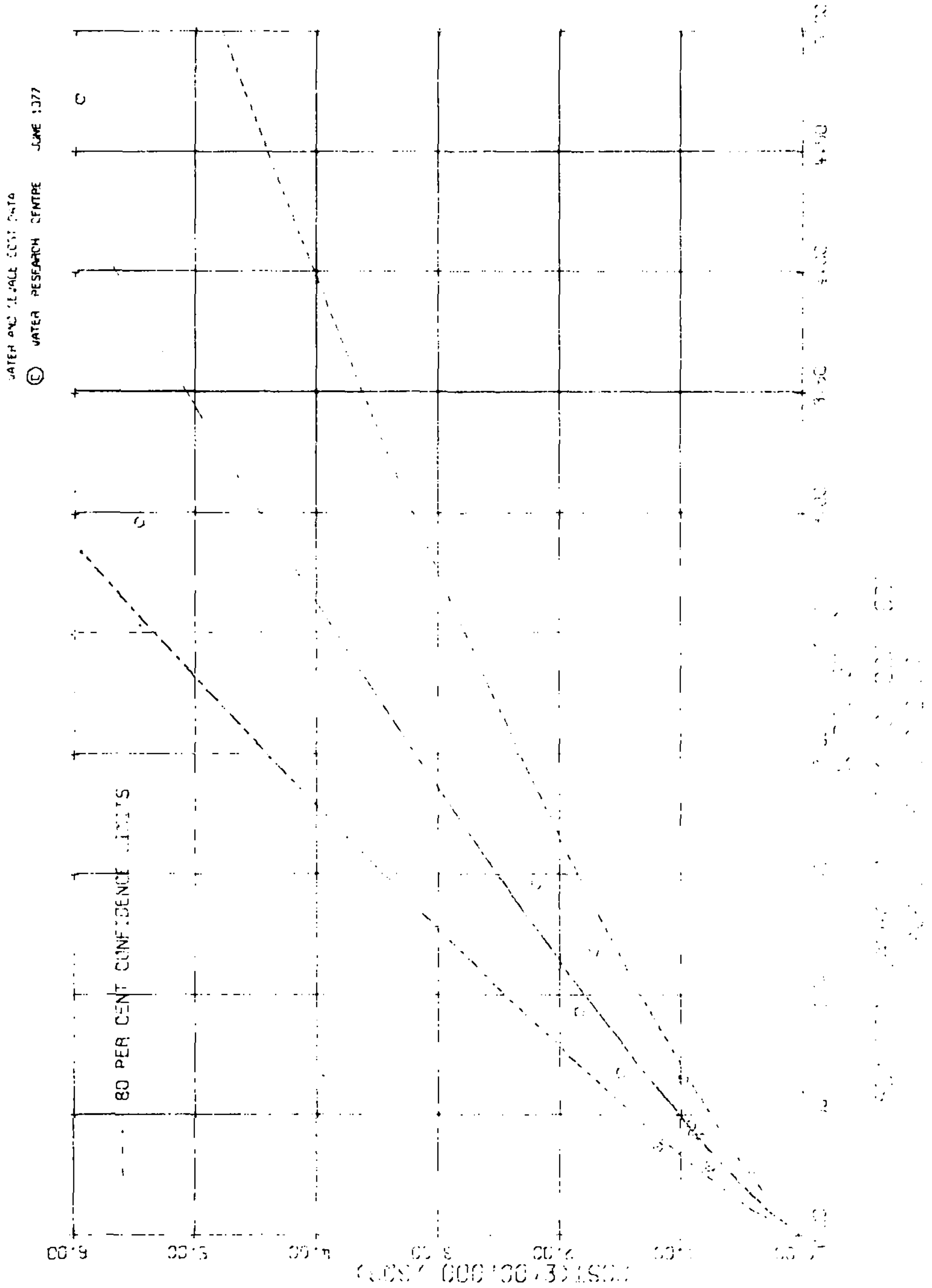
Confidence level	Lower	Upper
80%	0.74	1.34
95%	0.62	1.61

Figure 14-4 illustrates the recommended function.

(iii) The data

The sewage sludge treatment buildings data is listed in Table A-56.

Figure 14-4. Buildings—sewage sludge



14.3. SEWAGE PUMPING STATIONS

A. The modelling approach

The same set of sewage pumping stations used for modelling pump costs was used for pump building costs. Details of how construction costs and physical dimensions of the pumphouses were obtained are given in Section 10.4.1. Cost consists of all construction costs detailed in the tender documents and excludes costs for design and supervision of the works.

The following explanatory variables were considered:-

(i) volume of substructure (including walls and base);

(ii) combined volume of substructure and superstructure (volume of superstructure alone could not be used because it was frequently zero);

(iii) total floor area (including generator housing only if in the same building);

(iv) total head (static head and friction losses but excluding station losses);

(v) total design power (based on rated power of motors, and including standby motor sets);

(vi) total design capacity (based on rated duty of pumps, and including standby sets);

(vii) final number of pumps to be installed (including standby pumps).

The two variables most highly correlated with construction cost were total structural volume and total design power. However, both are difficult to estimate at the broader planning levels, and so the recommended function instead contains total design capacity and designed number of pumps. Both of these would need to be known before estimation of design power could be attempted.

Two other functions, relating construction cost to total structural volume and total floor area respectively, are also reported.

The New Construction Index was chosen for deflation of costs in preference to the DQSD and Basic Weekly Wage Rate Indices.

B. The results

(i) Data summary

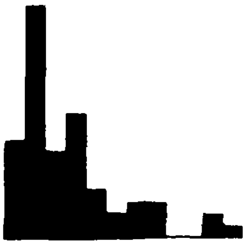
Table 14-4. Sewage pumping station data summary

Variable	Label	Unit	Min.	Max.	Mean	St. dev.
Total construction cost (corrected to 1976 Q3)	PUMPCOS	£'000	6.68	130	37.5	29.5
Total design capacity	DESCAP	l/s	2	1440	242	389
Design number of pumps	DESN-PUMP	-	1	7	2.74	1.29
Volume of sub-structure + vol. of superstructure	VOL	m^3	30.0	2210	401	418
Total floor area	AREA	m^2	6.0	300	66.5	58.7
Omnibus 23 (see Section 8.3.3)	Z23	-	0.37	8170	847	1800

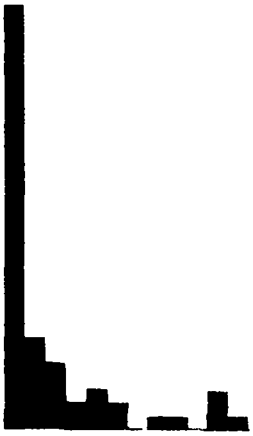
Note: 1. Number of cases: [illegible]

2. The New Construction Orders Index was used for deflation

Mini-histograms for the main variables of interest:


PUMPCOS


LOG PUMPCOS


DESCAP

14.3. Sewage pumping stations

(ii) The recommended cost function

The recommended function for sewage pumping stations is:-

$$\boxed{\text{PUMPCOS} = 6.97*\text{DESCAP}^{0.21}*\text{DESNPUMP}^{0.60}}$$

The statistical details of the function are as follows:-

Number of observations	:	58
Multiple correlation coefficient (R)	:	0.83
Coefficient of determination (R^2)	:	68%
Standard error of residuals (in $\log_{10}$ model)	:	0.185

Explanatory variable	Regression coefficient	Standard error	F-value	Significance level
DESCAP	0.214	0.042	25.8	$\ll 0.1\%$
DESNPUMP	0.602	0.177	11.5	$< 1.0\%$

Approximate multipliers for confidence intervals about a prediction:-

Confidence level	Lower	Upper
80%	0.58	1.74
95%	0.43	2.34

The omnibus variable is given by:

$$Z23 = 0.0609*DESCAP*DESNPUMP^{2.82}.$$

Figures 14-5 and 14-6 show the five standard diagrams in support of the function.

(iii) Other cost functions

A function with better predictive ability can be used if the total volume of substructure and superstructure is known:-

$$\boxed{PUMPCOS = 0.916*VOL^{0.63}}$$

The statistical details of the function are as follows:-

Number of observations : 58
Correlation coefficient (R) : 0.90
80% confidence interval multipliers : 0.66, 1.52
Standard error of residuals (in $\log_{10}$ model) : 0.140

If total floor area is the only physical variable that is known, the following cost function can be used:-

$$\boxed{PUMPCOS = 3.03*AREA^{0.59}}$$

The statistical details of the function are as follows:-

Number of observations : 58
Correlation coefficient (R) : 0.80
80% confidence interval multipliers : 0.56, 1.79
Standard error of residuals (in $\log_{10}$ model) : 0.195

(iv) The data

The sewage pumping station data is listed in Table A-57.

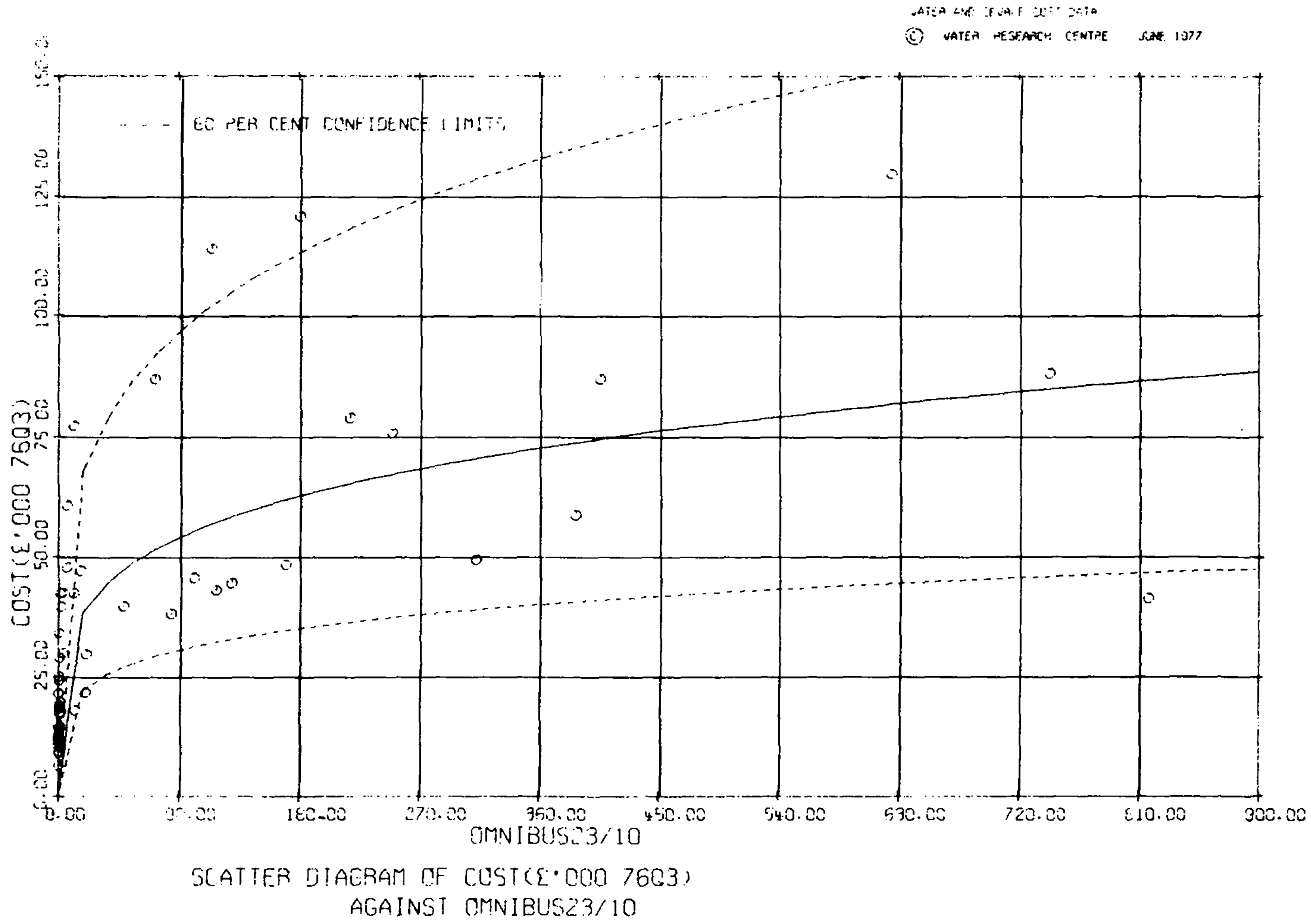
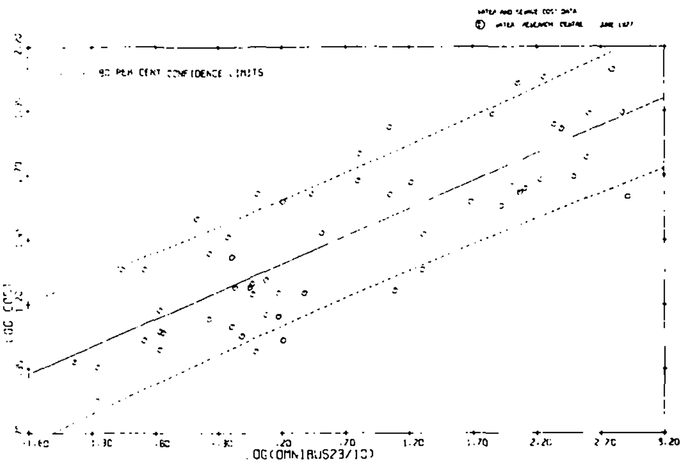
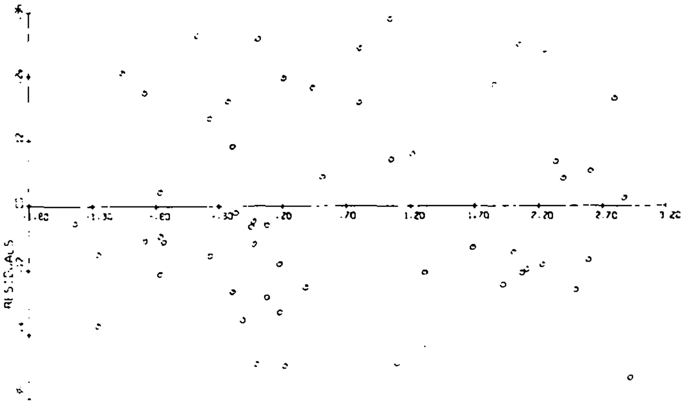


Figure 14-5. Buildings—sewage pumping stations

Figure 14-6. Buildings—sewage pumping stations

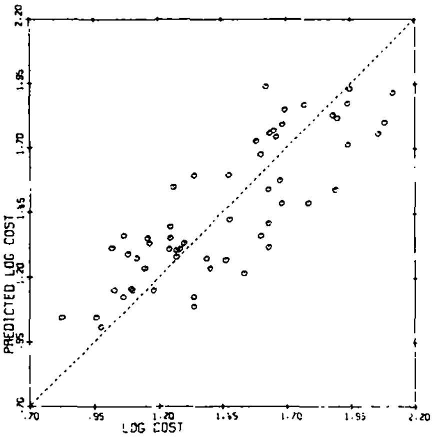


SCATTER DIAGRAM OF LOG COST
AGAINST LOG(OMNIBUS23/10)



SCATTER DIAGRAM OF RESIDUALS
AGAINST LOG(OMNIBUS23/10)

HISTOGRAM OF RESIDUALS



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

PART IV—USERS' DIGEST

INTRODUCTION

Part III contains a large number of cost functions. Many of these are subsidiary to the main function in the section, or require for their use detailed explanatory variables not of prime interest to the national or regional planner. It was felt, therefore, that it would be helpful to gather together in an abbreviated form the models which would be of most use at the broad planning level.

Part IV summarizes those cost functions which are separately required for estimating the total cost of major schemes. Thus for the planning of water distribution schemes, for example, it is necessary to present the water mains total cost function and also the water pumping plant and buildings cost functions. On the other hand, most of the cost functions for individual components of water treatment and sewage treatment works have not been included. In these areas, presentation of the recommended functions alone would not allow the planner to arrive at whole works cost estimates without a great deal of intricate calculation, perhaps not always warranted by the application. This difficulty was overcome by carrying out the necessary calculations for a variety of component combinations over a range of throughputs, to arrive at a table of 'typical costs'. A similar approach was taken with multiple borehole schemes and with intakes.

For each individual cost function quoted, the following details have been included:-

(i) size of the data sample;
(ii) the range spanned by each variable;
(iii) multipliers for confidence limits.

In each particular case, some indication is given of which items are included in the definition of cost. As a general rule, the quoted cost functions make no allowance for design, supervision, compensation and contingencies.

WARNING

Each model presented in Part III is accompanied by a full statistical and graphical back-up, together with details of its range of validity, how cost has been defined, what explanatory variables were tested, and other necessary comments or provisos. The condensed presentation of Part IV is unable to include many of these restrictions or qualifications. This heightens the risk of a model being applied incorrectly, and the reader must refer to the appropriate sections of Part III before using Part IV.

SEWERAGE

$$COST = 0.000717*LEN^{0.94}*DIAM^{0.72}*DEP^{0.57}$$

			Unit	Min.	Max.
where	COST	is total cost of scheme,	£'000 1976 Q3	2.5	2050
	LEN	is total length of pipework,	m	45	30 000
	DIAM	is mean diameter of scheme, weighting individual pipe diameters by their lengths,	mm	86	1440
and	DEP	is mean depth of scheme, weighting individual pipe depths by their corresponding excavated areas.	m	1.14	7.10

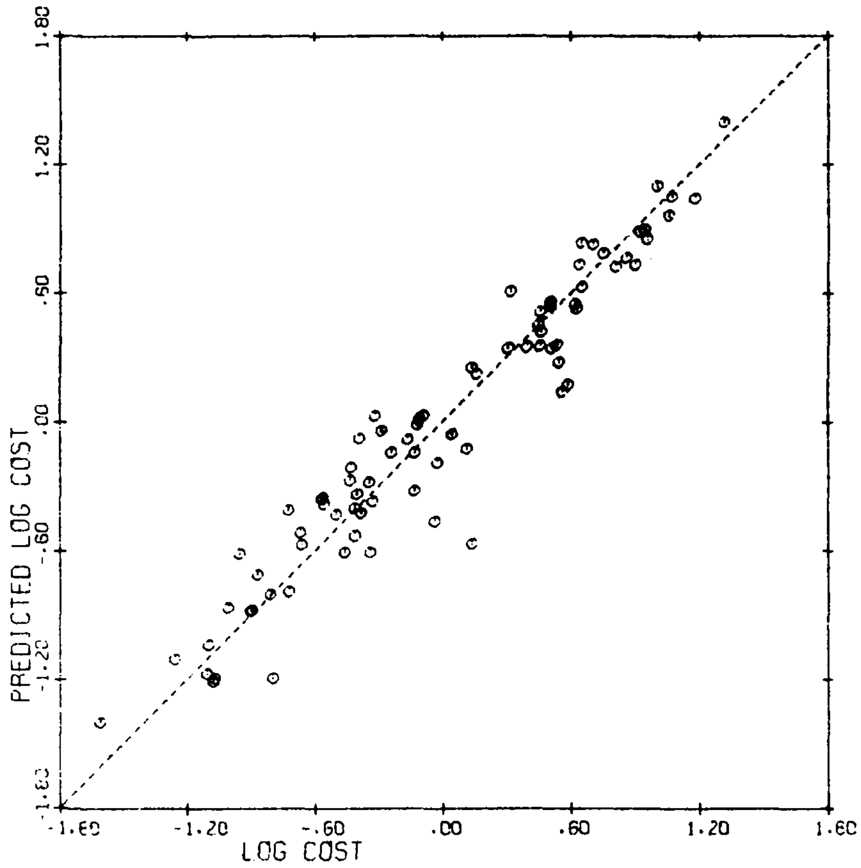
Number of cases: 80

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.56	1.78
95%	0.41	2.43

Note:

1. The New Construction Index should be used for inflation (value at 1976 Q3 = 263).
2. The data is listed in Table A-1.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. A more detailed presentation of the work in this area is contained in Section 10.1. In particular, it is possible to take some account of factors like ground condition, difficulty of reinstatement and manhole type by means of the 'over-under' factor.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

Note: **In this figure, costs are measured in units of £'00 000.**

WATER MAINS

$$\text{COST} = 0.0702{*}\text{LEN}^{0.73}{*}\text{DIAM}^{0.91(\text{DIAM}/(1000 + \text{DIAM}))}$$

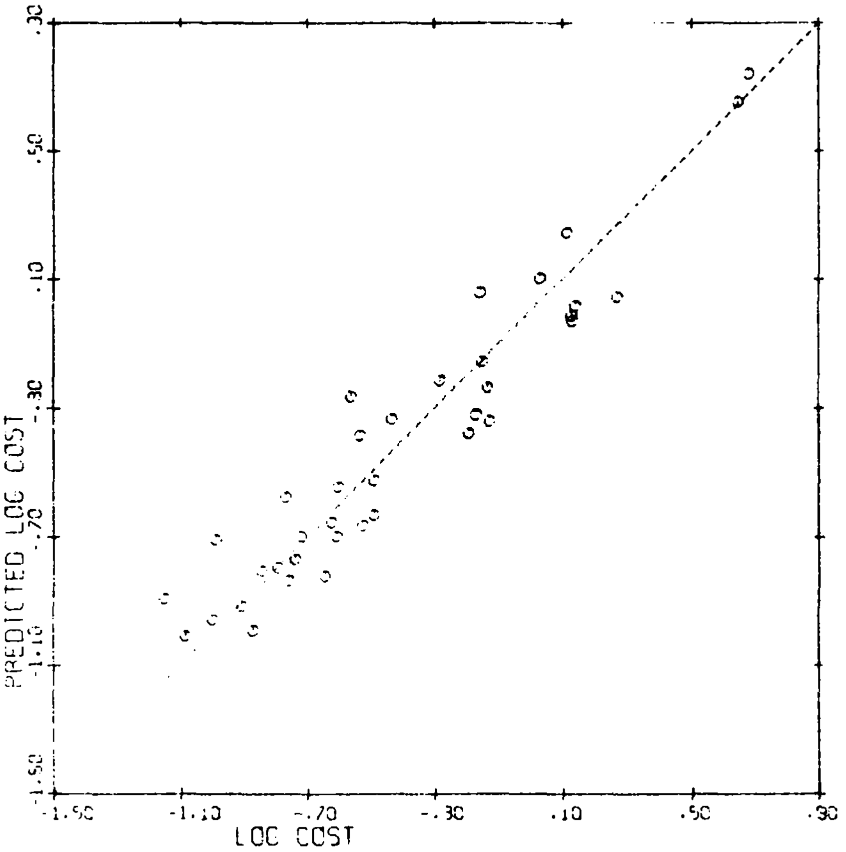
			Unit	Min.	Max.
where	COST	is total cost (i.e. installation and materials cost) of scheme,	£'000 1976 Q3	70.3	4770
	LEN	is total length of pipework,	m	744	45 500
and	DIAM	is mean diameter of scheme, weighting individual pipe diameters by their lengths.	mm	126	1830

Number of cases: 37

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.64	1.55
95%	0.51	1.98

Note:
1. The Construction Materials Index should be used for inflation (value at 1976 Q3 = 258).
2. The data is listed in Table A-3.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. Section 10.2 contains a more detailed presentation both of this model and of a model for installation cost alone.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

Note: In this figure, costs are measured in units of £ million.

TUNNELS AND SHAFTS

$$\boxed{\text{COST} = 0.0265*\text{VOL}^{1.07}}$$

			Unit	Min.	Max.
where	COST	is the total tunnels and shafts cost of a scheme (see Note 4 below),	£million 1976 Q3	0.148	4.23
and	VOL	is the sum of the excavated volumes of the individual tunnels and shafts making up the contract.	'000 m^3	4.75	131

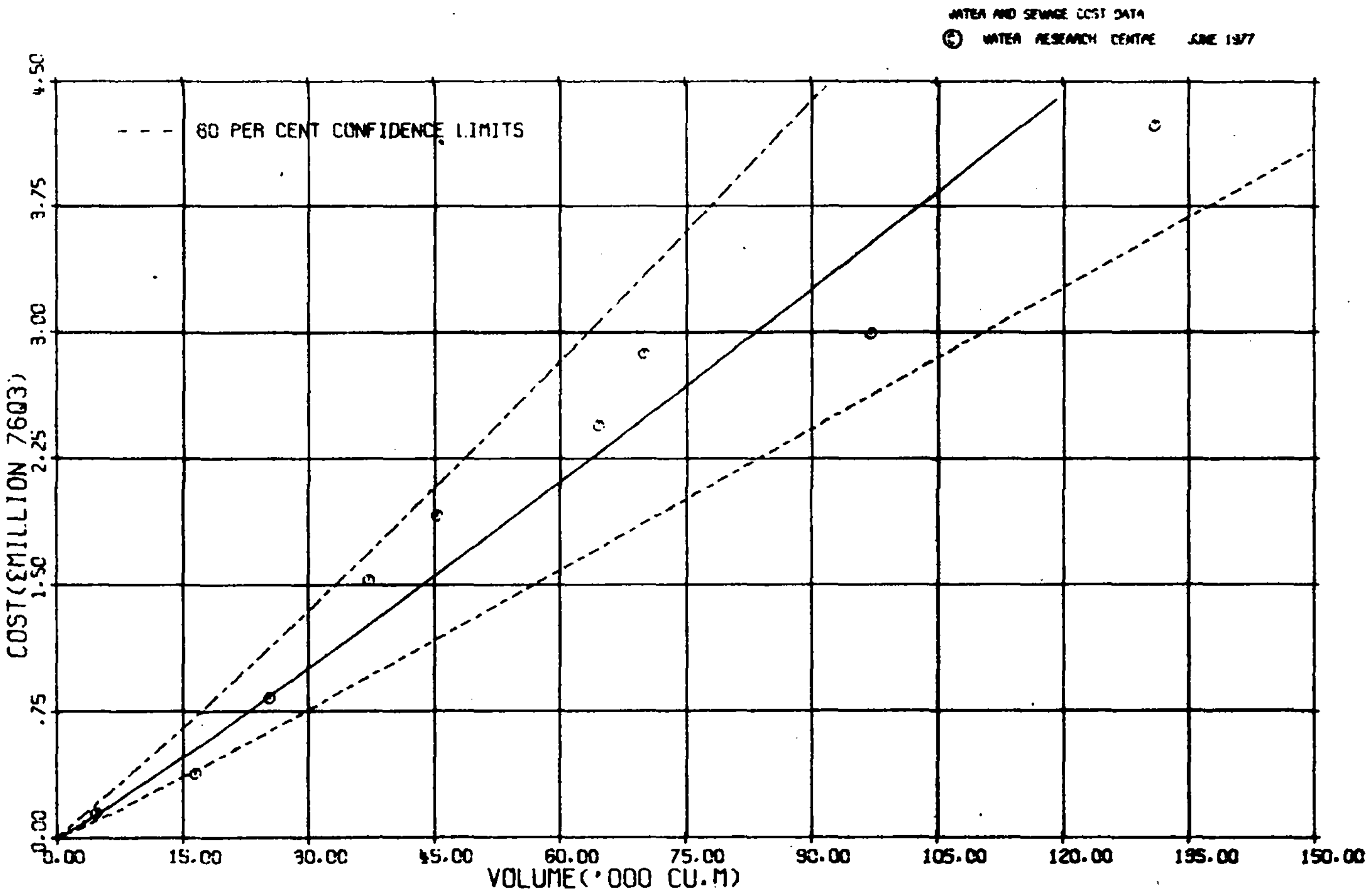
Number of cases: 9

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.76	1.31
95%	0.64	1.57

Note:

1. The Construction Materials Index should be used for inflation (value at 1976 Q3 = 258).
2. The data is listed in Table A-6.
3. A scatter diagram of COST against VOL is shown on the facing page.
4. COST is the cost of the individual tunnels and shafts making up the contract (assuming wedge-blocked lining), but excluding costs of secondary lining, shafts fittings, internal pipes and general and preliminary items.
5. Total contract cost may be estimated by first applying the above model and then multiplying by a LINING factor, which takes the value 1.43 for wedge-block lining, 1.57 for bolted concrete segment lining, and 2.00 for cast iron segment lining. This procedure is discussed more fully in Section 10.3D.
6. A more detailed presentation of the work in this area is contained in Section 10.3. In particular, models are available for tunnels and shafts separately.



SCATTER DIAGRAM OF COST(£MILLION 76Q3)
AGAINST VOLUME('000 CU.M)

WATER PUMPING PLANT

$$\boxed{\text{WATCOS} = 0.0229 * \text{NORMCAP}^{0.81} * \text{NORMHEAD}^{0.43}}$$

			Unit	Min.	Max.
where	WATCOS	is total cost of installation,	£'000 1976 Q3	2.49	390
	NORMCAP	is total installed capacity referring to normal rating of plant (see Note 4 below),	m^3/h	36	16 100
and	NORMHEAD	is normal operating head.	m	13.7	181

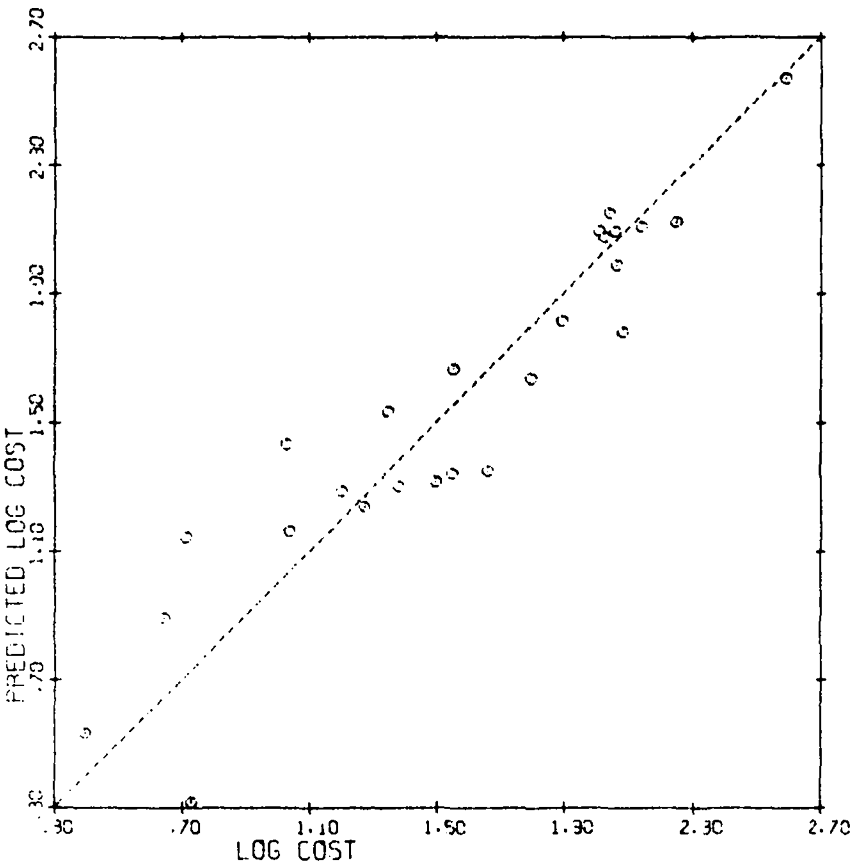
Number of cases: 25

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.52	1.93
95%	0.36	2.80

Note:

1. The Engineering and Allied Industries Index should be used for inflation (value at 1976 Q3 = 227).
2. The data is listed in Table A-7.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. NORMCAP is the combined operating and standby capacity (the extent of standby is decided by the user). The definitions of capacity and head are discussed in more detail in Section 10.4.1.
5. A more detailed presentation of the work in this area is given in Section 10.4.1. In particular, cost can be related to either NORMCAP or installed power alone.
6. To estimate the cost of a complete pumping station, this digest should be used in conjunction with the water pumping buildings digest.



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

WATER PUMPING BUILDINGS

$$\boxed{\text{WATPUMPCOS} = 4.00*\text{THRUPUT}^{0.79}}$$

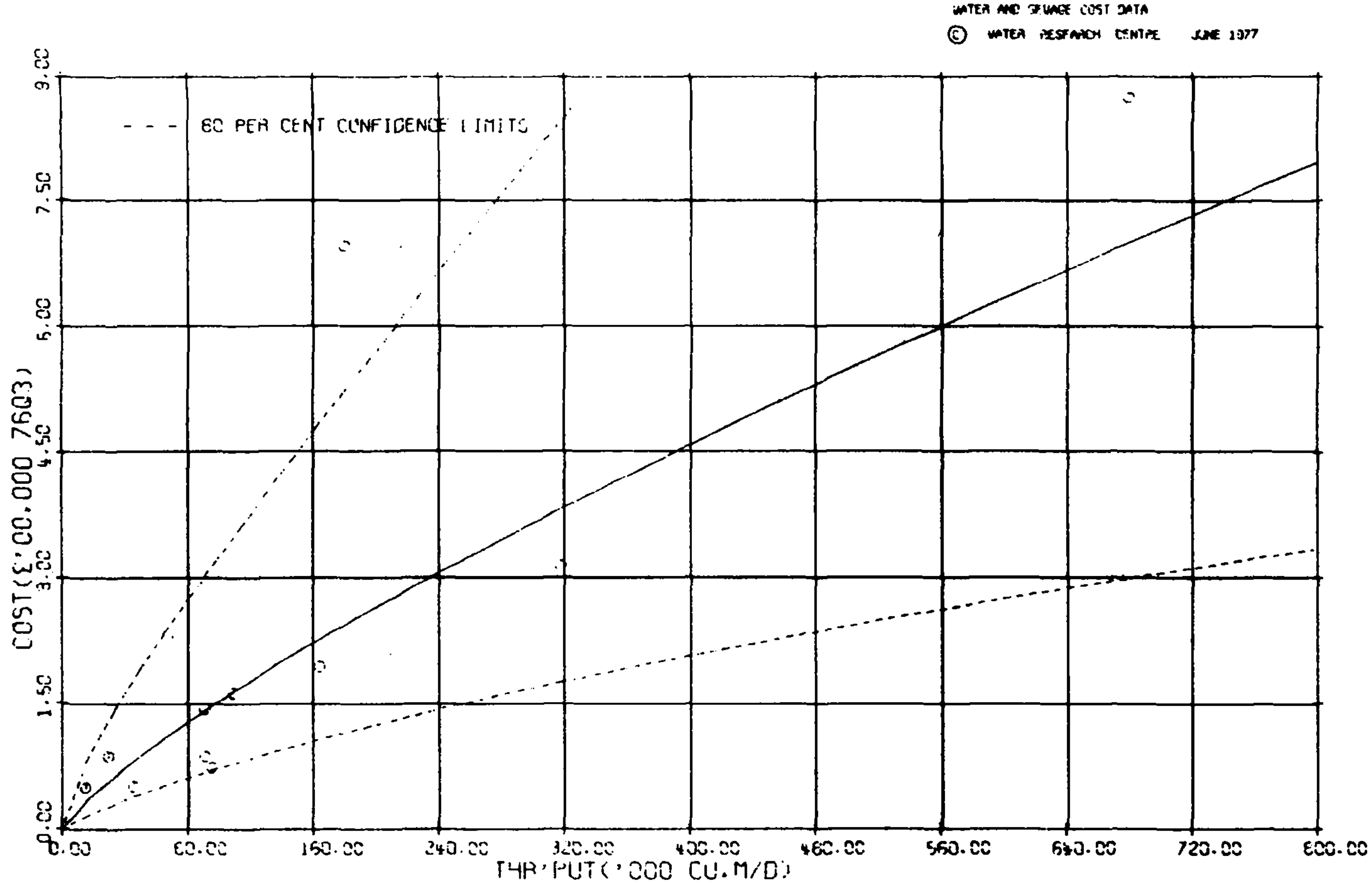
			Unit	Min.	Max.
where	WATPUMPCOS	is total construction cost,	£'000 1976 Q3	49.2	874
and	THRUPUT	is design throughput.	'000 m^3/d	15	680

Number of cases: 11

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.49	2.06
95%	0.31	3.26

Note:
1. The DQSD Index should be used for inflation (value at 1976 Q3 = 246).
2. The data is listed in Table A-55.
3. A scatter diagram of WATPUMPCOS against THRUPUT is shown on the facing page.
4. A more detailed presentation of the work in this area is given in Section 14.1. This includes a more satisfactory cost function based on the floor area of the pumping station. Reference should also be made to the intakes digest, and Sections 10.4.2 and 12.1.6D.
5. To estimate the cost of a complete pumping station, this digest should be used in conjunction with the water pumping plant digest.



WATER AND SEWAGE COST DATA
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SCATTER DIAGRAM OF COST(£'00,000 7603)
AGAINST THR'PUT('000 CU.M/D)

INTAKES

Intake stations should be considered as pumping stations (with or without pumping plant) together with the additional bankside civil engineering and screening plant costs. Both of these additional items depend largely upon circumstances, but making simplifying assumptions the following table can be constructed.

Throughput ('000 m^3/d)	£'000 1976 Q3		
	Pumping station		Intake station
	Building	Building and pumping plant	Pumping station with intake structure and plant
2	6.92	13.5	19.6
5	14.3	27.6	41.4
10	24.7	47.4	69.8
20	42.6	81.4	120
50	88.0	167	230
100	152	286	382
200	263	491	640
500	542	1000	1310

Note: 1. The multipliers for confidence intervals about a prediction have been assumed to be similar to those given for the water pumping station building and pumping plant models; approximate values are as follows:-

Confidence level	Lower	Upper
80%	0.5	2.0
95%	0.33	3.0

2. The New Construction Index should be used for inflation of civil engineering items (value at 1976 Q3 = 263).
3. The Engineering and Allied Industries Index should be used for inflation of plant items (value at 1976 Q3 = 227).
4. The figures assume a 50% standby pumping plant capacity.
5. Costs exclude any major interconnecting aqueduct between the intake and the pumping station.
6. More detailed information on work in this area is contained in Section 12.1.6D and also in Sections 10.4.1, 10.4.2, 12.2.2 and 14.1.

SEWERAGE PUMPING PLANT

$$\boxed{SEWCOS = 1.63 * CAP^{0.29} * HEAD^{0.19} * NPUMP^{0.89}}$$

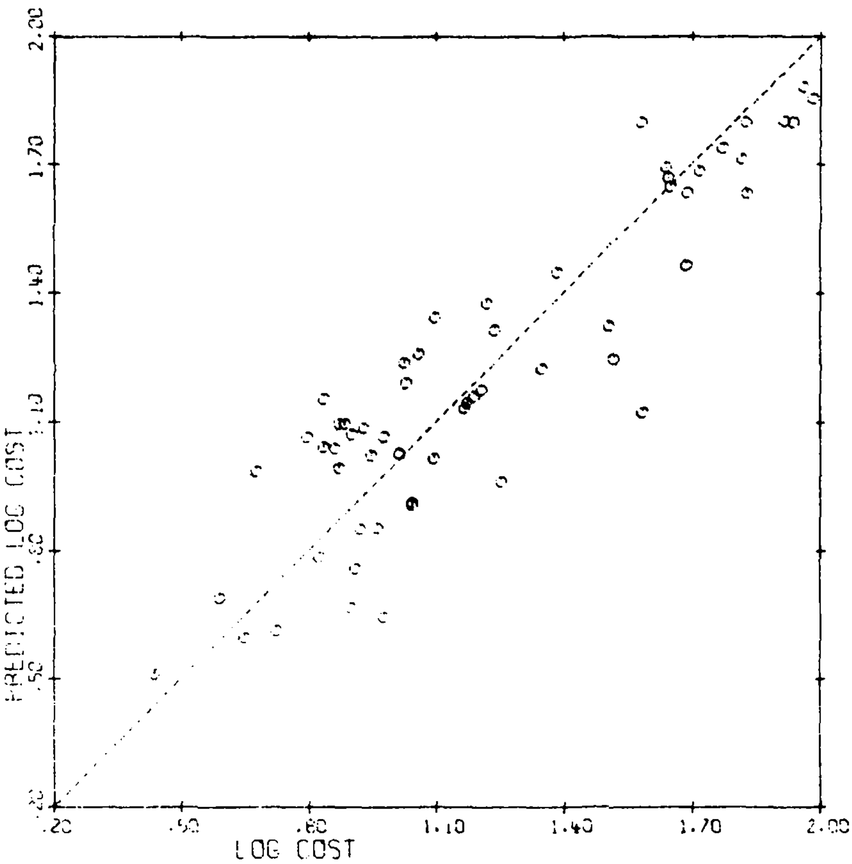
			Unit	Min.	Max.
where	SEWCOS	is total plant cost,	£'000 1976 Q3	2.74	96.0
	CAP	is total installed capacity (see Note 4 below),	l/s	1	1350
	HEAD	is total head,	m	1.5	60.9
and	NPUMP	is number of pumps installed.	-	1	7

Number of cases: 58

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.59	1.68
95%	0.45	2.23

Note:
1. The Engineering and Allied Industries Index should be used for inflation (value at 1976 Q3 = 227).
2. The data is listed in Table A-9.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. CAP is the combined operating and standby capacity (the extent of standby is decided by the user).
5. A more detailed presentation of the work in this area is given in Section 10.4.1. This contains an alternative function in which cost is expressed in terms of installed power alone.
6. To estimate the cost of a complete pumping station, this digest should be used in conjunction with the sewerage pumping buildings digest.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

SEWERAGE PUMPING BUILDINGS

$$\boxed{\text{COST} = 6.97 * \text{DESCAP}^{0.21} * \text{DESNPUMP}^{0.60}}$$

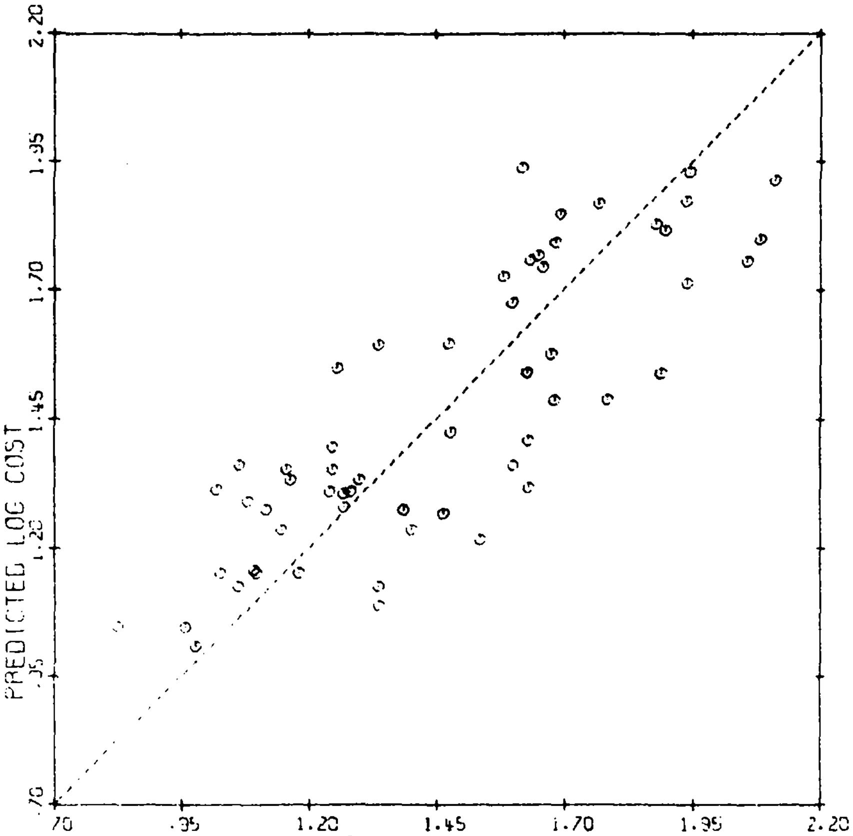
			Unit	Min.	Max.
where	PUMPCOS	is total construction cost,	£'000 1976 Q3	6.68	130
	DESCAP	is design capacity,	l/s	2	1440
and	DESNPUMP	is design number of pumps.	-	1	7

Number of cases: 58

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.58	1.74
95%	0.43	2.34

Note:
1. The New Construction Index should be used for inflation (value at 1976 Q3 = 263).
2. The data is listed in Table A-57.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. A more detailed presentation of the work in this area is contained in Section 14.3. This includes a more satisfactory model based on total volume of substructure and superstructure of the pumping station.
5. To estimate the cost of a complete pumping station, this digest should be used in conjunction with the sewerage pumping plant digest.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

PUMPING OPERATING COSTS

The cost of pumping at a given efficiency of pumping plant is calculated from:-

$$\boxed{\text{COST} = 0.00272*\text{TARIFF}*\text{CAPACITY}*\text{HEAD}/\text{EFFICIENCY}}$$

where COST is in £1976 Q3/h,
TARIFF is in £/kWh,
CAPACITY is in m^3/h,
HEAD is in m,
and EFFICIENCY is a proportion.

This is discussed more fully in Sections 10.4.1 and 10.4.4.

SINGLE BOREHOLES—TYPE 1 (no screen or pack)

$$\boxed{\mathrm{COST} = 0.851{*}\mathrm{DEP}^{0.49}{*}\mathrm{DIAM}^{0.64}{*}\mathrm{CASLEN}^{0.21}}$$

			Unit	Min.	Max.
where	COST	is total construction cost of a Type 1 borehole (see Note 4 below),	£'000 1976 Q3	5.18	24.3
	DEP	is depth of borehole,	m	51.8	241
	DIAM	is diameter of borehole,	m	0.300	1.00
and	CASLEN	is length of casing.	m	7.62	82.3

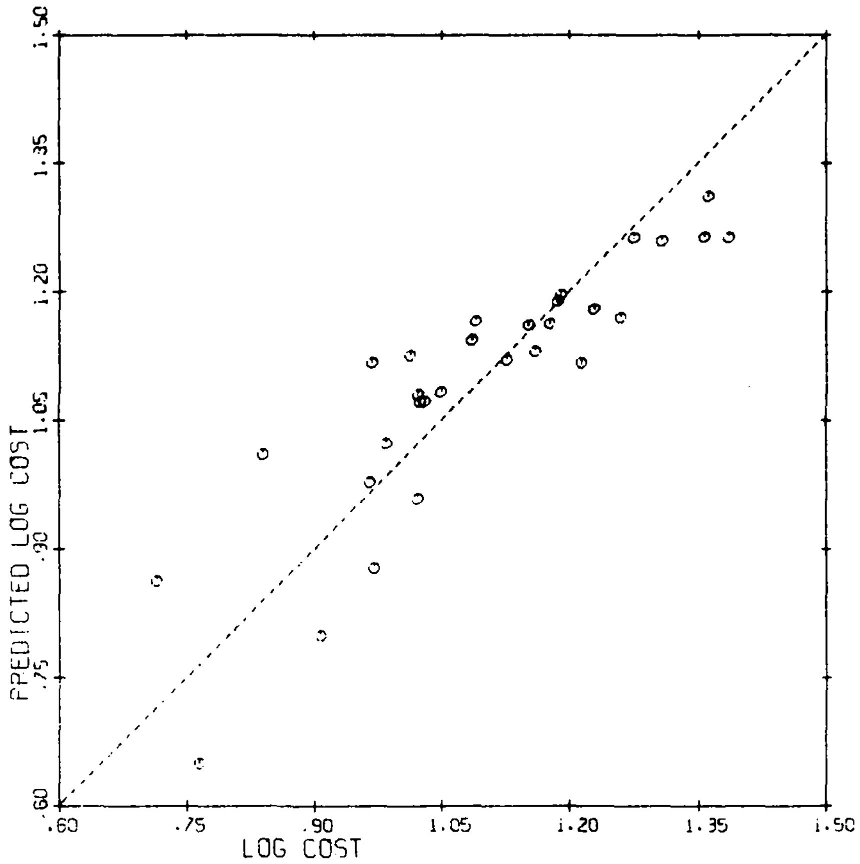
Number of cases: 30

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.77	1.30
95%	0.67	1.50

Note:
1. The Average Earnings Index should be used for inflation (value at 1976 Q3 = 241).
2. The data is listed in Table A-11.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. COST comprises the setting-up, drilling, casing and grouting costs of the borehole.
5. A more detailed presentation of the work in this area is contained in Section 11.1.1. In particular, models are available for the borehole sub-costs.

Type 1 boreholes



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

SINGLE BOREHOLES—TYPE 2 (with screen and pack)

$$\boxed{\mathrm{COST} = 1.94*\mathrm{DEP}^{0.62}*\mathrm{SCRTYP}^{-0.44}, \quad 0.5 < \mathrm{DIAM} < 0.8}$$

where COST is total construction cost of a Type 2 borehole (see Note 4 below),

DEP is the depth of borehole,

and SCRTYP is 1 for a screen made of stainless steel or rubber-coated steel with a pre-formed pack, and
2 for a mild steel slotted screen.

DIAM is the drilled diameter of borehole, and must lie between 0.5 and 0.8 m for valid use of the model.

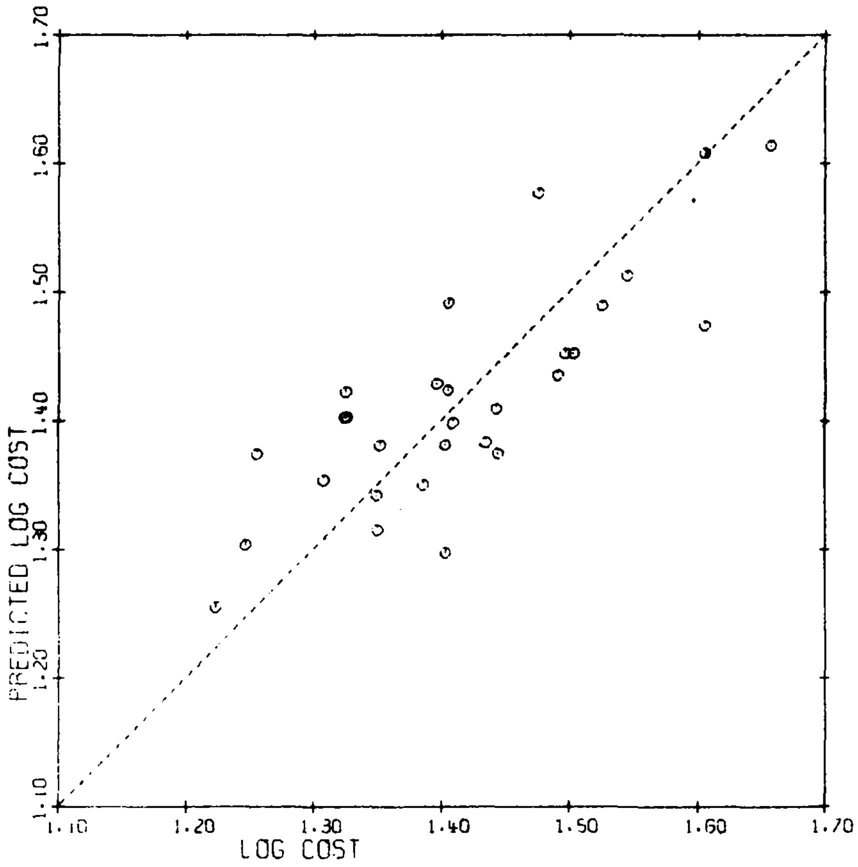
Unit	Min.	Max.
£'000 1976 Q3	16.7	45.4
m	35.4	137

Number of cases: 29

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.82	1.22
95%	0.73	1.37

Note:
1. The Steel Output Index should be used for inflation (value at 1976 Q3 = 282).
2. The data is listed in Table A-12.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. COST comprises the setting-up, drilling, casing, grouting, screening and packing costs of the borehole.
5. A more detailed presentation of the work in this area is contained in Section 11.1.1. In particular, a model suitable for Type 2 boreholes with drilled diameter greater than 0.8 m is presented. Also, models are available for the borehole sub-costs.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

MULTIPLE BOREHOLE SCHEMES

	Yield of scheme					
	45 Ml/d		90 Ml/d		135 Ml/d	
Aquifer type	Chalk	Permo-Triassic Sandstone	Chalk	Permo-Triassic Sandstone	Chalk	Permo-Triassic Sandstone
50% Probability yield of aquifer (Ml/d)	3.3	2.2	3.3	2.2	3.3	2.2
Number of boreholes required for scheme yield	14	20	27	41	41	61
	Cost (£'000 1976 Q3)					
<u>Construction cost</u>	203	275	365	567	567	841
<u>Additional costs</u>:						
A. Acidization cost (£2500 per borehole)	35	-	67	-	103	-
B. Test-pumping cost (£6000 per borehole)	84	120	162	246	246	366
C. Pump/rising main/ switchgear cost (£8000 per borehole)	112	160	216	328	328	488
D. Headworks chamber cost (£2000 per borehole)	28	40	54	82	82	122
Cost of abstraction boreholes (i. e. construction cost and additional costs)	462	595	864	1222	1326	1817
<u>Ancillary costs</u>:						
1. Exploratory boreholes (number required)	(2)	(2)	(2)	(3)	(3)	(4)
Construction cost (£6000 per borehole)	12	12	12	18	18	24
Acidization and/or test-pumping of exploratory boreholes	17	12	17	18	26	24
2. Observation boreholes (number required)	(28)	(40)	(50)	(60)	(60)	(80)
Construction cost (£2000 per borehole)	56	80	100	120	120	160
Total cost	547	699	993	1378	1490	2025

Note:

1. The construction cost in each case was estimated using the multiple boreholes cost function presented in Section 11.1.2, assuming a mean borehole diameter of 0.61 m, a casing length of 30 m per borehole, and a mean depth within the range 80 to 160 m.
2. 'Total cost' does not include pipeline costs, even though these will form a substantial part of the overall scheme cost, as it is not possible to estimate the length of pipeline required without more detailed knowledge of a scheme.
3. Instrumentation, compensation and design costs have not been included above, as these are related to the overall total cost of a scheme, including pipelines.
4. The Engineering and Allied Industries Index should be used for inflating cost item C (value at 1976 Q3 = 227); for all other costs the Average Earnings Index should be used (value at 1976 Q3 = 241).
5. The multiple borehole data is listed in Table A-13.
6. The assumptions and qualifications attached to each of the above cost estimates are discussed in detail in Section 11.1.2. It is important that these are studied before the figures are used for planning purposes.

CONCRETE DAMS

$$\boxed{\text{CONCOS} = 0.0569*\text{DAMVOL}^{0.95}}$$

where CONCOS is total cost of dam (see Note 5 below),

and DAMVOL is volume of fill of dam.

Unit	Min.	Max.
£ million 1976 Q3	1.13	12.1
'000 m^3	19	252

Number of cases: 13

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.77	1.29
95%	0.71	1.40

Note:

1. The Construction Materials Index should be used for inflation (value at 1976 Q3 = 258).
2. The data is listed in Table A-14.
3. A scatter diagram of CONCOS against DAMVOL is shown on the facing page.
4. The function applies only to mass concrete gravity dams.
5. CONCOS includes the cost of the dam, cut-off, adjacent or integral inlet and outlet works, integral pipe and tunnel works, and minor diversions and ancillary works.
6. A more detailed presentation of the work in this area is contained in Section 11.2.

WATER AND SEWAGE COST DATA
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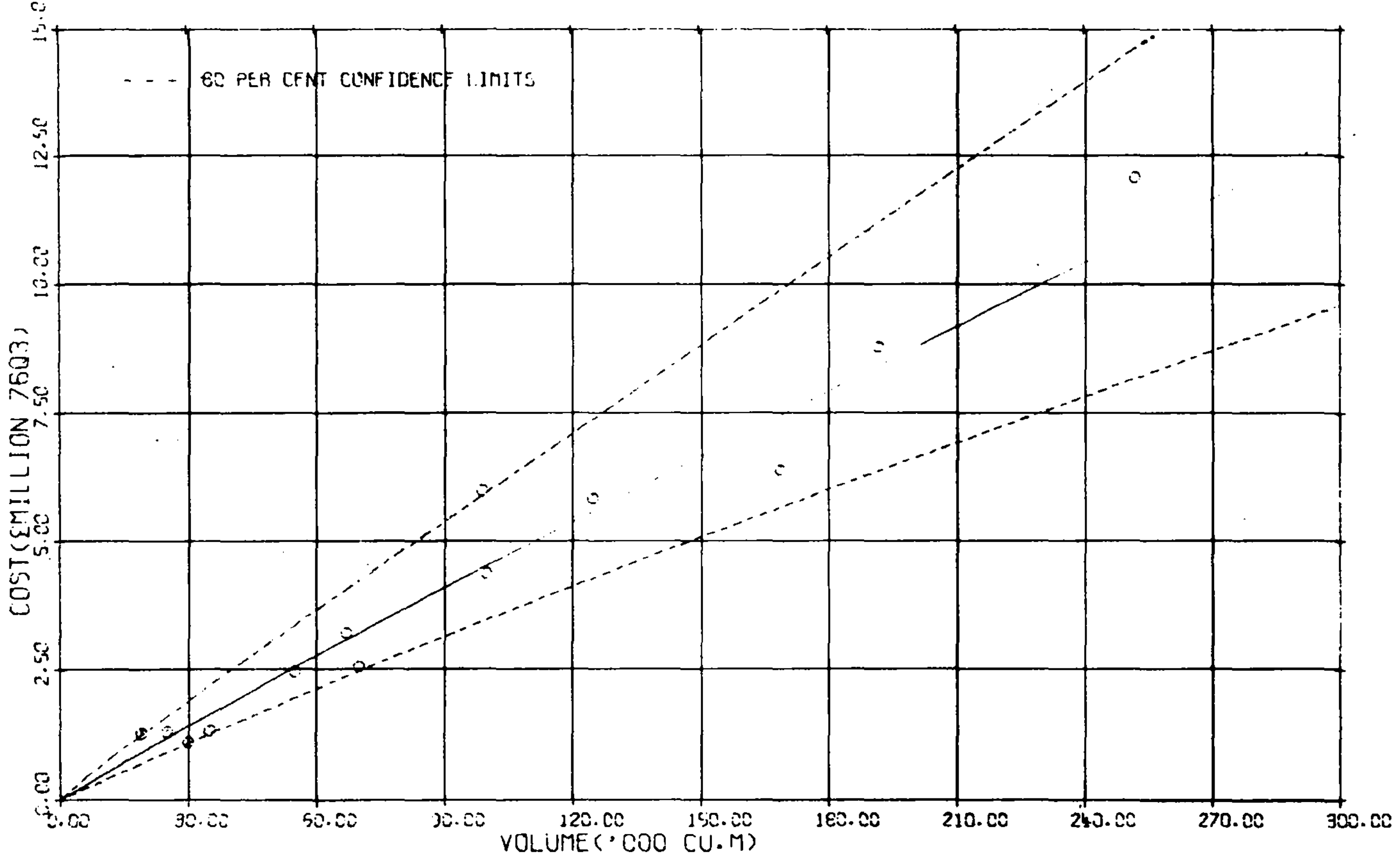


SCATTER DIAGRAM OF COST(£MILLION 76Q3)
AGAINST VOLUME('000 CU.M)

EARTHBANK DAMS (with concrete cut-off walls)

$$\boxed{\text{CONWALLCOS} = 8.97*\text{DAMVOL}^{0.66}}$$

			Unit	Min.	Max.
where	CONWALLCOS	is total cost of dam (see Note 5 below),	£ million 1976 Q3	2.61	18.9
and	DAMVOL	is volume of fill of dam, including all material placed and compacted.	million m^3	0.116	3.00

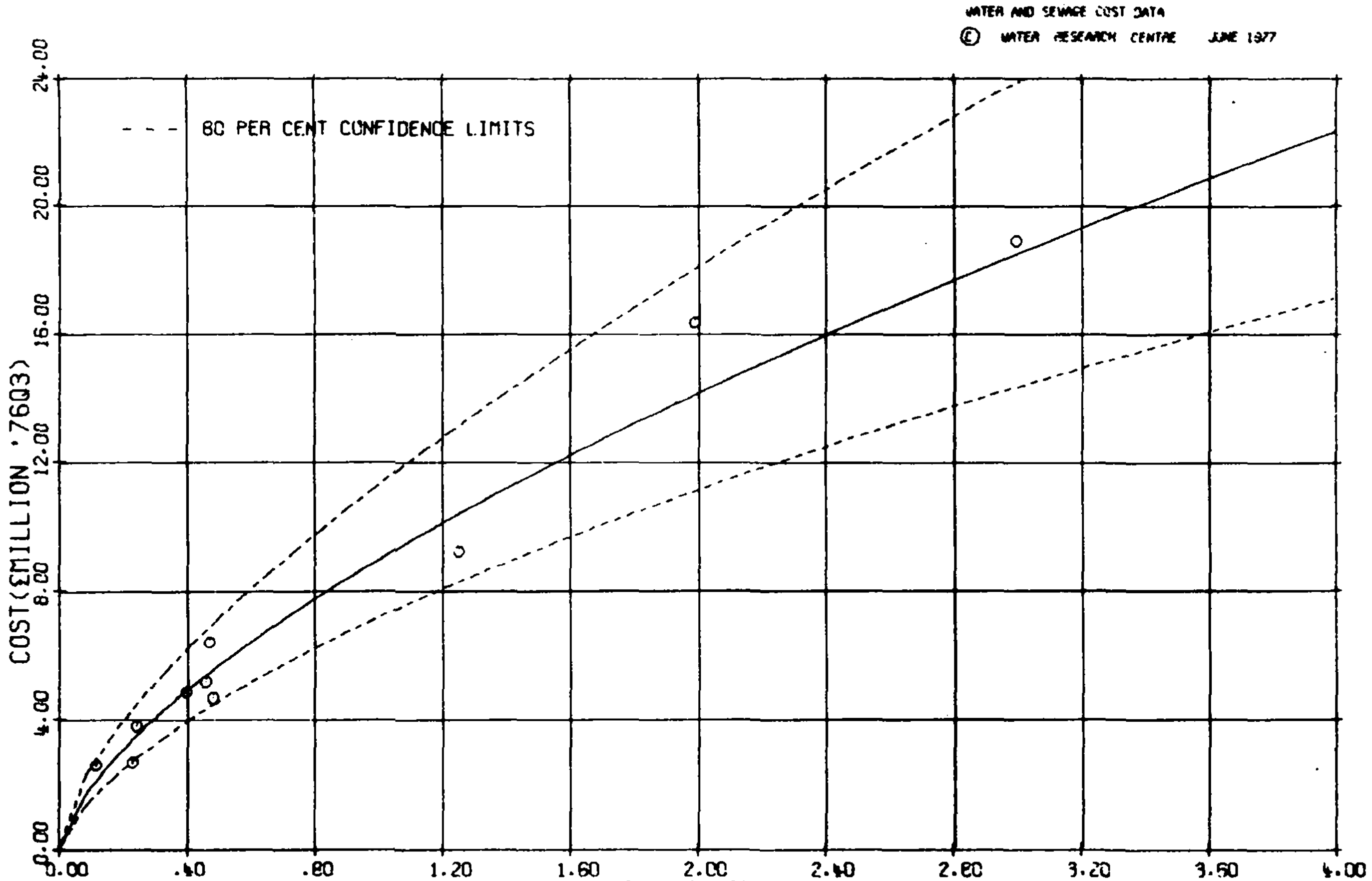
Number of cases: 10

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.81	1.24
95%	0.70	1.42

Note:

1. The Construction Materials Index should be used for inflation (value at 1976 Q3 = 258).
2. The data is listed in Table A-15(a).
3. A scatter diagram of CONWALLCOS against DAMVOL is shown on the facing page.
4. The function applies only to earthbank dams constructed with a concrete cut-off wall that is substantial enough to act also as the core.
5. CONWALLCOS includes the cost of the dam, cut-off, adjacent or integral inlet and outlet works, integral pipe and tunnel works, and minor diversions and ancillary works.
6. A more detailed presentation of the work in this area is contained in Section 11.2.



SCATTER DIAGRAM OF COST(£MILLION '76Q3)
AGAINST VOLUME(MILLION CU.M)

EARTHBANK DAMS (with clay cores)

$$\boxed{\mathrm{CLAYCORECOS} = 4.53 * \mathrm{DAMVOL}^{0.73} * \mathrm{TYPE}^{-0.58}}$$

where CLAYCORECOS is total cost of dam (see Note 5 below),

DAMVOL is volume of fill of dam, including all material placed and compacted,

and TYPE is 2 for clay-cored bunds (see Note 6 below), and
1 for other clay-cored dams.

Unit	Min.	Max.
£ million 1976 Q3	1.07	11.9
million m^3	0.195	7.65

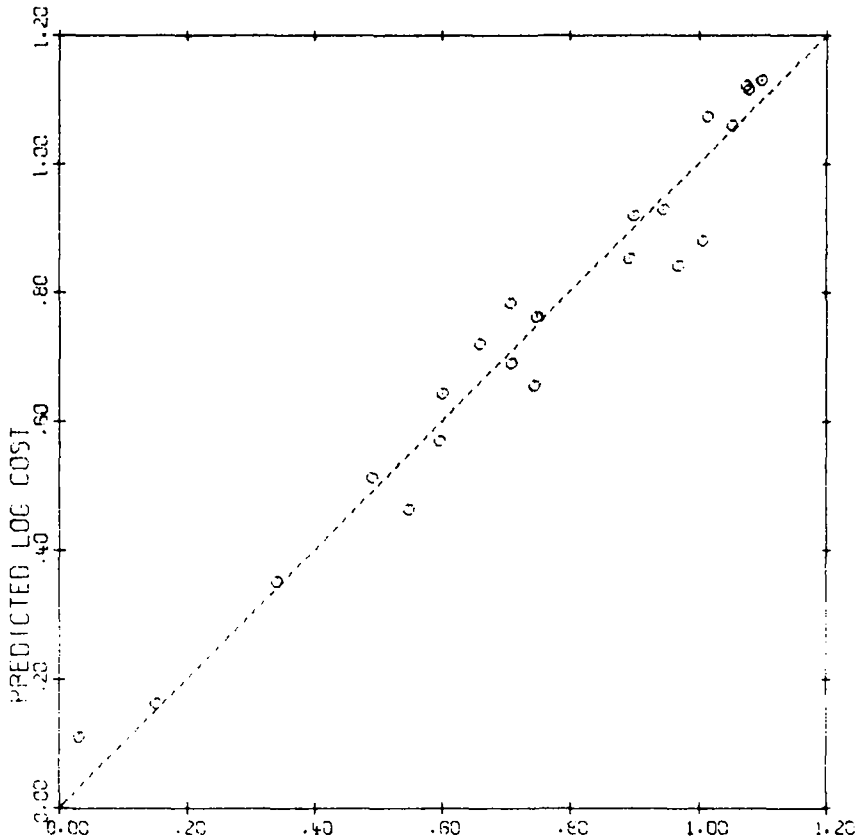
Number of cases: 22

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.82	1.22
95%	0.73	1.36

Note:

1. The Construction Materials Index should be used for inflation (value at 1976 Q3 - 258).
2. The data is listed in Table A-15(b).
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. The effect on cost of using some rockfill or concrete grouting was statistically insignificant.
5. CLAYCORECOS includes the cost of the dam, cut-off, adjacent or integral inlet and outlet works, integral pipe and tunnel works, and minor diversions and ancillary works.
6. A more detailed presentation of the work in this area is contained in Section 11.2. In particular, costs of reservoirs constructed with clay-cored bunds can also be estimated from volume of water stored.



SCATTER DIAGRAM OF PREDICTED LOG COST AGAINST LOG COST

RESERVOIRS AND LAGOONS

$$\text{CLAYBUNCOS} = 1.05*\text{RESVOL}^{0.68}$$

			Unit	Min.	Max.
where	CLAYBUNCOS	is total cost of embankment (see Note 5 below),	£ million 1976 Q3	0.0135	11.9
and	RESVOL	is the storage volume.	million m^3	0.00226	37.7

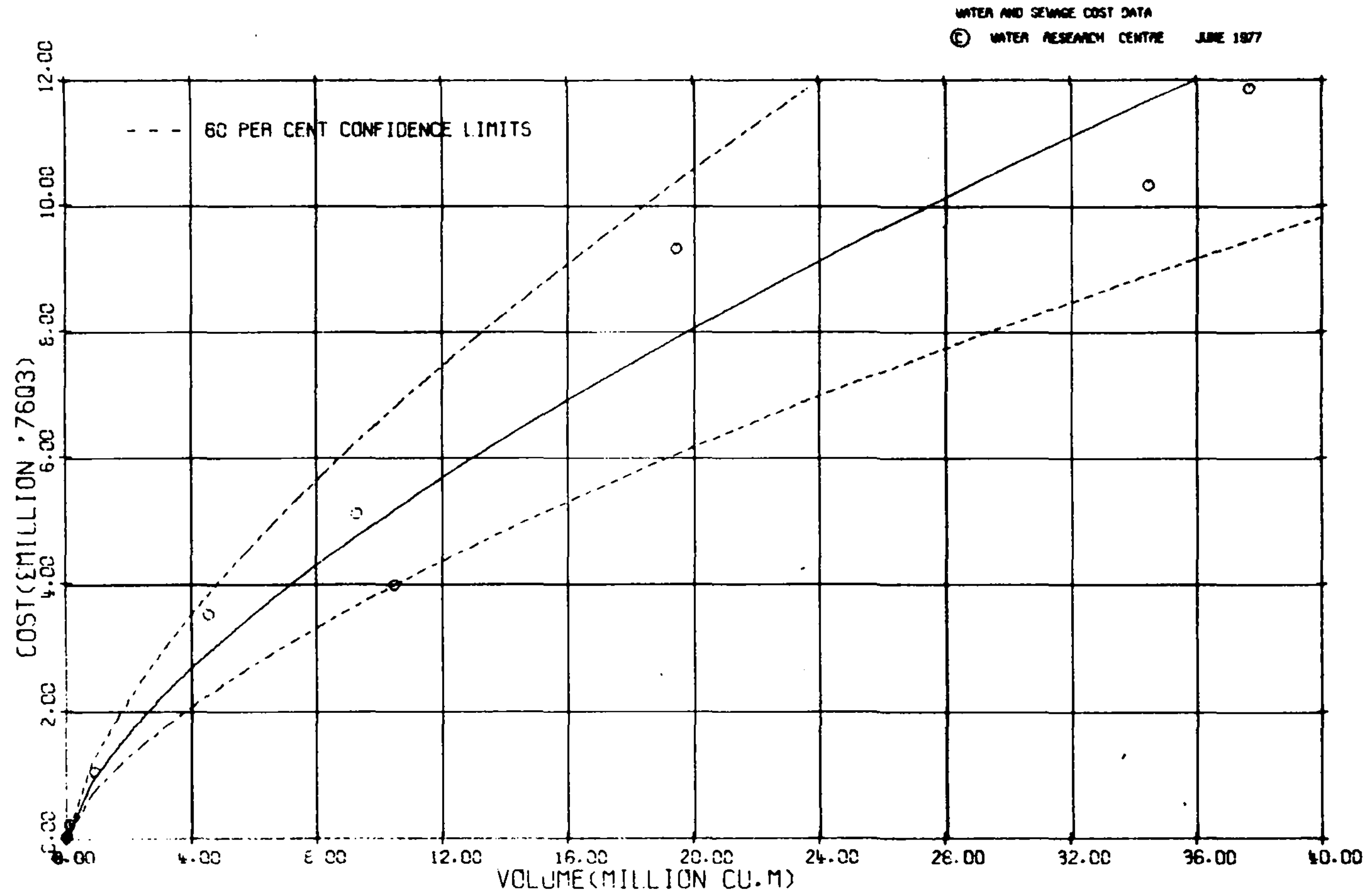
Number of cases: 13

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.78	1.29
95%	0.67	1.50

Note:

1. The Construction Materials Index should be used for inflation (value at 1976 Q3 = 258).
2. The data is listed in Table A-16.
3. A scatter diagram of CLAYBUNCOS against RESVOL is shown on the facing page.
4. The function applies only to clay-cored totally bunded reservoirs and simple excavated and/or bunded lagoons.
5. CLAYBUNCOS includes the cost of the dam, cut-off, adjacent or integral inlet and outlet works, integral pipe and tunnel works, and minor diversions and ancillary works.
6. A more detailed presentation of the work in this area is contained in Section 11.2. In particular, a cost function is available for reservoirs and lagoons of miscellaneous types of construction. A function is also available for clay-cored bunded reservoirs based on volume of embankment.



SCATTER DIAGRAM OF COST(£MILLION '76Q3)
AGAINST VOLUME(MILLION CU.M)

WHOLE WATER TREATMENT WORKS

Throughput ('000 m^3/d)	Total capital cost of water treatment works (£'000 1976 Q3)			
	Rock and moorland raw water Type (iii)		Moorland raw water Type (iv)	Lowland raw water Type (v)
	Pressure filtration	Gravity filtration	Sedimentation-filtration	
2	233	259	-	-
5	408	441	585	599
10	614	673	924	917
20	915	1 040	1 460	1 410
50	1 700	1 880	2 680	2 440
100	2 800	3 120	4 210	3 970
200	-	4 890	6 910	6 220
500	-	9 610	13 200	12 000

Confidence level		Approximate multipliers for confidence limits about a prediction			
80%	Upper	1.33	1.23	1.17	1.17
	Lower	0.75	0.81	0.85	0.85
95%	Upper	1.56	1.37	1.28	1.28
	Lower	0.64	0.72	0.78	0.78

Note:

1. Although no single index is appropriate for all the water treatment cost components, the New Construction Index was chosen in more than half the cases and so could reasonably be used here for inflation (value at 1976 Q3 = 263).
2. Cost includes civil engineering and building costs, mechanical and electrical engineering costs and sludge process costs, and includes all costs relating to conditions of contract. Costs associated with additional processes (see Section 12.6) and extra items (see Section 12.8.3) are excluded.

3. A much fuller presentation of the work in this area is contained in Section 12.1.6. Details are given there of the process component configurations examined; the cost estimates are broken down into civil engineering, plant and sludge process costs, and the confidence interval multipliers are supplied for each of these components.

4. Costs have not been estimated separately for treatment of groundwater (raw water Type (i)) or upland rock water (raw water Type (ii)). A suggested procedure for such cases is discussed in Section 12.1.6A.

WATER TREATMENT OPERATING COSTS

Throughput ('000 m^3/d)	Estimated annual cost (£'000 1976 Q3)			
	Rock and upland raw water Type (ii)	Rock and moorland raw water Type (iii)	Moorland raw water Type (iv)	Lowland raw water Type (v)
	Screening and chlorination	Filtration	Sedimentation-filtration	
2	4.29	13.6	-	-
5	4.91	24.2	30.0	32.8
10	5.80	36.3	51.5	56.9
20	11.5	48.6	77.8	88.2
50	16.9	81.9	138	163
100	28.1	128	234	284
200	44.8	214	421	520
500	92.5	469	981	1230

Note:

1. For throughputs below 20 000 m^3/d operating costs are predominated by labour costs, whilst for throughputs above 50 000 m^3/d chemicals become the most costly component. Consequently no single index is suitable for updating the total cost figures.
2. Because of the lack of appropriate data the costs have been built up synthetically, making a number of assumptions about unit rates and prices. These are discussed in detail in Sections 12.9.1 and 12.9.2.

SERVICE RESERVOIRS

$$\boxed{\text{COST} = 0.0636*\text{CAP}^{0.64}}$$

where COST is total cost of (rectangular concrete-covered) service reservoir,

and CAP is tank capacity.

	Unit	Min.	Max.
COST	£ million 1976 Q3	0.034	1.46
CAP	'000 m^3	0.340	114

Number of cases: 47

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.69	1.44
95%	0.57	1.76

Note:
1. The New Construction Index should be used for inflation (value at 1976 Q3 = 263).
2. The data is listed in Table A-31.
3. A scatter diagram of COST against CAP is shown on the facing page.
4. A more detailed presentation of the work in this area is contained in Section 12.7.1. In particular, models are available for rectangular storage tanks at both size extremes.
5. A cost function for circular storage tanks is given in Section 12.7.2.

WATER AND SEWAGE COST DATA
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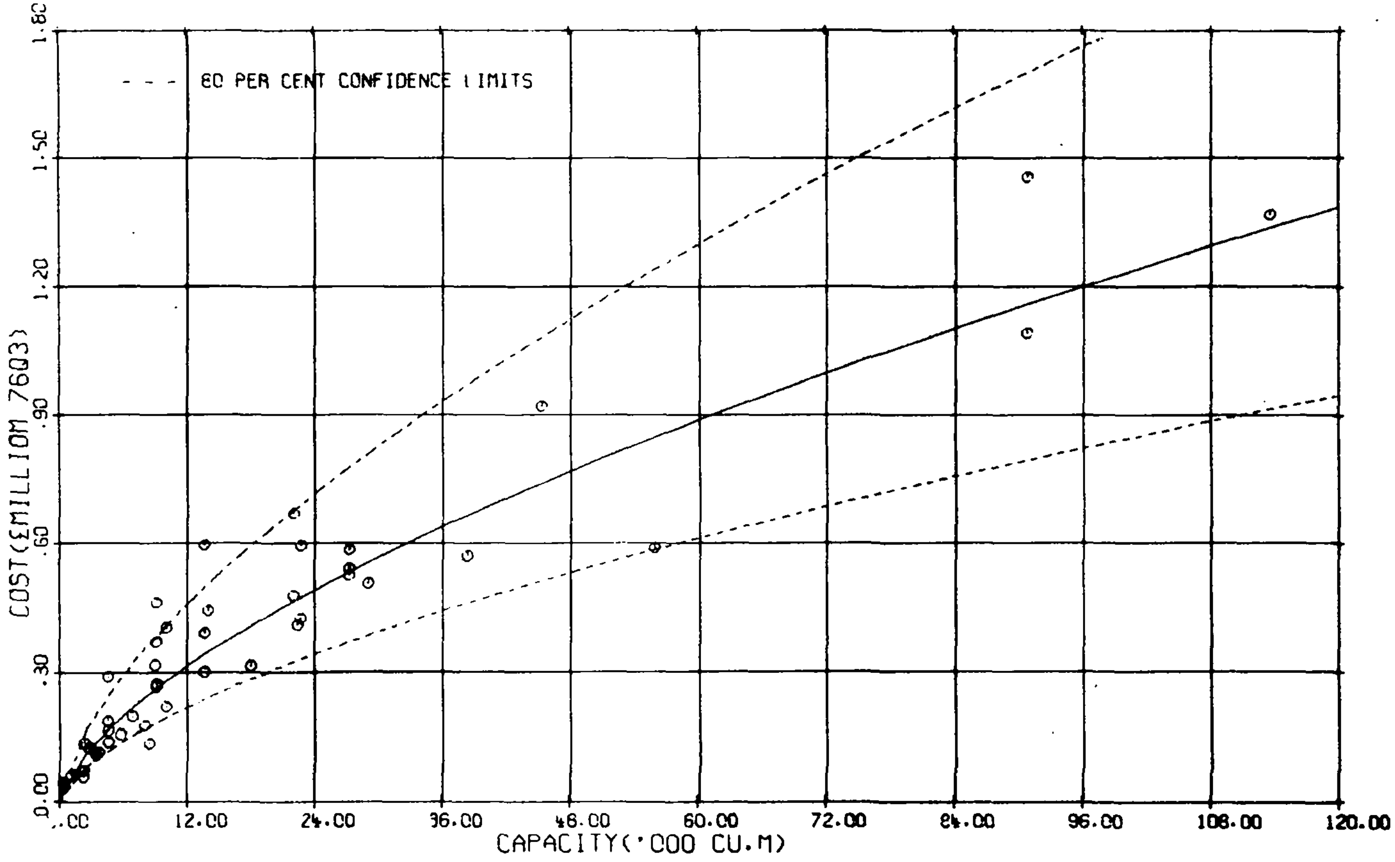


SCATTER DIAGRAM OF COST(£MILLION 76Q3)
AGAINST CAPACITY('000 CU.M)

WATER TOWERS

$$COST = 162*CAP^{0.77}*TYPE^{-0.56}$$

where COST is total cost,

CAP is tank capacity,

and TYPE is 1 for concrete water towers, and
2 for steel water towers.

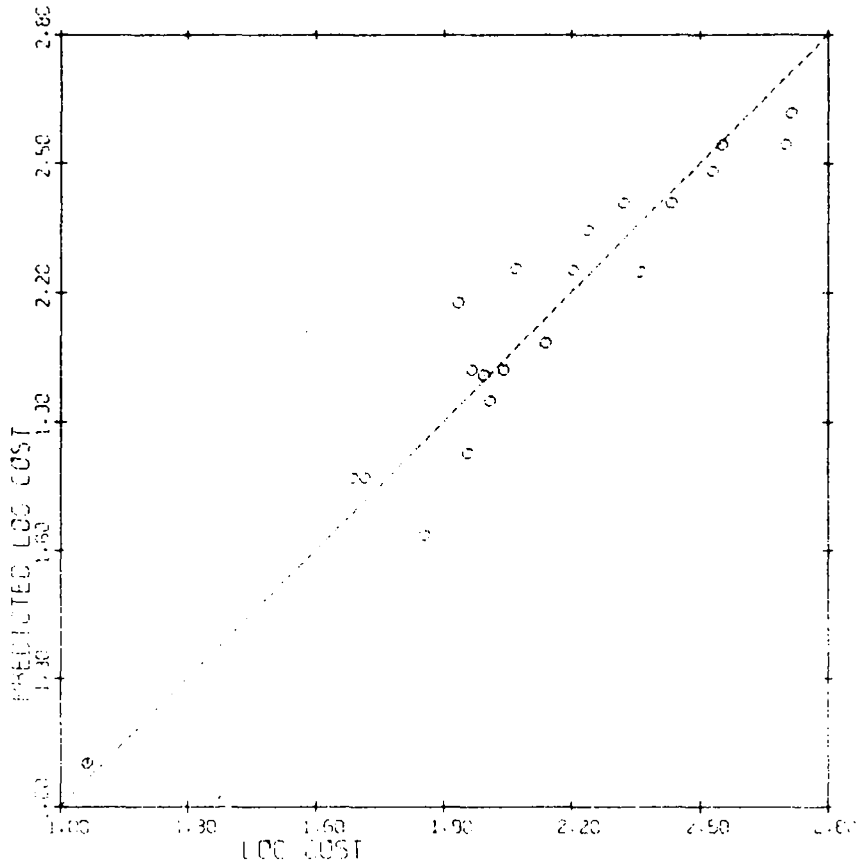
Unit	Min.	Max.
£'000 1976 Q3	11.5	514
'000 m^3	0.060	3.41

Number of cases: 21

Approximate multipliers for confidence limits about a prediction:-

Confidence level	Lower	Upper
80%	0.70	1.43
95%	0.57	1.77

Note:
1. The New Construction Index should be used for inflation (value at 1976 Q3 = 263).
2. The data is listed in Table A-35.
3. A scatter diagram of predicted against actual cost (on a log-log scale) is shown on the facing page.
4. The overall height of tower was not a significant variable; this is probably because of the limited variation of heights within the sample. The mean sample height was 25.1 m.
5. A more detailed presentation of the work in this area is contained in Section 12.7.3.



SCATTER DIAGRAM OF PREDICTED LOG COST
AGAINST LOG COST

WHOLE SEWAGE TREATMENT WORKS

(a) River and estuarine discharge

Dry weather flow ('000 m^3/d)	River				Estuarine	
	Capital costs (£'000 1976 Q3)					
	Effluent standard (SS/BOD/ammoniacal nitrogen)					
	10/10/10		30/20		150/200	
	Civil	Mech.	Civil	Mech.	Civil	Mech.
2.5	522	229	452	184	-	-
5	947	377	753	303	371	169
10	1060	563	889	391	588	328
20	1710	944	1410	654	838	350
40	2760	1430	2250	937	1410	604
80	4820	2620	3950	1780	2370	931
160	7960	4210	6480	2770	3880	1650

Confidence level		Approximate multipliers for confidence limits about a prediction					
80%	Upper	1.12	1.19	1.12	1.19	1.14	1.20
	Lower	0.89	0.84	0.89	0.84	0.88	0.83
95%	Upper	1.18	1.30	1.18	1.30	1.21	1.32
	Lower	0.85	0.77	0.85	0.77	0.83	0.76

Note:

1. The civil engineering and the mechanical engineering costs have both been presented so that cost predictions can be corrected for inflation. The New Construction Index should be used for inflation of the civil engineering costs (value at 1976 Q3 = 263); for the mechanical engineering costs the Engineering and Allied Industries Index should be used (value at 1976 Q3 = 227).
2. The costs include sludge process costs and all costs relating to conditions of contract. Costs associated with contractors' overheads, optional equipment such as administrative and laboratory buildings, and work specific to the site such as access roads, are excluded.
3. A much fuller presentation of the work in this area is contained in Section 13.1.6. Details are given there of the process component configurations examined; also, sludge process costs are considered separately from the civil and mechanical engineering costs.

WHOLE SEWAGE TREATMENT WORKS

(b) Sea outfalls

Bore of standard pipe (mm)	Maximum design flowrate ('000 m^3/d)	Total capital cost of sea-outfall works (£'000 1976 Q3)
444	27	490
597	48	760
746	76	1060
998	140	1620
1370	250	2600

Approximate multipliers for confidence limits about a prediction for a sea outfall works:-

Confidence level	Lower	Upper
80%	0.67	1.49
95%	0.52	1.91

Note:

1. The New Construction Index could reasonably be used for inflation as the mechanical engineering costs represent a very small part of the total cost.
2. Cost includes costs of preliminary works in addition to the outfall cost.
3. A much fuller presentation of the work in this area is contained in Section 13.1.6, where the cost estimates are broken down into outfall costs (see also Section 13.4) and preliminary works civil engineering, mechanical engineering and siteworks costs.

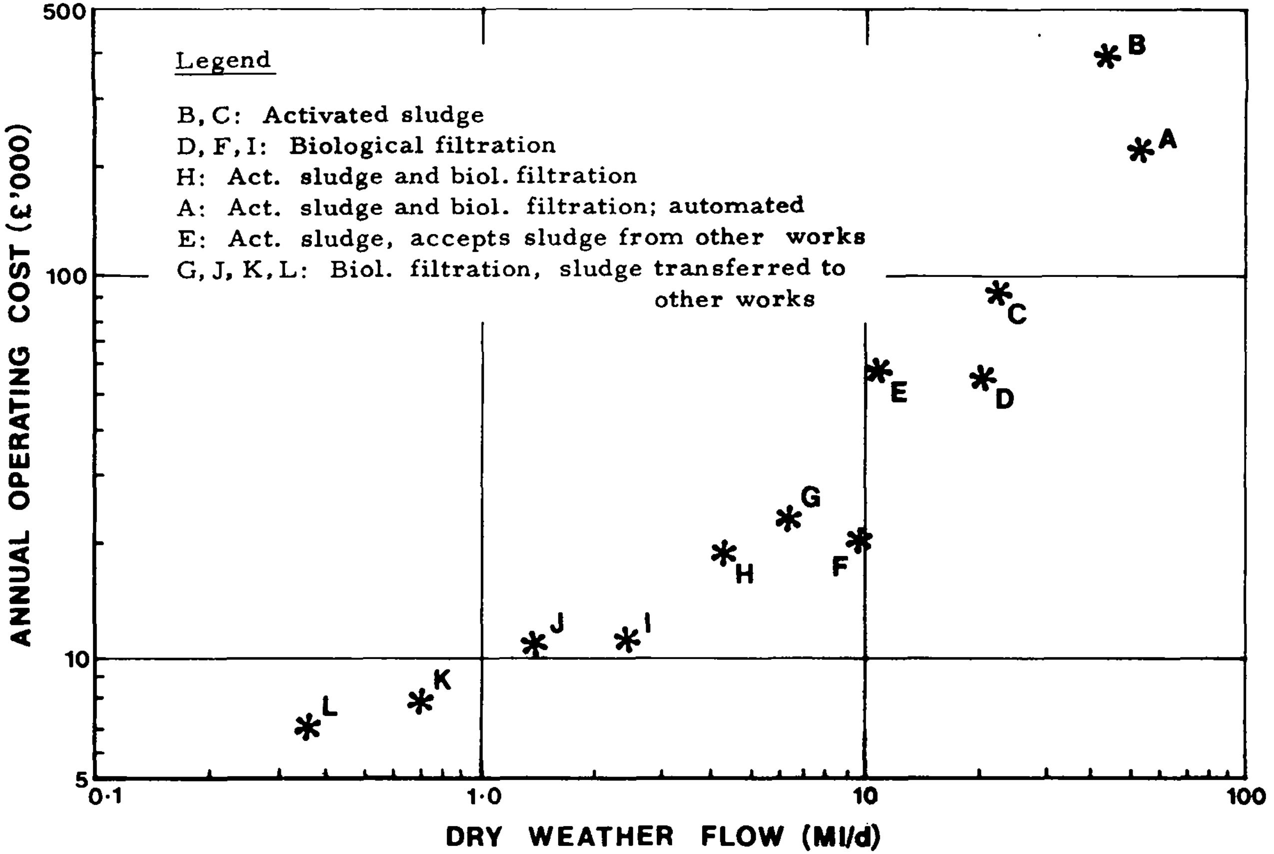
SEWAGE TREATMENT OPERATING COSTS

Design DWF (Ml/d)	Annual operating cost (£'000 1975/76) for whole works treating to 30/20 standard
0.5	7.5
1.0	9
2.0	11
5.0	20
10.0	39
20.0	80
50.0	310

Note:

1. These figures are based on operating cost data from 12 whole works, and should be regarded as providing no more than a very rough guide.
2. A scatter diagram of annual operating cost against design DWF for the 12 cases is shown on the facing page. The log-log scale which it was necessary to adopt conceals the full extent of the variability; for example, the operating cost for Works E is nearly three times that for Works F, although the two works have similar dry weather flows.
3. The costs include labour, supervision, scientific services, electricity, maintenance and supplies, but exclude local authority rates.
4. The data is discussed in more detail in Section 13.9.3.

Annual operating cost (1975/76) plotted against DWF for 12 sewage treatment works designed to produce a 30/20 final effluent



Note: 1. See Table 13-52 for a more detailed description of the 12 works.

2. Costs include labour, supervision, scientific services, electricity, maintenance and supplies.

3. Local authority rates are not included.

APPENDIX A—DATA LISTINGS

Table A-1. Sewerage

TOTAL COST (£'000)	TOTAL LENGTH (M)	AVERAGE DIAMETER (MM)	AVERAGE DEPTH (M)	OVER - UNDER FACTOR	OMNIBUS1	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
2.	265.	176.	1.60	18.	39.	1.09	2.	4.	-38.2
8.	61.	287.	4.89	42.	62.	1.09	8.	6.	35.4
8.	206.	225.	2.90	22.	65.	1.07	8.	6.	32.0
11.	45.	525.	4.20	41.	65.	1.50	16.	6.	147.5
7.	446.	150.	1.90	19.	68.	1.07	8.	7.	16.1
5.	175.	207.	2.00	42.	80.	1.10	6.	8.	-29.7
5.	379.	109.	1.80	40.	95.	1.60	8.	9.	-13.0
10.	238.	393.	1.50	39.	140.	1.20	12.	13.	-6.0
12.	656.	189.	1.00	23.	141.	1.09	13.	13.	-4.8
9.	155.	450.	3.00	37.	145.	1.09	10.	14.	-28.7
11.	690.	203.	1.65	26.	169.	1.45	15.	16.	-2.6
12.	324.	313.	2.23	34.	175.	1.60	19.	16.	15.1
12.	514.	216.	2.43	33.	212.	1.15	14.	20.	-31.1
10.	1132.	225.	2.00	21.	270.	1.08	11.	25.	-55.0
24.	910.	150.	2.39	32.	274.	1.93	46.	25.	83.3
33.	2526.	36.	1.14	28.	275.	1.06	35.	25.	39.0
20.	277.	900.	2.70	27.	299.	1.09	22.	27.	-19.5
87.	196.	649.	3.19	44.	302.	1.58	138.	27.	402.5
36.	1444.	160.	1.50	31.	332.	1.08	39.	30.	29.9
20.	2166.	97.	1.30	34.	343.	1.08	22.	31.	-30.3
56.	319.	831.	3.90	26.	390.	1.65	92.	35.	165.3
24.	288.	396.	4.10	52.	421.	1.33	32.	37.	-15.1
37.	416.	800.	3.33	25.	431.	1.11	41.	38.	8.7
9.	1389.	255.	2.20	24.	444.	2.07	19.	39.	-51.8
15.	389.	398.	3.90	43.	455.	2.61	39.	40.	-3.6
26.	412.	527.	2.90	41.	474.	1.08	28.	42.	-33.4
43.	669.	317.	3.43	35.	490.	1.09	47.	43.	9.5
25.	2118.	192.	1.80	25.	503.	1.09	27.	44.	-37.9
25.	583.	600.	1.87	37.	510.	1.08	27.	45.	-39.2
37.	786.	301.	2.70	39.	535.	1.09	40.	47.	-15.0
60.	1413.	298.	1.21	37.	553.	1.22	74.	48.	52.5
42.	618.	431.	3.60	36.	609.	1.08	45.	53.	-14.7
34.	2359.	166.	1.40	36.	625.	1.09	37.	54.	-32.1
34.	502.	603.	3.00	45.	721.	1.09	37.	62.	-39.9
47.	2464.	188.	1.87	32.	760.	2.00	95.	65.	45.9
53.	578.	547.	2.00	42.	856.	1.08	58.	73.	-20.8
64.	570.	856.	5.26	26.	856.	1.15	74.	73.	2.1
120.	1055.	518.	1.80	41.	896.	1.09	130.	76.	71.8
63.	1013.	416.	2.90	42.	998.	1.09	69.	84.	-17.8
37.	1331.	294.	2.70	44.	1007.	1.09	41.	85.	-51.9
64.	2028.	303.	2.70	30.	1057.	1.74	111.	89.	25.4
48.	1510.	525.	3.20	25.	1103.	1.08	52.	92.	-43.9
36.	995.	536.	3.10	40.	1180.	2.25	76.	98.	-22.2
53.	986.	641.	2.70	41.	1263.	1.46	78.	105.	-25.9
44.	560.	350.	4.60	43.	1299.	1.11	48.	108.	-55.1
75.	2539.	434.	1.90	28.	1310.	1.09	82.	108.	-24.5
235.	4546.	213.	1.82	36.	1715.	1.55	363.	140.	159.7
348.	7704.	155.	1.59	32.	1855.	1.11	387.	150.	157.1
134.	415.	1160.	7.10	56.	2107.	1.08	145.	169.	-14.7
126.	5861.	213.	1.90	36.	2266.	1.08	136.	181.	-25.0
322.	2413.	661.	3.50	27.	2408.	1.09	350.	192.	82.4
186.	3178.	477.	2.80	35.	2815.	1.74	325.	222.	46.0
188.	1082.	865.	3.60	55.	2823.	1.08	202.	223.	-9.2
232.	11369.	137.	1.90	33.	2860.	1.07	247.	226.	9.3
142.	3750.	450.	2.77	32.	2878.	2.00	285.	227.	25.6
303.	2607.	525.	3.63	38.	2932.	1.13	342.	231.	48.2
204.	5087.	279.	2.75	40.	3392.	1.42	288.	265.	8.9
192.	3707.	559.	2.50	37.	3669.	1.46	280.	285.	-1.7
262.	1507.	1016.	4.70	45.	4257.	1.09	285.	328.	-13.0
386.	10694.	242.	1.86	35.	4409.	1.10	425.	339.	25.3
292.	3915.	745.	3.70	29.	4630.	1.09	318.	353.	-9.7
377.	3762.	616.	3.34	36.	4656.	1.10	414.	357.	16.1
300.	1414.	1185.	4.70	48.	4807.	1.07	320.	367.	-13.0
191.	9832.	300.	2.00	38.	5402.	1.09	208.	410.	-49.2
420.	2630.	1102.	3.33	40.	5668.	1.07	448.	429.	4.5
592.	29960.	189.	1.84	25.	7112.	1.09	645.	531.	21.4
406.	3387.	865.	5.40	36.	7303.	1.08	437.	544.	-19.7
722.	5826.	528.	3.19	42.	7307.	1.11	801.	545.	47.1
332.	4812.	373.	3.40	36.	7875.	2.18	723.	584.	23.8
404.	7767.	653.	2.45	38.	8275.	1.39	563.	612.	-8.0
299.	3318.	946.	4.00	51.	9153.	1.69	505.	673.	-25.0
230.	6334.	470.	4.00	47.	9378.	1.93	443.	688.	-35.6
833.	7574.	454.	3.00	50.	9767.	1.09	906.	715.	26.8
637.	6128.	721.	2.96	48.	10714.	1.31	832.	780.	6.6
577.	5658.	1204.	3.28	34.	10928.	1.52	880.	795.	10.7
862.	2534.	1443.	6.60	50.	12870.	1.33	1145.	927.	23.6
1389.	6955.	1011.	2.70	50.	15546.	1.09	1512.	1106.	36.7
679.	13541.	485.	3.30	41.	15842.	1.74	1183.	1126.	5.1
938.	11323.	592.	2.47	56.	17868.	1.08	1011.	1261.	-19.8
1234.	14370.	793.	5.94	43.	36934.	1.67	2056.	2493.	-17.6

Table A-2. Water mains (installation cost)

TOTAL COST (£MILLION)	VOLUME OF EXCAVATION ('000 CU.M)	AVERAGE DIAMETER (MM)	AVERAGE DEPTH (M)	OVER-UNDER FACTOR	PROPORTION OF DUCTILE IRON PIPELENGTH + 1	TOTAL LENGTH (M)	OMNIBUS2	DEFLATION FACTOR	DEFLATED COST (£MILLION)	ESTIMATED COST (£MILLION)	PERCENTAGE ERROR
.017	2.8	760.	2.12	30.	1.00	875.	1.7	1.07	.018	.033	-44.0
.017	6.3	496.	1.75	30.	1.89	3247.	2.1	1.65	.029	.038	-24.5
.018	2.5	750.	2.27	40.	1.00	826.	2.7	2.93	.052	.046	11.6
.012	5.4	375.	1.50	30.	1.00	3629.	2.7	2.93	.036	.047	-23.4
.039	11.9	393.	1.74	30.	2.00	6890.	3.0	1.09	.042	.051	-16.9
.020	7.9	446.	1.72	34.	2.00	4359.	3.0	2.16	.043	.052	-16.7
.064	17.6	146.	1.28	23.	1.00	18449.	3.6	1.85	.119	.059	102.1
.052	13.2	424.	1.69	30.	1.99	7579.	3.8	1.50	.078	.061	27.4
.045	4.3	444.	1.41	44.	1.99	2793.	3.8	1.07	.048	.062	-23.0
.022	7.2	305.	1.46	34.	1.00	5393.	4.0	1.50	.033	.064	-48.6
.056	6.6	599.	1.87	38.	1.90	2898.	4.0	1.08	.060	.065	-7.2
.027	9.2	252.	1.57	38.	1.07	6918.	4.6	2.46	.066	.072	-8.1
.128	7.8	637.	2.48	41.	2.00	2181.	5.1	1.11	.142	.078	81.2
.025	6.5	300.	1.43	40.	1.00	4950.	5.1	1.85	.045	.079	-42.3
.041	11.1	297.	1.40	32.	1.00	8707.	5.5	3.23	.133	.083	59.9
.075	10.2	456.	1.58	39.	1.97	6043.	6.2	1.08	.081	.091	-11.1
.070	6.8	595.	1.90	38.	1.00	2966.	6.5	2.76	.193	.095	102.4
.041	12.4	329.	1.20	32.	1.24	10657.	7.3	2.16	.088	.104	-15.1
.065	8.9	493.	1.99	40.	1.00	3840.	7.3	2.76	.179	.105	71.0
.044	9.7	592.	1.72	33.	1.00	4651.	7.8	2.76	.121	.110	9.4
.051	21.9	239.	1.46	37.	2.00	16626.	8.2	2.46	.125	.115	8.7
.045	9.1	898.	2.11	34.	1.00	2822.	8.9	2.46	.111	.123	-9.8
.054	12.2	438.	1.90	39.	1.00	6178.	9.0	2.93	.157	.123	27.1
.035	7.8	771.	2.47	44.	1.00	2296.	9.2	1.50	.053	.126	-57.8
.064	1.3	1092.	.94	46.	1.00	744.	9.7	2.93	.187	.132	41.8
.057	14.7	595.	2.07	37.	1.00	5898.	11.7	3.11	.177	.153	15.9
.138	70.2	237.	2.23	30.	1.07	38074.	11.8	1.08	.149	.154	-3.2
.089	11.2	300.	1.61	35.	1.00	5958.	12.1	3.11	.273	.157	74.4
.173	24.1	862.	2.54	29.	1.01	6466.	12.2	1.15	.200	.158	26.4
.059	10.7	331.	1.43	47.	1.00	7798.	13.3	2.46	.145	.170	-14.6
.061	12.1	600.	1.00	27.	1.00	9167.	13.7	2.16	.131	.174	-24.4
.049	7.6	579.	1.40	44.	1.00	4308.	14.7	2.93	.143	.184	-21.9
.363	11.7	807.	2.16	43.	1.00	3808.	16.6	1.07	.388	.204	90.5
.272	22.2	596.	1.97	46.	1.99	9341.	18.4	1.08	.293	.221	32.5
.176	23.3	500.	1.63	63.	1.99	14389.	20.6	1.08	.189	.242	-21.8
.271	13.6	667.	1.64	44.	1.31	6979.	21.0	1.08	.292	.245	19.1
.104	27.2	1050.	2.40	36.	1.00	6748.	29.4	3.11	.324	.322	.7
.110	22.4	679.	1.54	43.	1.00	9314.	33.5	2.76	.303	.358	-15.3
.133	44.3	349.	1.49	38.	1.00	30656.	34.6	2.76	.367	.367	-.1
.126	12.1	504.	1.22	46.	1.00	7485.	36.3	2.76	.348	.382	-8.9
.160	45.1	515.	1.54	42.	1.98	27705.	40.9	2.76	.442	.420	5.0
.132	45.3	600.	1.78	36.	1.01	20784.	47.3	2.83	.375	.473	-20.8
.329	15.8	1106.	1.42	41.	1.00	6111.	50.7	3.20	1.053	.501	110.4
.506	31.6	900.	2.42	52.	1.00	8618.	64.6	1.09	.545	.609	-10.4
.286	25.0	1030.	2.18	51.	1.00	6870.	65.2	2.46	.704	.614	14.7
.208	46.5	1067.	1.99	35.	1.00	13541.	66.7	2.15	.446	.624	-28.2
.415	32.0	877.	1.46	40.	1.00	13997.	73.7	1.08	.447	.677	-34.0
.251	69.3	900.	1.93	37.	1.00	29976.	119.4	3.11	.781	1.000	-21.9
1.016	145.9	1189.	2.93	43.	1.00	28174.	198.5	2.46	2.495	1.508	65.4
1.281	78.1	1817.	3.22	53.	1.00	9904.	227.2	1.15	1.478	1.682	-12.1
1.307	101.6	1828.	3.20	62.	1.00	12847.	423.9	1.34	1.750	2.734	-37.1

Table A-3. Water mains (total cost)

TOTAL COST (£ MILLION)	TOTAL LENGTH (M)	AVERAGE DIAMETER (MM)	OMNIBUS3 / 1000	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.035	6115.	228.	.9	2.37	.082	.098	-16.7
.048	7413.	203.	1.0	2.80	.134	.102	31.4
.055	2435.	445.	1.1	1.82	.100	.111	-9.7
.057	2793.	444.	1.2	1.43	.124	.122	1.4
.049	975.	760.	1.3	1.43	.070	.129	-45.5
.078	10198.	234.	1.6	2.22	.174	.146	18.8
.102	4012.	429.	1.7	2.22	.226	.151	49.5
.064	13449.	146.	1.8	2.22	.143	.157	-9.0
.072	3247.	496.	1.8	2.22	.161	.161	-.2
.077	4359.	448.	2.0	2.37	.182	.171	6.6
.077	6890.	390.	2.4	1.32	.102	.197	-48.0
.155	2898.	599.	2.5	1.23	.190	.201	-5.3
.125	29214.	126.	2.5	1.97	.246	.201	22.2
.126	11854.	309.	2.6	2.37	.298	.218	37.1
.198	6043.	455.	2.8	1.20	.238	.222	7.1
.105	744.	1092.	3.0	3.07	.323	.234	38.0
.083	2296.	771.	3.6	2.06	.171	.267	-35.9
.105	45541.	134.	4.0	2.37	.250	.287	-13.1
.232	2181.	837.	4.3	1.40	.324	.300	8.0
.113	2822.	398.	6.7	2.58	.292	.415	-29.7
.511	3806.	807.	6.8	1.26	.644	.420	53.3
.409	6979.	667.	7.7	1.82	.745	.459	62.2
.155	9167.	600.	7.9	2.37	.368	.466	-21.1
.550	14389.	500.	8.2	1.23	.676	.481	40.6
.223	25163.	415.	9.6	1.23	.274	.546	-50.0
.263	9314.	579.	10.7	2.80	.736	.585	25.8
.203	5769.	862.	11.4	2.58	.523	.612	-14.5
.386	6466.	802.	13.8	1.82	.703	.701	.3
.780	8618.	900.	20.6	1.73	1.350	.938	43.9
.521	4894.	1124.	21.7	2.58	1.345	.975	38.0
.493	6870.	1030.	23.6	2.80	1.379	1.043	32.3
.575	6111.	1108.	26.0	3.23	1.858	1.113	66.9
.497	8134.	1015.	27.1	1.40	.695	1.146	-39.3
.748	13997.	877.	31.2	1.43	1.070	1.270	-15.7
.749	9622.	1131.	49.1	1.73	1.296	1.766	-26.6
2.420	9904.	1517.	176.1	1.82	4.404	4.500	-2.1
2.420	12847.	1828.	235.5	1.97	4.767	5.512	-13.5

Table A-4. Tunnels

TOTAL COST (£ MILLION)	EXCAVATED VOLUME ('000 CU.M)	TUNNEL LENGTH (M)	TUNNEL DIAMETER (M)	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.006	.50	39.	4.04	2.58	.015	.021	-27.2
.029	.97	156.	2.82	2.90	.083	.040	108.3
.010	1.04	137.	3.11	3.07	.030	.042	-29.0
.038	3.71	594.	2.82	3.07	.118	.142	-17.4
.117	5.95	953.	2.82	2.90	.340	.223	52.4
.090	7.76	605.	4.04	2.58	.232	.287	-19.1
.160	13.10	715.	4.83	2.58	.413	.473	-12.7
.260	16.56	2652.	2.82	1.47	.383	.591	-35.2
.493	20.87	5068.	2.29	2.90	1.429	.737	93.9
.362	33.70	5395.	2.82	2.90	1.050	1.163	-9.7
.470	36.73	5880.	2.82	3.07	1.442	1.262	14.3
.500	40.72	6520.	2.82	3.07	1.535	1.392	10.2
.480	42.28	6769.	2.82	2.58	1.238	1.443	-14.2
.601	42.43	6794.	2.82	2.22	1.336	1.448	-7.7
.568	44.55	7133.	2.82	2.22	1.263	1.517	-16.7
.825	59.69	9556.	2.82	2.58	2.135	2.004	6.6
1.085	62.77	10050.	2.82	2.22	2.412	2.102	14.7
.925	89.66	14356.	2.82	2.90	2.681	2.952	-9.2

Table A-5. Shafts

TOTAL COST (£"000)	SHAFT DEPTH (M)	SHAFT DIAMETER (M)	OMNIBUS4	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
5.3	17.1	4.00	13.1	3.07	16.3	20.8	-21.0
12.0	19.2	3.66	13.4	3.07	36.9	21.2	74.4
10.1	13.7	5.84	16.5	2.58	26.1	26.4	-1.1
8.6	21.3	4.01	16.5	2.90	24.9	26.5	-6.1
12.1	21.9	4.02	17.0	2.22	26.9	27.3	-1.6
8.8	21.9	4.02	17.0	2.90	25.5	27.3	-6.7
8.9	22.3	4.02	17.2	2.90	25.8	27.7	-7.0
9.2	23.2	4.01	17.9	2.90	26.7	28.9	-7.6
10.5	24.1	4.26	20.0	3.07	32.3	32.3	-.0
10.1	25.9	4.01	20.1	2.90	29.3	32.5	-9.7
19.5	31.4	3.66	21.8	3.07	59.7	35.5	68.4
13.9	29.6	4.02	22.9	2.58	35.9	37.4	-4.0
11.2	29.9	4.01	23.1	3.07	34.4	37.7	-8.7
13.3	30.2	4.21	24.7	3.07	40.8	40.5	.9
18.2	30.2	4.57	27.2	2.58	47.0	44.7	5.0
14.2	35.7	4.19	29.0	3.07	43.5	47.8	-9.1
13.4	36.3	4.18	29.4	3.07	41.0	48.6	-15.5
18.7	35.4	4.36	30.1	3.07	57.4	49.8	15.3
20.9	39.0	4.02	30.2	2.22	46.5	49.9	-6.9
18.1	24.1	6.17	30.8	2.58	46.8	50.9	-8.1
18.2	31.7	4.95	31.4	2.90	52.8	51.9	1.7
19.2	32.6	4.94	32.2	2.90	55.5	53.3	4.2
25.2	31.1	5.22	32.7	2.22	56.0	54.2	3.2
19.2	40.2	4.32	33.9	3.07	58.8	56.4	4.3
20.5	28.0	6.12	35.5	2.58	53.0	59.2	-10.5
20.0	43.9	4.29	36.7	3.07	61.4	61.3	.1
20.9	31.4	6.45	42.3	2.22	46.4	71.0	-34.6
40.6	43.0	4.93	42.3	2.22	90.2	71.2	26.8
30.4	39.9	5.30	42.7	2.22	67.5	71.9	-6.1
33.9	33.5	6.40	44.7	2.58	87.5	75.4	16.0
29.3	36.0	6.24	46.6	2.58	75.5	78.7	-4.0
30.5	37.8	6.23	48.8	2.58	78.6	82.7	-4.9
32.1	40.2	6.16	51.3	2.58	82.9	87.2	-4.9
31.2	54.6	4.94	53.8	2.90	90.4	91.6	-1.3
55.5	24.1	10.65	58.1	2.22	123.4	99.3	24.3
28.3	42.7	6.56	58.5	2.22	62.9	100.0	-37.1
38.8	68.3	4.94	67.3	2.90	112.4	115.8	-3.0
54.2	40.5	7.76	67.8	2.22	120.6	116.6	3.5
53.9	26.5	11.26	68.4	2.22	119.7	117.8	1.7
59.7	42.1	8.28	75.6	2.22	132.7	131.0	1.3
68.5	30.5	11.28	78.6	2.22	152.2	136.4	11.6
52.5	37.8	9.99	84.7	2.58	135.5	147.4	-8.1
67.3	48.2	8.26	86.7	3.07	206.7	151.1	36.8
65.1	36.9	11.30	95.3	2.58	167.9	167.0	.6
92.5	84.1	7.93	143.9	2.90	266.0	257.4	4.1

Table A-6. Tunnels and shafts

TOTAL COST (£ MILLION)	EXCAVATED VOLUME ("000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.05	4.75	3.07	.15	.14	5.3
.26	16.56	1.47	.38	.53	-28.0
.32	25.43	2.58	.83	.84	-1.0
.50	37.26	3.07	1.53	1.27	20.6
.62	45.45	3.07	1.91	1.56	22.1
.95	64.72	2.58	2.44	2.28	6.9
1.29	70.10	2.22	2.87	2.49	15.4
1.35	97.30	2.22	2.99	3.53	-15.3
1.46	131.10	2.90	4.23	4.85	-12.9

Table A-7. Water pumping

TOTAL COST (£'000)	TOTAL INSTALLED CAPACITY (CU.M/HR)	NORMAL OPERATING HEAD (M)	TOTAL INSTALLED POWER (KW)	TOTAL NUMBER OF PUMPS INSTALLED	OMNIBUS10 / 1000	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
1.9	36.	44.8	15.	1.	.029	2.77	5.4	2.1	159.6
.9	46.	91.4	22.	1.	.054	2.77	2.5	3.4	-27.0
1.6	136.	82.3	60.	2.	.150	2.77	4.4	7.8	-43.7
1.8	473.	30.5	56.	1.	.310	2.91	5.2	14.0	-63.2
4.1	473.	34.1	75.	4.	.329	2.67	10.9	14.7	-25.9
6.3	273.	144.8	143.	2.	.407	2.95	18.7	17.4	7.2
5.6	636.	38.1	119.	4.	.469	2.84	15.9	19.5	-18.6
8.5	318.	152.4	108.	6.	.487	2.84	24.0	20.1	19.0
10.8	818.	27.4	45.	1.	.506	2.91	31.5	20.8	51.5
12.9	946.	24.1	97.	4.	.547	2.77	35.6	22.1	60.8
15.7	855.	30.5	145.	2.	.560	2.95	46.2	22.5	105.0
4.0	982.	36.9	142.	4.	.711	2.67	10.7	27.3	-60.9
8.0	909.	73.2	283.	1.	.945	2.77	22.3	34.4	-35.2
23.5	1718.	38.1	227.	2.	1.266	2.67	62.8	43.5	44.4
12.3	1137.	96.6	403.	3.	1.369	2.91	35.8	46.3	-22.7
45.0	1137.	181.4	805.	4.	1.910	2.70	121.6	60.5	100.9
27.0	4910.	13.7	298.	4.	2.108	2.91	78.6	65.6	19.9
41.0	2546.	121.9	1007.	3.	3.466	2.84	116.3	97.9	18.9
36.2	4551.	64.0	1051.	3.	4.409	2.95	106.8	118.8	-10.1
36.0	4801.	64.0	1342.	4.	4.652	2.84	102.2	124.0	-17.6
40.5	4801.	64.0	1342.	4.	4.652	2.84	114.9	124.0	-7.3
50.0	10910.	14.6	761.	6.	4.844	2.77	138.4	128.1	8.0
66.5	4541.	82.6	1745.	6.	5.034	2.67	177.6	132.2	34.4
38.0	5728.	62.5	2013.	6.	5.481	2.91	110.6	141.6	-21.9
146.0	16093.	86.3	5332.	10.	18.259	2.67	389.9	373.2	4.5

Table A-8. Borehole pumping

TOTAL COST (£'000)	DESIGNED CAPACITY (CU.M/HR)	DESIGNED OPERATING HEAD (M)	OMNIBUS11	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
2.27	208.	24.0	107.	4.22	3.85	9.8
2.59	208.	35.0	133.	4.82	4.57	5.4
2.37	313.	22.0	153.	4.41	5.10	-13.6
2.99	417.	14.7	161.	5.56	5.32	4.6
3.03	208.	49.5	162.	5.64	5.36	5.3
2.94	208.	51.0	165.	5.47	5.43	.8
3.08	208.	58.0	178.	5.73	5.76	-.5
3.05	417.	19.2	188.	5.68	6.01	-5.6
3.27	417.	20.8	197.	6.08	6.23	-2.4
3.50	208.	72.0	202.	6.51	6.36	2.5
4.27	208.	77.0	210.	7.95	6.55	21.2
3.89	208.	79.5	214.	7.24	6.65	8.8
3.55	208.	83.5	220.	6.61	6.80	-2.9
3.46	208.	88.5	227.	6.44	6.98	-7.8
3.85	417.	27.0	229.	7.16	7.02	2.0
3.69	208.	92.0	232.	6.87	7.11	-3.4
3.84	208.	98.5	242.	7.14	7.33	-2.6
4.03	208.	102.0	247.	7.50	7.45	.6
3.99	208.	102.0	247.	7.42	7.45	-.4
4.15	208.	103.0	248.	7.72	7.48	3.2
3.93	208.	103.0	248.	7.31	7.48	-2.3
4.08	208.	104.0	249.	7.59	7.52	1.0
3.23	208.	107.5	254.	6.01	7.63	-21.3
4.15	208.	108.0	255.	7.72	7.65	1.0
3.72	208.	112.0	260.	6.92	7.78	-11.0
4.22	208.	112.0	260.	7.85	7.78	1.0
5.61	208.	122.0	274.	10.44	8.09	29.1
4.81	208.	146.0	304.	8.95	8.78	2.0
4.49	417.	45.0	308.	8.35	8.87	-5.8
3.21	313.	78.0	318.	5.97	9.09	-34.3
4.45	313.	86.0	336.	8.28	9.51	-12.9
6.08	417.	59.0	360.	11.31	10.04	12.7
6.50	417.	63.0	374.	12.09	10.34	17.0
6.32	417.	77.0	420.	11.76	11.33	3.8
5.36	417.	78.0	423.	9.97	11.40	-12.5
7.01	417.	81.0	433.	13.04	11.60	12.5
7.25	417.	89.0	457.	13.49	12.11	11.4
7.12	417.	90.0	460.	13.25	12.17	8.9

Table A-9. Sewage pumping

TOTAL PLANT COST ($'000)	TOTAL HEAD (M)	TOTAL INSTALLED CAPACITY (L/S)	NUMBER OF PUMPS INSTALLED	OMNIBUS12	DEFLATION FACTOR	DEFLATED COST ($'000)	ESTIMATED COST ($'000)	PERCENTAGE ERROR
1.4	40.	1.	1.	.01	1.96	2.7	3.2	-15.7
2.3	4.	9.	1.	.02	1.89	4.4	4.0	12.0
2.8	5.	9.	1.	.02	1.89	5.3	4.1	28.4
6.5	18.	5.	1.	.03	1.45	9.4	4.4	114.0
5.1	2.	30.	1.	.04	1.54	7.9	4.7	69.5
2.1	24.	6.	1.	.05	1.89	3.9	4.9	-20.6
6.3	6.	3.	2.	.08	1.28	8.1	5.8	41.2
3.4	61.	7.	1.	.10	1.96	6.7	6.1	8.9
6.5	34.	2.	2.	.17	1.29	8.4	7.1	17.4
7.1	12.	4.	2.	.17	1.28	9.1	7.2	27.5
9.8	23.	4.	2.	.26	1.12	11.0	8.1	35.5
9.8	25.	4.	2.	.28	1.12	11.0	8.2	34.4
16.6	11.	10.	2.	.41	1.08	17.9	9.2	94.8
2.3	15.	10.	2.	.50	2.06	4.7	9.7	-51.2
3.9	7.	18.	2.	.53	1.89	7.4	9.9	-24.9
6.3	6.	7.	3.	.64	1.96	12.4	10.4	19.2
4.3	9.	19.	2.	.68	2.06	8.9	10.6	-16.4
5.3	3.	320.	1.	.70	1.96	10.3	10.7	-3.6
5.3	3.	320.	1.	.70	1.95	10.3	10.7	-3.6
3.9	15.	15.	2.	.77	1.89	7.3	11.0	-33.6
4.4	8.	24.	2.	.72	1.54	6.8	11.1	-38.5
3.3	12.	22.	2.	.95	1.89	6.2	11.7	-46.6
4.6	6.	35.	2.	.96	2.06	9.5	11.7	-18.9
6.2	14.	21.	2.	1.00	1.28	8.0	11.8	-32.6
6.6	26.	16.	2.	1.12	1.28	8.5	12.2	-30.5
3.8	32.	15.	2.	1.25	1.96	7.4	12.6	-40.6
3.9	32.	15.	2.	1.25	1.96	7.7	12.6	-38.8
23.2	10.	40.	2.	1.50	1.66	38.5	13.3	189.6
11.5	26.	23.	2.	1.64	1.28	14.7	13.6	7.7
11.6	23.	25.	2.	1.81	1.29	14.9	14.0	6.2
4.4	7.	54.	2.	1.93	1.54	6.9	14.3	-52.1
12.1	15.	35.	2.	2.02	1.28	15.5	14.5	6.9
11.0	28.	31.	2.	2.29	1.46	16.1	15.0	7.1
5.7	40.	26.	2.	2.62	1.86	10.7	15.6	-31.5
17.4	37.	38.	2.	3.40	1.28	22.3	16.8	32.5
5.4	14.	82.	2.	3.80	1.96	10.6	17.4	-39.0
25.6	48.	38.	2.	4.02	1.28	32.9	17.6	86.5
6.6	13.	100.	2.	4.47	1.75	11.5	18.2	-36.9
8.8	14.	150.	2.	7.01	1.96	17.3	20.7	-16.4
25.1	43.	76.	2.	7.45	1.28	32.1	21.0	52.6
6.1	12.	55.	3.	8.80	2.06	12.6	22.1	-43.1
10.7	12.	264.	2.	11.57	1.54	16.6	23.9	-30.6
12.4	31.	260.	2.	20.08	1.96	24.2	28.2	-14.0
29.3	20.	110.	3.	23.27	1.66	48.5	29.2	66.4
57.7	23.	385.	3.	89.90	1.16	67.2	42.9	56.5
25.8	12.	238.	4.	90.40	1.89	48.7	43.0	13.3
26.9	4.	1346.	3.	101.55	1.65	44.5	44.4	.2
34.4	15.	275.	4.	121.58	1.28	44.1	46.8	-5.8
29.8	10.	207.	3.	136.99	1.75	52.1	48.4	7.6
34.1	12.	69.	7.	146.07	1.28	43.7	49.4	-11.5
34.6	16.	379.	4.	171.99	1.89	65.5	51.7	26.7
31.3	22.	378.	4.	210.33	1.89	59.1	54.7	8.0
46.0	7.	1280.	4.	341.35	1.46	66.9	62.9	6.5
74.0	29.	516.	4.	342.92	1.16	86.2	63.0	36.9
19.5	18.	720.	4.	343.45	1.96	38.2	63.0	-39.3
68.1	10.	1080.	4.	349.64	1.21	82.2	63.3	29.9
92.2	31.	774.	4.	533.01	1.04	96.0	71.4	34.4
62.7	7.	1310.	5.	674.56	1.46	91.2	76.4	19.3

Table A-10. Diesel alternators

TOTAL COST (£'000)	TOTAL POWER ('000 KVA)	NUMBER OF UNITS	OMNIBUS9	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
9.0	.07	1.	.05	1.46	13.15	8.73	50.7
3.6	.13	1.	.09	2.49	8.86	14.51	-39.0
12.3	.19	1.	.13	1.96	24.07	21.13	13.9
13.0	.25	2.	.33	1.96	25.38	48.30	-47.4
19.0	.49	1.	.33	2.77	52.60	49.19	6.9
23.2	.61	1.	.42	2.70	62.72	59.77	4.9
32.8	.63	1.	.43	1.38	45.12	61.54	-26.7
30.0	1.00	1.	.69	2.77	83.02	93.86	-11.5
108.0	.54	2.	.71	1.96	211.40	96.41	119.3
23.9	1.31	1.	.90	2.95	70.46	119.20	-40.9
128.2	.72	3.	1.36	1.96	250.87	173.69	44.4
349.0	2.00	1.	1.37	1.21	421.45	174.90	141.0
140.3	1.70	2.	2.22	1.96	274.61	269.10	2.0
105.0	1.80	2.	2.35	1.96	205.44	283.27	-27.5
247.6	8.37	1.	5.75	2.49	617.74	632.46	-2.3
201.1	3.39	3.	6.45	2.67	536.98	701.36	-23.4

Table A-11. Type I boreholes

TOTAL COST (£'000)	BOREHOLE DEPTH (M)	BOREHOLE DIAMETER (M)	CASING DEPTH (M)	OMNIBUS6	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
2.2	61.0	.30	7.9	13.3	2.63	5.8	4.5	30.2
3.1	106.7	.34	7.6	27.0	2.63	8.1	6.3	28.2
3.2	91.4	.38	15.5	36.5	1.74	5.2	7.3	-29.0
4.3	51.8	.61	15.9	39.2	2.22	9.3	7.6	23.5
4.8	76.2	.61	15.8	57.6	2.32	10.5	9.1	15.5
5.7	81.0	.68	12.2	63.2	1.74	9.2	9.5	-3.2
4.1	73.0	.53	47.0	73.7	1.80	6.9	10.3	-32.7
5.5	91.0	.68	15.3	78.2	1.92	9.6	10.6	-8.6
3.2	183.0	.33	30.8	98.7	2.93	10.7	11.8	-9.4
3.1	183.0	.38	30.8	98.7	2.93	10.6	11.8	-10.6
5.2	120.0	.60	22.0	102.5	2.10	10.5	12.0	-12.7
7.1	90.0	.68	30.0	104.0	1.48	11.2	12.1	-7.8
6.8	100.6	.65	33.7	122.3	2.53	16.3	13.1	24.7
5.6	121.9	.76	15.5	122.5	1.79	9.3	13.1	-29.3
5.6	91.4	.76	31.1	124.4	2.43	13.4	13.2	1.0
6.2	106.7	.76	23.2	127.6	1.79	10.3	13.4	-23.2
12.4	180.0	.60	15.0	130.1	1.24	14.4	13.5	6.7
8.9	130.0	.68	25.0	138.7	1.35	12.2	13.9	-12.7
4.7	143.3	.53	51.5	150.9	2.88	14.2	14.5	-2.2
4.4	121.9	.53	76.2	151.9	2.93	15.0	14.6	3.2
3.6	152.0	.61	30.8	153.7	3.01	12.3	14.7	-16.1
11.7	90.0	1.00	24.0	157.5	1.56	18.2	14.8	22.7
5.0	128.0	.53	82.3	165.0	2.93	16.9	15.2	11.6
11.2	121.9	.68	47.2	171.6	1.33	15.3	15.5	-.9
3.9	176.0	.61	30.8	178.0	3.13	15.5	15.7	-1.7
13.0	135.0	1.00	25.0	240.4	1.58	20.3	18.2	11.4
4.8	241.4	.61	30.8	244.1	3.13	18.9	18.3	2.8
16.5	180.0	.61	60.3	244.1	1.46	24.3	18.3	32.5
19.5	210.0	.60	45.0	245.2	1.24	22.7	18.4	23.6
13.7	152.4	.76	76.2	306.6	1.79	23.0	20.5	12.1

Table A-12. Type 2 boreholes

TOTAL COST (£"000)	BOREHOLE DEPTH (M)	SCREEN TYPE	OMNIBUS7	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
5.7	35.4	1.	35.4	2.91	16.7	18.0	-7.2
9.5	67.1	2.	41.3	2.67	25.3	19.8	27.7
4.7	68.6	2.	42.3	3.72	17.6	20.1	-12.3
16.9	71.6	2.	44.1	1.32	22.4	20.7	8.3
13.8	48.8	1.	48.8	1.62	22.4	22.0	1.7
7.2	50.3	1.	50.3	3.37	24.3	22.4	8.5
5.4	82.6	2.	50.9	3.77	20.3	22.6	-10.0
5.1	54.9	1.	54.9	3.56	18.0	23.7	-23.9
22.1	55.0	1.	55.0	1.26	27.8	23.7	17.3
7.5	91.4	2.	56.3	3.37	25.3	24.1	5.2
6.2	91.4	2.	56.3	3.61	22.5	24.1	-6.4
8.1	92.1	2.	56.7	3.37	27.2	24.2	12.7
12.9	60.0	1.	60.0	1.99	25.7	25.0	2.5
5.7	61.0	1.	61.0	3.72	21.2	25.3	-16.2
13.0	61.0	1.	61.0	1.62	21.1	25.3	-16.6
11.1	62.5	1.	62.5	2.50	27.7	25.7	8.0
5.6	65.5	1.	65.5	3.78	21.1	26.5	-20.1
7.1	65.8	1.	65.8	3.56	25.4	26.5	-4.3
9.5	67.1	1.	67.1	2.62	24.9	26.9	-7.2
8.8	68.6	1.	68.6	3.52	31.0	27.3	13.6
9.0	73.2	1.	73.2	3.56	31.9	28.3	12.5
8.3	73.2	1.	73.2	3.77	31.4	28.3	10.9
12.0	79.3	1.	79.3	3.37	40.3	29.8	35.3
12.6	83.8	1.	83.8	2.67	33.6	30.9	8.8
7.2	137.2	2.	84.5	3.56	25.5	31.0	-17.9
9.7	91.4	1.	91.4	3.61	35.1	32.6	7.7
22.7	115.8	1.	115.8	1.32	30.0	37.8	-20.6
16.1	129.8	1.	129.8	2.50	40.3	40.5	-.6
12.0	132.6	1.	132.6	3.79	45.4	41.1	10.4

Table A-13. Multiple boreholes

TOTAL COST (£"000)	NUMBER OF BOREHOLES	AVERAGE BOREHOLE DIAMETER (M)	AVERAGE CASING LENGTH (M)	AVERAGE BOREHOLE DEPTH (M)	OMNIBUS6	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
11.0	4.	.28	30.0	110.6	1.77	1.57	17.3	17.9	-3.3
10.2	2.	.53	79.5	125.0	2.99	3.39	34.7	32.9	5.4
17.8	3.	.76	19.0	119.3	3.05	1.67	29.7	33.7	-11.6
14.6	3.	.53	51.7	143.3	3.56	3.04	44.5	40.2	10.6
40.5	6.	.55	15.7	90.0	3.58	1.30	52.7	44.5	18.3
24.3	5.	.60	22.0	122.0	4.27	2.02	49.0	49.7	-1.5
12.6	8.	.44	30.5	125.6	5.83	4.23	53.3	71.5	-25.4
57.2	7.	.73	16.6	90.6	6.33	1.74	99.7	78.7	26.6
52.8	6.	.68	30.2	149.2	6.95	1.74	92.0	87.7	4.9
40.1	8.	.71	17.0	108.5	7.12	1.74	69.9	90.2	-22.5
66.3	6.	.60	58.2	163.8	8.67	1.74	115.6	113.3	2.0
53.6	18.	.46	15.4	81.4	9.50	2.80	149.9	126.1	18.9
73.5	11.	.75	16.6	95.3	10.27	1.74	128.2	138.0	-7.1

Table A-14. Concrete dams

TOTAL COST (£ MILLION)	VOLUME OF DAM ("000 CU.M)	DEFLATION FACTOR	CORRECTED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.36	19.	3.58	1.29	.94	37.6
.70	25.	1.89	1.32	1.21	9.1
.32	30.	3.53	1.13	1.44	-21.7
.40	35.	3.38	1.35	1.67	-19.2
.70	55.	3.53	2.47	2.57	-3.8
.90	67.	3.58	3.22	3.10	3.9
1.60	70.	1.61	2.58	3.23	-20.3
1.80	99.	3.33	6.00	4.50	33.5
1.70	100.	2.58	4.38	4.54	-3.5
1.70	125.	3.44	5.85	5.61	4.3
2.10	169.	3.05	6.40	7.48	-14.4
2.80	192.	3.14	8.80	8.44	4.2
4.30	252.	2.81	12.10	10.93	10.6

Table A-15. (a) Earthbank dams with concrete cut-off walls
(b) Earthbank dams with clay cores

TOTAL COST (£ MILLION)	STORAGE VOLUME (MILLION CU.M)	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.90	.12	2.90	2.61	2.17	20.0
.75	.23	3.58	2.69	3.40	-21.0
.75	.24	5.06	3.79	3.52	7.6
1.50	.40	3.23	4.84	4.89	-1.2
1.60	.46	3.23	5.16	5.37	-3.9
2.20	.47	2.90	6.38	5.46	16.8
1.30	.48	3.58	4.66	5.55	-16.1
3.00	1.25	3.07	9.21	10.39	-11.3
4.63	1.99	3.53	16.36	14.11	15.9
8.50	3.00	2.22	18.91	18.49	2.2

TOTAL COST (£ MILLION)	VOLUME OF FILL (MILLION CU.M)	TYPE OF DAM	OMNIBUSS	DEFLATION FACTOR (£ MILLION)	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.48	.31	2.	.18	2.22	1.07	1.29	-16.9
.28	.21	1.	.21	5.06	1.42	1.46	-2.7
.68	.38	1.	.38	3.23	2.19	2.25	-2.5
1.04	.95	2.	.54	3.39	3.53	2.91	21.4
.90	.64	1.	.64	3.44	3.10	3.27	-5.2
1.36	.77	1.	.77	2.90	3.94	3.73	5.8
1.30	1.68	2.	.96	3.07	3.99	4.40	-9.3
2.50	1.00	1.	1.00	2.22	5.56	4.53	22.8
2.72	1.95	2.	1.12	1.88	5.12	4.90	4.4
2.42	1.23	1.	1.23	1.88	4.56	5.26	-13.4
2.97	1.40	1.	1.40	1.88	5.59	5.78	-3.2
1.66	1.50	1.	1.50	3.07	5.10	6.08	-16.1
2.60	3.15	2.	1.80	3.58	9.32	6.95	34.1
2.00	1.87	1.	1.87	3.91	7.82	7.13	9.6
3.50	2.04	1.	2.04	2.90	10.15	7.60	33.5
2.31	2.31	1.	2.31	3.44	7.95	8.32	-4.4
2.50	2.38	1.	2.38	3.53	8.84	8.50	4.0
9.00	3.60	1.	3.60	1.25	11.27	11.48	-1.8
3.28	6.57	2.	3.76	3.15	10.32	11.85	-12.9
3.90	4.30	1.	4.30	3.07	11.98	13.06	-8.3
4.23	7.65	2.	4.38	2.80	11.86	13.24	-10.4
5.30	4.50	1.	4.50	2.37	12.54	13.50	-7.1

Table A-16. Clay-cored bunded reservoirs and lagoons

TOTAL COST (£ MILLION)	STORAGE VOLUME (MILLION CU.M)	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.0048	.0023	2.80	.01	.02	-19.0
.0068	.0025	2.80	.02	.02	7.1
.0071	.0032	2.90	.02	.02	-3.0
.0144	.0041	2.37	.03	.02	36.7
.0176	.0109	2.22	.04	.05	-19.3
.0702	.1090	3.31	.23	.23	-.0
.4830	.9100	2.22	1.07	.98	9.2
1.0400	4.5500	3.39	3.53	2.94	20.1
2.7200	9.2800	1.88	5.12	4.78	7.3
1.3000	10.5000	3.07	3.99	5.19	-23.1
2.6000	19.5000	3.58	9.32	7.91	17.7
3.2800	34.5000	3.15	10.32	11.67	-11.5
4.2300	37.7000	2.80	11.86	12.39	-4.3

Table A-17. Chemical plant

TOTAL COST (£'000)	TREATMENT WORKS OUTPUT ('000 CU.M/DAY)	CHEMICAL TREATMENT PARAMETER	TYPE OF CHEMICAL PLANT	OMNIBUS16	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
3.	4.5	2.	1.	.48	2.77	9.	10.	-9.5
5.	4.6	3.	1.	.72	2.70	14.	16.	-10.9
10.	3.6	4.	1.	.88	2.49	25.	20.	22.9
20.	7.8	5.	1.	1.43	2.06	42.	37.	11.2
17.	118.2	2.	1.	1.72	2.95	49.	45.	10.1
16.	9.1	6.	1.	1.88	3.15	52.	50.	4.0
23.	54.0	3.	1.	1.90	2.06	47.	50.	-5.9
20.	7.7	3.	2.	1.91	2.58	50.	50.	-.3
26.	5.5	4.	2.	2.22	1.96	50.	60.	-16.7
45.	15.0	3.	2.	2.43	2.49	111.	68.	62.2
55.	8.7	5.	2.	3.33	2.58	142.	97.	46.5
32.	27.0	7.	1.	3.37	2.49	79.	98.	-19.8
39.	77.3	6.	1.	4.36	2.77	107.	133.	-19.2
86.	11.4	5.	2.	4.44	1.46	126.	136.	-7.5
52.	22.7	5.	2.	4.86	2.06	107.	151.	-29.2
80.	108.0	6.	1.	4.95	2.27	181.	155.	16.7
69.	68.2	4.	2.	5.99	2.49	173.	193.	-10.0
123.	30.0	6.	2.	6.50	1.66	203.	212.	-4.3
169.	45.5	6.	2.	7.65	1.38	232.	257.	-9.6
140.	145.5	9.	1.	8.39	2.49	349.	286.	22.0
111.	45.5	7.	2.	8.93	1.89	210.	308.	-31.6
177.	72.6	6.	2.	9.20	2.06	366.	319.	14.7
214.	45.5	9.	2.	11.48	2.77	591.	413.	43.2
149.	54.6	9.	2.	12.34	2.67	397.	449.	-11.5
332.	81.8	12.	2.	19.29	2.27	753.	758.	-.6
582.	126.0	12.	2.	22.85	1.80	1049.	924.	13.4

Table A-18. Pyramidal tanks (sedimentation)

TOTAL AREA ('000 SQ.M)	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
.14	111.	72.	53.6
.16	53.	82.	-35.2
.19	69.	95.	-27.1
.23	132.	117.	13.0
.23	94.	117.	-19.9
.34	120.	169.	-28.9
.40	212.	196.	8.5
.44	301.	213.	41.0
.64	492.	309.	59.4
.79	403.	377.	6.8
.80	378.	380.	-.6
.86	629.	407.	54.6
1.53	578.	709.	-18.5
1.63	553.	842.	-34.3

Table A-19. Proprietary tanks (sedimentation)

TOTAL AREA OF TANKS ("000 SQ.M)	DEFLATED TOTAL COST (£MILLION)	ESTIMATED TOTAL COST (£MILLION)	PERCENTAGE ERROR
.091	.068	.064	6.5
.412	.228	.199	14.6
.440	.168	.209	-19.4
.455	.218	.214	1.9
.455	.179	.214	-16.3
.828	.547	.337	62.4
.911	.314	.362	-13.2
.911	.332	.362	-8.2
.917	.348	.364	-4.5
2.048	.575	.669	-14.0
3.480	1.121	.999	12.3

Table A-20. Flotation for water clarification

TOTAL FLOTATION AREA (SQ.M)	DEFLATED TOTAL COST (£"000)	ESTIMATED TOTAL COST (£"000)	PERCENTAGE ERROR
17.	55.	53.	4.1
34.	70.	76.	-9.1
42.	179.	85.	109.7
68.	89.	110.	-18.5
150.	114.	166.	-31.3
160.	140.	172.	-18.7
195.	141.	190.	-25.7
320.	239.	246.	-3.1
524.	335.	319.	5.2
640.	408.	354.	15.4
1670.	739.	583.	26.7

Table A-21. Rapid gravity filters

TOTAL AREA OF TANKS ("000 SQ.M)	DEFLATED TOTAL COST (£ MILLION)	ESTIMATED TOTAL COST (£ MILLION)	PERCENTAGE ERROR
.097	.219	.171	28.0
.116	.102	.196	-47.7
.139	.209	.212	-1.2
.165	.262	.253	3.6
.188	.327	.279	17.1
.240	.570	.335	70.3
.282	.328	.377	-13.0
.374	.491	.399	22.9
.386	.372	.475	-21.7
.592	.553	.654	-15.5
.703	.716	.744	-4.1
1.120	1.212	1.051	15.3
1.782	1.389	1.485	-6.5

Table A-22. Horizontal pressure filters

COST (£"000)	TOTAL FILTRATION AREA (SQ.M)	TYPE OF COST	NUMBER OF FILTERS	OMNIBUS15	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
26.1	44.7	2.	2.	15.2	1.77	46.2	45.0	2.7
16.5	44.7	2.	2.	15.2	2.58	42.6	45.5	-6.4
23.9	34.2	1.	2.	23.4	2.12	51.1	48.7	4.9
22.5	89.3	2.	4.	30.5	2.35	52.9	58.0	-8.6
22.7	89.3	2.	4.	30.5	2.27	51.5	56.0	-7.5
40.0	102.7	2.	6.	35.1	1.99	79.7	74.5	6.9
48.1	53.6	1.	4.	35.6	1.70	81.9	76.5	7.1
42.5	179.6	2.	9.	51.0	2.79	118.6	103.3	14.9
59.4	89.3	1.	4.	61.1	1.70	101.1	103.9	-2.7
45.5	111.6	1.	5.	76.3	2.35	106.9	118.0	-9.4
50.2	116.6	1.	5.	79.3	2.70	135.5	121.1	11.9
67.2	179.6	1.	8.	122.2	2.35	157.9	155.7	1.4
46.2	179.6	1.	8.	122.2	3.01	139.1	155.7	-10.7

Table A-23. Vertical pressure filters

TOTAL COST (£"000)	TOTAL FILTRATION AREA (SQ.M)	NUMBER OF FILTERS	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
17.3	18.7	4.	2.03	35.0	35.4	-1.2
32.4	47.4	8.	2.94	95.2	85.0	12.0
31.4	47.4	8.	2.35	73.7	85.0	-13.3
41.9	56.1	12.	2.55	107.1	99.8	7.3
76.4	126.3	27.	2.64	201.8	214.1	-5.7
135.5	159.9	12.	2.03	275.0	267.2	2.9

Table A-24. Upflow filters

TOTAL FILTRATION AREA (SQ.M)	NUMBER OF FILTERS	RATIO : CIVIL COST / PLANT COST	DEFLATED TOTAL COST (£"000)	ESTIMATED TOTAL COST (£"000)	PERCENTAGE ERROR
25.	2.	.86	88.	134.	-34.0
39.	4.	1.15	254.	179.	42.0
67.	5.	.85	302.	258.	17.2
100.	4.	1.09	374.	341.	9.9
223.	6.	.89	678.	585.	16.0
335.	12.	.69	441.	769.	-42.7
552.	9.	.35	1344.	1078.	24.7

Table A-25. Slow sand filters

TOTAL COST OF FILTER SHELLS (£ MILLION)	TOTAL FILTRATION AREA ("000 SQ.M)	NUMBER OF FILTERS	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.016	.2	1.	2.38	.038	.013	166.2
.017	1.2	1.	2.73	.047	.076	-38.6
.016	1.2	1.	3.00	.048	.076	-36.6
.014	1.2	1.	3.61	.050	.076	-34.4
.022	2.4	2.	4.05	.087	.139	-37.3
.037	2.7	1.	2.38	.089	.153	-42.0
.166	7.4	6.	3.61	.602	.366	64.6
.375	9.3	2.	1.00	.375	.447	-16.0
.317	12.0	5.	2.04	.646	.557	16.1
1.427	15.6	12.	1.24	1.776	.699	154.2
.347	16.2	7.	1.70	.592	.723	-18.1
.670	46.5	18.	4.29	2.871	1.793	60.1
.664	111.8	34.	4.05	2.693	3.820	-29.5

Table A-26. Chlorination equipment

TOTAL COST (£'000)	CHLORINE CAPACITY ('000 KG/DAY)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
1.4	.008	2.70	3.9	4.9	-21.1
2.0	.022	2.49	5.0	7.7	-35.0
8.6	.044	1.66	14.3	10.6	34.5
6.9	.086	2.06	14.2	14.6	-2.6
12.0	.096	1.96	23.5	15.3	53.6
5.7	.096	2.58	14.8	15.3	-3.3
9.6	.136	2.67	25.5	18.0	41.9
14.3	.522	2.58	37.0	33.4	10.8
25.7	.523	1.38	35.4	33.4	5.9
43.3	1.296	2.06	89.1	50.8	75.4
10.4	1.309	2.27	23.7	51.0	-53.6
26.7	1.745	1.89	50.4	56.3	-13.5
22.1	2.095	2.49	55.0	63.4	-13.3

Table A-27. Rectangular tanks—sludge (civil engineering)

TOTAL COST (£'000)	TOTAL VOLUME OF TANKS ('000 CU.M)	WIDTH OF TANK (M)	NUMBER OF TANKS	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
3.5	.24	4.6	2.	4.05	14.1	17.0	-17.0
6.3	.31	4.0	2.	2.73	17.3	20.6	-16.0
9.1	.49	5.2	2.	3.00	27.4	28.3	-3.3
20.6	.56	8.0	2.	1.78	36.6	31.3	17.0
35.5	.63	13.5	2.	1.14	40.4	33.7	20.0
18.8	.69	12.5	1.	3.00	56.4	36.2	55.9
14.0	.81	5.4	2.	2.73	38.1	40.4	-5.8
16.0	1.08	4.7	3.	2.38	38.1	49.8	-23.5
38.8	1.65	9.2	2.	1.94	75.1	67.3	11.6
33.5	2.08	14.0	2.	3.00	100.4	79.4	26.4
32.5	2.48	9.0	2.	2.38	77.4	90.0	-14.0
19.6	2.53	7.6	3.	3.61	70.8	91.3	-22.4

Table A-28. Pyramidal tanks—sludge

TOTAL COST (£'000)	VOLUME OF TANK ('000 CU.M)	PLAN AREA OF TANK (SQ.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
12.5	.11	32.	1.63	20.5	16.0	27.9
7.7	.29	76.	2.83	21.6	27.5	-21.4
11.2	.61	214.	3.29	36.9	41.8	-12.1
16.5	.75	162.	2.46	40.5	46.9	-13.6
16.1	.76	189.	3.29	52.9	47.3	11.8
21.2	.84	232.	2.21	46.9	50.0	-6.2
33.8	1.02	234.	1.63	55.1	55.9	-1.4
28.8	1.51	344.	2.63	75.6	69.7	8.5
31.8	1.73	400.	2.21	70.2	75.4	-7.0
27.1	1.99	408.	2.83	76.6	81.6	-6.1
33.2	2.04	404.	3.33	110.4	82.6	33.7

Table A-29. Conical tanks—sludge (civil engineering)

COST PER TANK (£'000)	DIAMETER OF TANK (M)	VOLUME OF TANK (CU.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
4.0	6.1	74.	2.37	9.4	9.4	-.3
2.0	6.1	101.	2.37	4.7	9.4	-50.7
8.4	7.3	123.	2.58	21.7	12.2	78.2
9.3	11.0	493.	2.22	20.6	21.5	-4.3
16.4	12.0	648.	2.37	38.9	24.3	60.2
10.1	12.3	493.	1.97	19.9	25.1	-21.0
20.2	14.5	466.	2.37	47.9	31.6	51.2
21.9	21.0	1560.	2.22	48.8	53.0	-8.0
14.2	21.4	1609.	2.58	36.8	54.3	-32.3

Table A-30. Sludge drying beds

TOTAL COST (£'000)	TOTAL AREA ('000 SQ.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
2.8	.057	1.77	5.0	4.8	2.6
8.0	.078	1.15	9.2	6.1	51.4
3.5	.080	1.08	3.8	6.2	-38.4
3.1	.108	2.46	7.5	7.6	-1.6
5.0	.251	2.83	14.0	13.8	1.1
6.1	.287	2.16	13.2	15.2	-13.2
14.7	.365	1.50	22.0	18.0	21.9
8.3	.535	2.16	17.9	23.7	-24.4
33.3	.598	1.06	35.5	25.6	38.5
37.1	1.560	1.34	49.9	50.5	-1.1
24.1	1.586	2.16	51.9	51.0	1.7
37.1	5.193	3.00	111.4	118.2	-5.8

Table A-31. Rectangular concrete service reservoirs

TOTAL COST (£MILLION)	CAPACITY OF TANK ('000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£MILLION)	ESTIMATED COST (£MILLION)	PERCENTAGE ERROR
.020	.3	2.21	.045	.032	42.0
.020	.3	2.21	.043	.032	36.4
.014	.5	2.46	.034	.039	-12.7
.034	1.1	1.87	.063	.069	-9.2
.027	2.3	2.63	.072	.108	-33.0
.052	2.3	2.63	.137	.108	26.8
.020	2.3	2.92	.059	.108	-45.3
.076	2.8	1.63	.124	.122	1.9
.041	3.4	2.63	.107	.140	-23.4
.044	3.6	2.63	.115	.146	-21.5
.163	4.5	1.15	.188	.168	12.3
.059	4.5	2.83	.165	.168	-1.8
.056	4.6	2.46	.139	.169	-17.8
.094	4.6	3.09	.290	.169	71.9
.059	5.7	2.63	.156	.195	-20.0
.089	6.9	2.21	.197	.220	-10.1
.150	8.0	1.18	.176	.243	-27.3
.046	8.4	2.92	.135	.251	-46.1
.143	9.0	2.21	.316	.262	20.8
.189	9.1	2.46	.462	.263	75.4
.104	9.1	2.63	.274	.263	3.8
.095	9.1	2.83	.268	.263	1.6
.116	9.1	3.21	.371	.263	40.8
.307	10.0	1.32	.403	.280	44.0
.123	10.0	1.79	.221	.280	-21.2
.227	13.6	2.63	.596	.342	74.3
.126	13.6	3.09	.391	.342	14.2
.097	13.6	3.09	.300	.342	-12.2
.097	13.6	3.09	.300	.342	-12.2
.180	14.0	2.46	.443	.348	27.3
.142	18.0	2.21	.313	.409	-23.5
.128	18.0	2.46	.315	.409	-22.9
.458	22.0	1.46	.670	.465	43.9
.246	22.0	1.95	.479	.465	2.9
.145	22.4	2.63	.409	.471	-13.0
.129	22.7	3.29	.425	.475	-10.5
.210	22.7	2.83	.594	.475	25.0
.200	27.3	2.92	.584	.534	9.4
.165	27.3	3.29	.541	.534	1.3
.158	27.3	3.33	.525	.534	-1.8
.173	29.1	2.92	.507	.557	-9.0
.202	38.4	2.83	.570	.666	-14.4
.298	45.5	3.09	.921	.742	24.1
.266	56.0	2.21	.588	.849	-30.7
.328	90.9	3.33	1.093	1.160	-5.8
.996	91.0	1.46	1.455	1.161	25.4
.557	113.7	2.46	1.368	1.339	2.2

Table A-32. Small rectangular concrete covered tanks

TOTAL COST (£'000)	CAPACITY OF TANK ('000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
9.1	.20	3.29	30.	32.	-5.7
20.4	.34	2.21	45.	41.	10.0
19.6	.34	2.21	43.	41.	5.7
20.7	.46	1.74	36.	47.	-24.0
13.7	.46	2.46	34.	47.	-29.0
26.2	.64	2.46	65.	56.	15.9
30.4	.68	3.29	100.	57.	74.1
58.4	1.11	1.63	95.	73.	31.3
33.7	1.14	1.87	63.	74.	-14.6
28.8	1.54	3.33	96.	85.	12.5
27.5	2.27	2.63	72.	103.	-29.7
52.0	2.27	2.63	137.	103.	33.1
27.9	2.27	2.83	79.	103.	-23.2
20.2	2.27	2.92	59.	103.	-42.6
34.1	2.27	3.21	109.	103.	6.4
76.1	2.75	1.63	124.	113.	10.2
40.8	3.41	2.63	107.	125.	-14.3
43.6	3.64	2.63	115.	129.	-11.2
163.1	4.50	1.15	188.	143.	31.4
58.5	4.54	2.83	165.	144.	15.1
56.4	4.55	2.46	139.	144.	-3.7
93.7	4.55	3.09	290.	144.	101.4
59.2	5.68	2.63	156.	160.	-2.6
39.0	6.46	2.46	96.	171.	-43.8
89.3	6.85	2.21	197.	175.	12.5

Table A-33. Large rectangular concrete covered tanks

TOTAL COST (£ MILLION)	CAPACITY OF TANK ('000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£ MILLION)	ESTIMATED COST (£ MILLION)	PERCENTAGE ERROR
.458	22.0	1.46	.67	.50	33.9
.246	22.0	1.95	.48	.50	-4.3
.145	22.4	2.83	.41	.51	-19.0
.129	22.7	3.29	.42	.51	-16.7
.210	22.7	2.83	.59	.51	16.3
.202	25.0	2.83	.57	.54	5.5
.325	25.5	2.46	.80	.55	45.7
.217	27.3	2.46	.53	.57	-6.9
.200	27.3	2.92	.58	.57	2.2
.165	27.3	3.29	.54	.57	-5.3
.158	27.3	3.33	.52	.57	-5.3
.173	29.1	2.92	.51	.60	-14.9
.361	36.0	2.21	.80	.66	17.2
.202	38.4	2.83	.57	.71	-19.5
.276	39.4	2.46	.68	.72	-5.9
.298	45.5	3.09	.92	.79	17.1
.398	46.5	2.21	.88	.80	10.3
.266	56.0	2.21	.59	.90	-34.4
.328	90.9	3.33	1.09	1.21	-9.9
.996	91.0	1.46	1.46	1.21	19.9
.557	113.7	2.46	1.37	1.39	-1.9
.489	113.7	3.29	1.61	1.39	15.4

Table A-34. Circular tanks

TOTAL COST (£"000)	CAPACITY OF TANK ("000 CU.M)	MATERIAL TYPE	OMNIBUS15	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
6.4	.36	2.	.17	3.33	21.3	11.7	82.7
11.7	.46	1.	.46	1.20	14.0	23.6	-40.9
6.2	.46	1.	.46	3.65	22.6	23.6	-4.1
19.7	1.14	1.	1.14	3.09	61.0	44.6	36.6
10.1	1.14	1.	1.14	3.65	36.9	44.6	-17.3
9.5	1.14	1.	1.14	3.65	34.7	44.6	-22.2
47.6	4.11	2.	1.92	1.32	62.6	64.3	-2.6
49.9	2.05	1.	2.05	2.21	110.3	67.3	63.8
30.4	4.55	2.	2.12	2.21	67.2	69.0	-2.7
17.6	4.55	2.	2.12	3.09	54.5	69.0	-21.1
39.2	2.25	1.	2.25	1.95	76.4	71.9	6.3
33.5	2.27	1.	2.27	2.46	82.3	72.3	13.9
46.5	2.31	1.	2.31	1.74	81.0	73.2	10.6
29.9	5.68	2.	2.65	1.32	39.3	80.7	-51.2
36.7	5.68	2.	2.65	2.21	81.1	80.7	.6
38.4	10.23	2.	4.78	3.09	118.6	121.8	-2.5
109.6	10.57	2.	4.94	1.74	190.9	124.6	53.2
26.3	6.14	1.	6.14	3.65	96.1	145.3	-33.9
41.7	9.04	1.	9.04	3.55	148.2	190.5	-22.2
42.7	9.09	1.	9.09	3.33	142.2	191.2	-25.7
140.0	13.64	1.	13.64	2.83	395.9	254.2	55.8
114.5	13.64	1.	13.64	3.42	391.1	254.2	53.9

Table A-35. Water towers

TOTAL COST (£"000)	CAPACITY OF TANK ("000 CU.M)	MATERIAL TYPE	OMNIBUS14	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
3.6	.060	2.	.036	3.21	11.5	12.7	-8.9
21.5	.180	1.	.180	3.33	71.6	43.3	65.3
21.1	.270	1.	.270	2.46	51.9	59.1	-12.3
17.2	.270	1.	.270	2.83	48.6	59.1	-17.7
29.3	.320	1.	.320	3.09	90.7	67.3	34.6
34.8	.460	1.	.460	2.92	101.7	89.0	14.3
30.0	.910	2.	.551	3.29	98.6	102.2	-3.5
59.0	.570	1.	.570	1.87	110.0	104.9	4.9
27.1	.570	1.	.570	3.42	92.6	104.9	-11.8
42.0	1.140	2.	.690	3.29	138.1	121.5	13.7
32.6	.910	1.	.910	2.63	85.7	150.2	-42.9
140.6	1.130	1.	1.130	1.63	229.7	177.4	29.5
50.0	1.140	1.	1.140	3.21	160.4	178.6	-10.2
37.9	1.160	1.	1.160	3.09	117.3	181.0	-35.2
56.0	1.510	1.	1.510	3.09	173.0	221.6	-21.9
95.0	1.820	1.	1.820	2.21	210.0	255.8	-17.9
122.5	1.820	1.	1.820	2.21	270.7	255.8	5.8
92.3	2.270	1.	2.270	3.65	337.2	303.1	11.2
418.5	2.730	1.	2.730	1.20	500.3	349.2	43.3
161.0	2.730	1.	2.730	2.21	355.8	349.2	1.9
264.0	3.410	1.	3.410	1.95	514.3	414.2	24.2

Table A-36. Preliminary treatment (civil engineering)

TOTAL COST (£'000)	MAXIMUM DESIGN FLOWRATE ('000 CU.M/DAY)	DEFLATION FACTOR	TREATMENT DESCRIPTION PARAMETER	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
1.4	.7	2.63	7.	3.8	3.5	8.7
1.5	3.3	2.68	3.	9.7	9.5	1.5
8.5	5.0	1.47	6.	14.6	12.4	17.4
4.7	7.6	2.06	3.	22.7	16.2	40.1
10.1	9.1	1.83	6.	21.5	18.2	17.8
14.1	11.9	1.42	7.	20.0	21.6	-7.2
12.3	17.4	1.91	6.	27.4	27.6	-.6
19.7	20.1	1.18	6.	27.1	30.2	-10.4
7.8	26.2	1.50	3.	27.4	35.8	-23.4
25.6	37.6	1.70	6.	50.7	45.0	12.6
11.0	50.1	2.95	6.	37.9	54.0	-29.7
18.9	54.7	1.59	6.	34.9	57.1	-38.8
26.6	56.2	2.36	9.	48.9	58.1	-15.8
35.1	61.3	2.45	10.	60.3	61.4	-1.7
24.5	81.9	1.73	6.	49.5	73.7	-32.9
93.8	99.4	1.26	6.	137.4	83.4	64.7
50.7	125.1	1.79	6.	106.1	96.5	9.9
57.3	150.0	1.79	9.	79.9	108.3	-26.2
107.1	402.0	2.41	6.	300.7	202.5	48.4
123.4	409.0	1.93	6.	277.3	204.8	35.5
107.5	409.0	2.50	9.	209.0	204.8	2.1

NOTE : DEFLATED COST = COST * DEFL. FACTOR * (7 / TREATMENT DESC. PARAMETER)

Table A-37. Mechanically raked screens

TOTAL COST (£'000)	NUMBER OF SCREENS	COST PER SCREEN (£'000)	SUBMERGED AREA AT MDF (SQ.M)	DEFLATION FACTOR	DEFLATED COST PER SCREEN (£'000)	ESTIMATED COST PER SCREEN (£'000)	PERCENTAGE ERROR
1.86	1.	1.86	.14	2.06	3.82	4.59	-16.8
3.77	1.	3.77	.24	1.93	7.26	5.66	28.2
4.68	1.	4.68	.53	1.87	8.74	7.69	13.6
3.29	1.	3.29	.60	2.06	6.76	8.06	-16.2
8.12	2.	4.06	.79	1.90	7.71	9.02	-14.5
14.40	2.	7.20	.85	1.78	12.80	9.28	37.9
12.50	3.	4.17	1.05	2.00	8.33	10.18	-18.1
5.12	1.	5.12	1.12	2.09	10.72	10.31	4.0
42.40	6.	7.07	2.03	1.84	12.97	12.99	-.1
14.00	2.	7.00	2.66	1.81	12.65	14.42	-12.3
27.08	2.	11.54	3.30	1.52	17.58	15.66	12.2

Table A-38. Comminutors

TOTAL COST (£'000)	NUMBER OF MACHINES	COST PER MACHINE (£'000)	MAXIMUM DESIGN FLOWRATE ('000 CU.M/DAY)	DEFLATION FACTOR	DEFLATED COST PER MACHINE (£'000)	ESTIMATED COST PER MACHINE (£'000)	PERCENTAGE ERROR
1.90	1.	1.90	4.1	1.90	3.60	3.24	11.2
3.69	2.	1.84	9.1	1.93	3.56	4.01	-11.3
4.61	2.	2.31	9.1	1.90	4.38	4.01	9.2
1.77	1.	1.77	9.1	2.15	3.82	4.01	-4.8
4.23	2.	2.12	42.0	2.11	4.47	6.04	-26.0
11.93	2.	5.97	42.0	1.19	7.11	6.04	17.6
5.75	2.	2.88	42.0	2.00	5.75	6.04	-4.8
9.45	2.	4.73	90.9	1.82	8.61	7.42	15.9
10.27	3.	3.42	90.9	2.20	7.52	7.42	1.3

Table A-39. Detritus removal equipment

TOTAL COST (£'000)	MAXIMUM DESIGN FLOWRATE ('000 CU.M/DAY)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
15.00	57.7	1.81	27.1	24.5	-9.7
17.00	57.7	1.85	31.5	24.5	-22.2
8.87	72.0	2.13	18.9	27.7	46.3
17.30	115.0	1.98	34.3	35.9	4.7
22.10	157.1	1.91	42.3	42.7	.9
24.50	171.8	1.81	44.3	44.9	1.4
29.10	271.4	2.24	65.2	57.9	-11.2
38.00	389.6	1.82	69.2	70.8	2.3

Table A-40. Circular sedimentation tanks (civil engineering)

COST PER TANK (£'000)	WETTED AREA ('000 SQ.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
4.0	.13	2.53	10.2	9.9	2.9
6.4	.14	1.45	9.4	10.1	-7.6
7.8	.18	1.92	14.9	13.2	13.0
5.2	.18	2.44	12.8	13.2	-3.6
7.5	.20	2.46	18.4	14.5	27.1
9.2	.22	1.72	15.8	16.5	-4.7
9.7	.25	1.72	16.7	18.2	-8.5
9.8	.27	2.39	23.4	19.8	18.2
8.6	.31	2.39	20.6	22.9	-10.1
10.1	.38	3.08	31.0	27.8	11.6
8.0	.42	3.09	24.7	30.6	-19.1
9.9	.44	3.08	30.4	32.1	-5.2
13.2	.44	2.46	32.5	32.6	-.3
10.1	.50	3.11	31.4	36.8	-14.7
12.3	.52	3.06	37.6	37.9	-.8
16.4	.60	2.99	49.2	44.0	11.8
31.6	.60	1.42	44.9	44.1	1.7
38.6	.60	1.25	48.4	44.3	9.2
33.1	.65	1.52	50.3	47.9	5.0
41.7	.67	1.25	52.2	49.1	6.2
33.4	1.07	2.44	81.2	77.8	4.4

Table A-41. Circular sedimentation tanks (mechanical engineering)

COST PER TANK (£'000)	DIAMETER OF TANK (M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
3.15	12.0	1.75	5.52	5.17	6.7
3.76	12.0	1.75	6.58	5.17	27.4
2.51	12.2	1.93	4.85	5.21	-6.9
2.94	12.2	1.93	5.67	5.21	8.8
2.26	14.6	2.22	5.01	5.71	-12.3
1.96	18.2	2.52	4.92	6.40	-23.0
1.87	18.2	2.52	4.70	6.40	-26.5
2.89	19.7	1.93	5.58	6.66	-16.2
2.97	19.7	1.93	5.74	6.66	-13.7
5.17	21.0	1.84	9.49	6.88	37.9
6.57	22.3	1.57	10.29	7.09	45.1
3.62	23.0	1.91	6.93	7.21	-3.8
4.61	24.2	1.57	7.22	7.40	-2.4
5.07	25.8	1.82	9.23	7.64	20.8
2.91	27.0	2.00	5.81	7.82	-25.7
3.81	27.0	2.00	7.61	7.82	-2.7
4.63	27.3	1.79	8.29	7.87	5.4
5.15	27.3	1.79	9.22	7.87	17.2

Table A-42. Rectangular tanks (civil engineering)

CIVIL COST (£'000)	TOTAL VOLUME ('000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
3.9	.07	2.10	8.3	9.9	-16.6
14.4	.40	2.60	37.5	34.8	7.6
13.6	.42	2.09	28.3	35.9	-21.2
18.4	.50	2.44	44.9	41.3	8.8
29.5	.61	2.26	66.6	47.6	40.1
24.9	.74	2.36	58.8	55.0	6.9
21.2	.91	3.09	65.5	63.8	2.7
29.9	.94	2.24	67.0	65.5	2.3
38.4	.95	2.26	86.8	66.1	31.3
40.9	1.17	2.00	81.9	76.7	6.8
36.3	1.28	2.44	88.3	82.0	7.7
23.6	1.49	2.55	60.2	91.9	-34.5
53.1	1.68	1.99	105.9	100.1	5.8
72.5	3.42	1.93	140.1	168.8	-17.0
102.5	3.50	1.74	178.6	171.7	4.0
68.4	4.59	2.79	191.1	209.2	-8.7
73.0	5.26	2.87	209.8	231.3	-9.3
102.8	5.53	2.24	230.0	240.1	-4.2
139.0	5.54	1.84	255.6	240.3	6.4
210.9	6.07	1.26	266.0	257.0	3.5
398.5	14.29	1.38	551.6	481.7	14.5
175.4	15.62	2.53	443.5	514.1	-13.7
191.4	19.38	2.53	483.9	602.5	-19.7
470.6	34.99	2.44	1146.0	929.3	23.3
798.3	38.00	1.25	999.7	987.2	1.3

Table A-43. Holding tanks

COST PER TANK (£'000)	VOLUME PER TANK ('000 CU.M)	NUMBER OF TANKS	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
2.8	.053	2.	2.07	5.8	6.5	-10.8
3.9	.069	2.	2.71	10.5	7.4	42.2
2.6	.102	2.	2.46	6.4	9.1	-29.6
6.1	.174	2.	2.37	14.3	12.0	19.0
9.4	.234	1.	1.99	18.7	14.1	33.2
7.2	.240	2.	2.44	17.6	14.2	23.6
5.7	.263	4.	2.77	15.8	14.9	5.4
8.6	.310	2.	1.73	14.9	16.3	-8.7
13.0	.519	1.	1.52	19.8	21.3	-7.2
17.5	.599	2.	1.79	31.3	23.0	36.4
5.4	.691	1.	3.09	16.6	24.7	-32.8
5.0	.843	2.	3.37	16.8	27.4	-38.8
7.6	.853	2.	3.06	23.3	27.6	-15.6
10.4	1.190	1.	3.13	32.6	32.9	-.9
11.9	1.450	1.	2.96	35.2	36.4	-3.4
10.4	1.720	8.	3.21	33.4	39.8	-16.2
15.5	2.460	2.	3.13	48.5	48.0	1.1
36.5	5.800	4.	3.21	117.1	75.1	55.9

Table A-44. Sea outfalls

TOTAL COST (£'000)	LENGTH OF OUTFALL (KM)	DIAMETER OF PIPE (MM)	OMNIBUS19	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
89.	.49	610.	.30	2.1	185.	222.	-16.8
127.	.83	686.	.61	3.1	388.	414.	-6.3
160.	1.37	610.	.83	3.1	495.	537.	-7.8
360.	.67	1090.	1.11	3.0	1064.	692.	53.7
483.	1.26	762.	1.12	1.6	775.	697.	11.1
160.	.99	914.	1.20	3.2	520.	744.	-30.2
391.	2.47	610.	1.49	3.0	1182.	893.	32.3
485.	2.88	686.	2.13	3.1	1483.	1217.	21.9
1106.	2.75	1035.	4.15	2.5	2718.	2166.	25.5
997.	3.35	1067.	5.33	1.9	1914.	2689.	-28.8
968.	4.95	900.	5.86	2.6	2546.	2919.	-12.8

Table A-45. Biological filters (civil engineering)

TOTAL COST (£"000)	NUMBER OF FILTERS	COST PER FILTER ("000)	DIAMETER OF FILTER (M)	VOLUME OF FILTER ("000 CU.M)	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
1.31	1.	1.31	7.0	.07	2.28	3.00	3.05	-1.8
4.95	2.	2.48	8.2	.10	2.00	4.95	3.87	28.1
5.32	1.	5.32	16.8	.40	1.83	9.75	10.91	-10.7
5.53	2.	2.77	16.8	.40	2.77	7.65	10.91	-29.9
6.13	1.	6.13	17.1	.42	2.41	14.75	11.21	31.6
11.22	2.	5.61	17.7	.45	1.30	7.29	11.80	-38.2
14.34	2.	7.17	17.8	.46	1.74	12.51	11.94	4.8
21.04	3.	7.01	19.7	.56	2.06	14.47	13.77	5.1
39.01	3.	13.00	21.3	.65	1.88	24.50	15.52	57.8
31.78	4.	7.94	22.0	.70	1.83	14.55	16.23	-10.4
16.92	3.	5.64	23.4	.79	2.55	14.38	17.76	-19.0
21.87	2.	10.94	23.8	.81	1.40	15.29	18.20	-16.0
40.94	4.	10.23	23.8	.81	1.40	14.31	18.20	-21.4
13.34	2.	6.67	24.0	.83	2.55	17.00	18.42	-7.7
46.62	3.	15.54	25.0	.90	2.13	33.12	19.56	69.4
41.94	4.	10.48	29.0	1.21	1.98	20.81	24.28	-14.3
205.28	8.	25.66	30.5	1.34	1.47	37.69	26.14	44.2
47.87	8.	5.98	30.5	1.34	3.10	18.52	26.14	-29.1
24.69	2.	12.34	31.0	1.38	1.69	20.84	26.76	-22.1
112.04	8.	14.00	31.4	1.42	3.06	42.84	27.27	57.1
82.31	8.	10.29	32.0	1.47	3.02	31.10	28.03	11.0
80.38	4.	20.10	32.6	1.53	1.56	31.29	28.82	8.6
149.62	4.	37.40	35.0	1.76	1.18	44.01	31.95	37.7
42.55	4.	10.64	35.1	1.77	2.50	26.59	32.01	-16.9
104.44	4.	26.11	39.0	2.19	1.21	31.57	37.41	-15.6

Table A-46. Full bridge distributors

COST PER DISTRIBUTOR (£"000)	DIAMETER OF DISTRIBUTOR (M)	DEFLATION FACTOR	DEFLATED COST PER DISTRIBUTOR (£"000)	ESTIMATED COST PER DISTRIBUTOR (£"000)	PERCENTAGE ERROR
.69	8.2	1.94	1.27	1.33	-4.1
.84	11.2	2.00	1.68	1.71	-2.2
1.33	15.0	1.87	2.49	2.18	14.3
1.38	17.8	1.52	2.11	2.51	-16.0
1.36	18.2	2.00	2.72	2.56	6.5
1.94	18.3	1.51	2.93	2.57	14.3
2.14	22.0	1.75	3.74	2.99	25.2
1.32	23.6	1.96	2.59	3.16	-18.2
1.58	24.0	1.88	2.98	3.21	-7.1
1.66	26.0	1.84	3.05	3.43	-11.1
1.64	26.0	1.85	3.03	3.43	-11.7
2.73	31.0	1.98	5.40	3.96	36.4
1.87	34.9	2.09	3.91	4.37	-10.5

Table A-47. Biological filter media

COST PER CU.M (£)	VOLUME OF MEDIA ("000 CU.M)	DEFLATION FACTOR	DEFLATED COST PER CU.M (£)	ESTIMATED COST PER CU.M (£)	PERCENTAGE ERROR
6.00	.08	2.28	13.68	12.40	10.4
6.43	.20	2.00	12.86	12.40	3.7
5.43	.42	2.41	13.07	12.40	5.4
4.93	.78	2.77	13.64	12.40	10.0
5.95	.90	1.74	10.38	12.40	-16.2
6.02	.95	1.30	7.83	12.40	-36.9
4.52	1.52	2.55	11.52	12.40	-7.1
5.30	1.65	2.39	12.64	12.40	1.9
5.17	2.35	2.41	12.45	12.40	.4
6.52	2.78	1.83	11.94	12.40	-3.8
5.92	2.78	1.95	11.57	12.40	-6.6
7.52	2.86	2.55	19.17	12.40	54.6
7.04	5.06	1.56	10.96	12.40	-11.6
7.82	5.25	2.34	18.32	12.40	47.7
5.55	6.61	2.50	13.88	12.40	11.9
6.74	6.71	1.21	8.15	12.40	-34.3
10.34	7.70	1.18	12.16	12.40	-1.9
6.95	9.94	1.47	10.21	12.40	-17.7
3.78	12.52	3.10	11.70	12.40	-5.7
3.98	17.00	3.06	12.17	12.40	-1.9

Table A-48. Aeration equipment

TOTAL COST (£'000)	TOTAL INSTALLED POWER (KW)	TYPE OF AERATION EQUIPMENT	DEFLATION FACTOR	DEFLATED COST (£'000)	ESTIMATED COST (£'000)	PERCENTAGE ERROR
25.	30.	1.	1.88	47.	42.	12.1
28.	30.	1.	1.95	54.	42.	27.5
20.	33.	1.	1.66	33.	46.	-29.0
43.	44.	1.	1.20	52.	59.	-11.8
31.	44.	1.	1.79	55.	59.	-6.5
36.	65.	1.	1.79	64.	82.	-22.4
55.	90.	2.	1.46	81.	109.	-25.9
90.	110.	1.	1.88	169.	130.	29.7
100.	131.	1.	1.96	197.	152.	29.9
148.	179.	2.	1.85	274.	199.	37.8
317.	208.	2.	1.28	406.	226.	79.3
149.	298.	2.	1.87	278.	309.	-10.1
257.	376.	2.	1.08	277.	378.	-26.8
230.	480.	1.	1.52	351.	468.	-25.0
639.	1050.	2.	1.79	1145.	922.	24.1
355.	1080.	2.	2.17	771.	945.	-18.4

Table A-49. Mesophilic digesters (total cost)

CIVIL COST (£'000)	MECH. COST (£'000)	VOLUME PER TANK ('000 CU.M)	NUMBER OF TANKS	OMNIBUS20	DEFLATED TOTAL COST (£'000)	ESTIMATED TOTAL COST (£'000)	PERCENTAGE ERROR
15.1	14.9	.60	1.	.26	86.2	96.7	-10.9
13.2	10.1	.61	1.	.26	51.5	98.4	-47.7
28.8	34.4	.73	1.	.31	86.4	108.6	-20.4
36.8	47.4	.82	1.	.35	157.0	116.8	34.4
51.0	58.5	.89	1.	.38	156.0	121.7	28.2
15.3	28.2	.90	1.	.36	122.0	122.7	-.6
33.5	59.4	.50	2.	.62	212.0	161.7	31.1
27.6	26.3	1.58	1.	.68	155.0	170.2	-9.0
17.3	39.9	1.86	1.	.81	161.0	188.3	-14.5
43.1	45.2	1.90	1.	.81	205.0	189.4	8.2
40.9	35.1	1.91	1.	.82	217.0	190.0	14.2
96.4	50.5	2.04	1.	.87	310.0	197.4	57.1
40.2	32.2	.90	2.	1.12	214.0	227.9	-6.1
58.2	60.3	1.05	2.	1.31	316.0	249.8	26.5
58.5	70.9	1.15	2.	1.44	368.0	263.3	39.7
44.6	29.5	1.49	2.	1.80	197.0	305.9	-35.6
45.5	50.2	1.56	2.	1.95	305.0	314.1	-2.9
37.8	85.1	.35	3.	1.99	308.0	317.7	-3.1
61.4	62.0	1.77	2.	2.21	358.0	338.0	5.9
162.0	185.0	1.97	2.	2.47	402.0	359.6	11.8
45.3	78.3	2.10	2.	2.63	351.0	373.1	-5.9
65.0	82.4	2.61	2.	3.27	419.0	423.1	-1.0
59.1	41.3	2.98	2.	3.73	311.0	456.9	-31.9
115.0	170.0	3.70	2.	4.63	531.0	517.8	2.5
96.8	173.0	2.68	3.	6.28	702.0	617.5	13.7
141.0	223.0	5.15	4.	18.81	1055.0	1165.6	-9.5

Table A-50. Mesophilic digesters (civil engineering)

CIVIL COST (£"000)	VOLUME PER TANK ("000 CU.M)	NUMBER OF TANKS	OMNIBUS22	DEFLATION FACTOR	DEFLATED CIVIL COST (£"000)	ESTIMATED CIVIL COST (£"000)	PERCENTAGE ERROR
15.1	.60	1.	.30	3.05	46.1	47.5	-3.0
13.2	.61	1.	.31	2.36	31.1	48.4	-35.8
28.8	.73	1.	.37	1.34	38.5	53.9	-28.6
36.8	.82	1.	.42	1.83	67.2	58.2	15.4
51.0	.89	1.	.45	1.38	70.6	60.9	15.9
15.3	.90	1.	.46	3.05	46.8	61.4	-23.8
33.5	.50	2.	.59	2.50	83.7	72.2	15.9
27.6	1.58	1.	.80	3.04	84.1	87.5	-3.9
17.3	1.88	1.	.96	3.16	54.6	97.5	-44.0
43.1	1.90	1.	.97	2.62	113.0	98.2	15.1
40.9	1.91	1.	.97	3.03	124.0	98.5	25.9
96.4	2.04	1.	1.04	2.19	211.0	102.7	105.5
40.2	.90	2.	1.07	3.17	127.0	104.6	21.4
58.2	1.05	2.	1.26	2.82	164.0	115.6	41.9
58.5	1.15	2.	1.37	3.05	179.0	122.3	46.3
37.6	.85	3.	1.67	2.83	107.0	138.3	-22.7
44.6	1.49	2.	1.78	2.79	124.0	143.8	-13.8
45.5	1.56	2.	1.80	3.50	159.0	148.0	7.4
61.4	1.77	2.	2.12	3.05	188.0	160.2	17.4
162.0	1.97	2.	2.36	1.25	203.0	171.7	18.5
45.3	2.10	2.	2.51	3.11	141.0	178.2	-20.9
65.0	2.61	2.	3.12	3.05	198.0	204.2	-3.0
59.1	2.98	2.	3.56	3.34	197.0	221.8	-11.2
115.0	3.70	2.	4.42	1.83	210.0	254.0	-17.3
96.8	2.68	3.	5.28	2.86	277.0	283.6	-2.3
141.0	5.15	4.	14.45	3.23	456.0	532.5	-14.4

Table A-51. Mesophilic digesters (mechanical engineering)

MECH. COST (£"000)	VOLUME PER TANK ("000 CU.M)	NUMBER OF TANKS	OMNIBUS21	DEFLATION FACTOR	DEFLATED MECH. COST (£"000)	ESTIMATED MECH. COST (£"000)	PERCENTAGE ERROR
14.9	.60	1.	.20	2.68	40.0	47.6	-16.0
10.1	.61	1.	.21	2.02	20.4	48.4	-57.9
34.4	.73	1.	.25	1.39	47.8	53.0	-9.8
47.4	.82	1.	.28	1.89	89.6	56.5	58.5
58.5	.89	1.	.30	1.45	85.0	58.7	44.8
28.2	.90	1.	.31	2.67	75.2	59.1	27.2
26.3	1.58	1.	.54	2.68	70.5	79.7	-11.5
39.9	1.88	1.	.65	2.68	107.0	87.3	22.5
45.2	1.90	1.	.65	2.04	92.4	87.8	5.2
59.4	.50	2.	.66	2.16	128.0	88.0	45.5
35.1	1.91	1.	.66	2.66	93.4	88.1	6.1
50.5	2.04	1.	.70	1.96	99.0	91.2	8.6
32.2	.90	2.	1.19	2.68	86.3	120.3	-28.3
60.3	1.05	2.	1.39	2.52	152.0	130.7	16.3
70.9	1.15	2.	1.52	2.67	189.0	137.2	37.8
29.5	1.49	2.	1.98	2.47	72.8	157.2	-53.7
50.2	1.56	2.	2.07	2.90	146.0	161.1	-9.4
62.0	1.77	2.	2.35	2.74	170.0	172.2	-1.3
85.1	.85	3.	2.48	2.36	201.0	177.3	13.4
185.0	1.97	2.	2.61	1.08	199.0	182.2	9.2
78.3	2.10	2.	2.78	2.68	210.0	183.4	11.5
82.4	2.61	2.	3.46	2.68	221.0	211.3	4.6
41.3	2.98	2.	3.95	2.76	114.0	226.6	-49.7
170.0	3.70	2.	4.91	1.89	322.0	253.9	26.8
173.0	2.68	3.	7.82	2.45	425.0	324.7	30.9
223.0	5.15	4.	26.30	2.68	599.0	615.3	-2.6

Table A-52. Filter plate presses (civil engineering)

TOTAL COST (£"000)	MAXIMUM FILTRATION AREA ("000 SQ.M)	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
72.1	.58	2.05	147.5	117.8	25.2
42.8	.59	2.34	100.3	120.1	-16.5
54.8	.59	2.43	133.2	120.1	10.9
61.1	.76	2.22	135.7	143.8	-5.7
71.4	.95	2.50	178.5	170.3	4.8
74.2	1.34	2.80	207.5	219.4	-5.5
201.4	1.37	1.25	251.7	224.0	12.4
124.9	2.37	1.81	225.5	335.9	-32.9
386.7	5.35	1.69	652.9	615.8	6.0
430.3	6.09	2.24	964.5	837.8	15.1

Table A-53. Filter plate presses (mechanical engineering)

TOTAL COST (£"000)	MAXIMUM FILTRATION AREA ("000 SQ.M)	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
64.5	.30	1.88	121.4	97.8	24.1
74.6	.42	2.02	150.6	131.2	14.8
67.0	.45	1.85	123.9	141.0	-12.1
62.1	.50	2.46	152.9	153.4	-.3
96.7	.89	2.51	242.8	254.7	-4.7
175.8	1.07	1.81	317.7	298.6	6.4
106.5	1.34	2.45	260.7	362.6	-28.1
374.4	3.56	1.85	693.1	852.8	-18.8
1208.0	8.09	1.95	2353.0	1741.7	35.1

Table A-54. Water works and water pumphouse buildings

TOTAL COST (£"000)	TOTAL FLOOR AREA ("000 SQ.M)	TYPE OF BUILDING	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
17.	.06	1.	2.63	46.	17.	167.7
18.	.07	2.	2.63	47.	21.	125.9
22.	.12	1.	2.63	57.	33.	71.5
23.	.12	2.	1.20	27.	34.	-19.6
7.	.14	1.	2.92	21.	38.	-44.5
24.	.14	2.	1.25	31.	38.	-20.3
11.	.15	1.	3.29	36.	43.	-16.8
16.	.16	2.	2.46	39.	44.	-11.1
7.	.17	1.	3.55	26.	47.	-45.0
41.	.23	2.	2.63	108.	63.	72.2
26.	.24	1.	2.46	64.	64.	-.8
19.	.27	1.	2.46	46.	72.	-36.1
10.	.27	1.	3.55	34.	73.	-53.2
26.	.28	1.	2.46	65.	75.	-14.0
21.	.29	1.	2.46	51.	77.	-33.3
24.	.29	1.	1.46	36.	78.	-54.1
51.	.32	1.	2.46	125.	85.	46.2
31.	.35	1.	2.83	88.	94.	-6.4
52.	.39	1.	3.09	162.	103.	57.4
90.	.41	2.	2.46	220.	108.	104.1
62.	.43	2.	2.60	162.	113.	44.3
39.	.43	1.	2.92	113.	113.	.7
30.	.43	2.	1.11	33.	114.	-70.7
37.	.48	2.	2.83	103.	124.	-16.6
47.	.48	2.	2.46	115.	125.	-8.1
63.	.50	2.	2.56	162.	130.	24.5
52.	.52	1.	2.46	128.	133.	-4.0
119.	.56	1.	2.21	263.	144.	81.9
168.	.62	2.	1.00	168.	158.	5.9
99.	.73	1.	2.21	218.	184.	18.9
46.	.75	2.	3.09	141.	189.	-25.4
48.	.80	1.	2.83	135.	201.	-32.9
55.	.85	1.	3.09	170.	213.	-20.2
106.	1.09	1.	2.46	262.	269.	-2.7
83.	1.24	1.	2.63	217.	304.	-28.5
210.	1.42	2.	2.21	465.	344.	35.2
122.	1.60	1.	2.52	307.	385.	-20.2
148.	1.64	1.	2.92	432.	394.	9.7
420.	1.72	1.	3.09	1297.	411.	215.5
240.	2.40	1.	2.46	591.	562.	5.2
188.	2.98	1.	3.33	627.	687.	-8.8
405.	3.44	2.	2.46	996.	787.	26.6

Table A-55. Water pumphouses

TOTAL COST (£"000)	DESIGNED THROUGHPUT ("000 CU.M/DAY)	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
28.	15.	1.77	49.	34.	44.0
35.	30.	2.46	87.	58.	49.2
18.	45.	2.83	51.	82.	-37.7
36.	91.	2.41	87.	142.	-38.6
61.	91.	2.34	144.	142.	.9
24.	55.	3.00	73.	149.	-50.5
57.	109.	2.83	162.	164.	-1.6
90.	164.	2.16	193.	227.	-14.9
394.	160.	1.77	696.	244.	134.9
293.	318.	1.07	315.	384.	-18.0
405.	680.	2.16	874.	700.	24.7

Table A-56. Sewage sludge treatment buildings

TOTAL COST (£"000)	TOTAL FLOOR AREA ("000 SQ.M)	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
23.7	.243	1.63	38.6	55.9	-30.8
31.0	.288	2.46	76.2	64.3	18.5
53.9	.371	2.21	119.0	79.3	50.1
37.2	.402	2.21	82.2	84.7	-3.0
40.7	.418	2.21	90.0	87.5	2.9
37.2	.457	2.46	91.6	94.2	-2.8
34.0	.649	2.92	99.1	125.9	-21.2
61.0	.674	2.46	150.1	129.9	15.6
65.2	.930	2.83	184.4	169.5	8.8
111.2	1.183	1.55	172.4	206.8	-16.6
175.9	1.463	1.25	219.9	246.5	-10.8
313.9	2.964	1.74	546.1	441.8	23.6
270.0	4.716	2.21	596.7	648.5	-8.0

Table A-57. Sewage pumping stations

TOTAL COST (£"000)	TOTAL DESIGN CAPACITY (L/S)	DESIGN NUMBER OF PUMPS	TOTAL VOLUME OF STRUCTURE (CU.M)	TOTAL FLOOR AREA (SQ.M)	OMNIBUS23	DEFLATION FACTOR	DEFLATED COST (£"000)	ESTIMATED COST (£"000)	PERCENTAGE ERROR
5.5	6.	1.	66.	18.	.4	1.74	9.5	10.2	-7.1
3.4	9.	1.	34.	6.	.5	1.99	6.7	11.1	-40.1
4.6	9.	1.	30.	6.	.5	1.99	9.1	11.1	-18.6
15.7	2.	2.	111.	24.	.9	1.38	21.7	12.3	76.6
15.7	3.	2.	117.	24.	1.3	1.38	21.7	13.4	62.0
5.2	3.	2.	66.	18.	1.3	2.21	11.5	13.4	-14.0
11.2	4.	2.	90.	40.	1.7	1.11	12.5	14.2	-12.0
13.6	4.	2.	84.	40.	1.7	1.11	15.1	14.2	6.3
9.5	4.	2.	86.	19.	1.7	1.11	10.6	14.2	-25.2
8.5	30.	1.	30.	7.	1.8	1.46	12.4	14.4	-14.1
23.5	8.	2.	309.	33.	3.4	1.46	34.3	16.5	107.8
18.2	10.	2.	186.	13.	4.3	1.38	25.2	17.3	45.5
5.9	10.	2.	112.	25.	4.3	2.37	14.0	17.3	-19.2
13.2	14.	2.	224.	46.	6.0	2.21	29.1	18.6	56.5
7.0	15.	2.	142.	32.	6.4	1.87	13.1	18.9	-30.7
11.0	15.	2.	158.	33.	6.4	2.21	24.3	18.9	29.0
11.0	15.	2.	143.	33.	6.4	2.21	24.3	18.9	29.0
13.4	16.	2.	122.	33.	6.9	1.38	18.6	19.1	-2.9
6.0	18.	2.	39.	8.	7.7	1.99	12.0	19.6	-38.7
13.4	21.	2.	137.	33.	9.0	1.38	18.6	20.3	-8.4
8.7	7.	3.	237.	48.	9.4	2.21	19.2	20.5	-6.3
9.3	22.	2.	172.	32.	9.4	1.87	17.4	20.5	-14.9
7.5	23.	2.	51.	9.	9.9	1.38	10.4	20.7	-49.5
26.1	24.	2.	127.	15.	10.3	1.63	42.7	20.9	104.5
10.5	28.	2.	61.	9.	12.0	1.38	14.6	21.6	-32.3
10.7	28.	2.	227.	54.	12.0	1.87	19.9	21.6	-7.8
10.4	35.	2.	89.	9.	15.0	1.38	14.3	22.6	-36.6
7.2	35.	2.	263.	51.	15.0	2.44	17.6	22.6	-21.9
8.4	38.	2.	86.	17.	16.3	1.38	11.6	23.0	-49.7
28.7	38.	2.	510.	82.	16.3	1.38	39.8	23.0	72.8
7.2	56.	2.	263.	51.	24.0	2.44	17.6	25.0	-29.4
26.1	64.	2.	146.	15.	27.5	1.63	42.7	25.7	65.9
21.8	76.	2.	339.	74.	32.6	1.38	30.1	26.7	13.0
32.7	47.	3.	508.	81.	63.2	1.46	47.8	30.7	55.6
26.6	150.	2.	433.	84.	64.4	2.29	60.7	30.8	96.8
41.5	260.	2.	760.	139.	111.6	1.87	77.4	34.7	123.2
26.0	264.	2.	522.	81.	113.3	1.63	42.4	34.8	21.9
7.4	92.	3.	381.	82.	123.8	2.44	18.0	35.5	-49.2
21.3	123.	3.	431.	66.	165.5	2.21	47.1	37.7	24.9
11.6	150.	3.	150.	16.	201.8	1.87	21.7	39.4	-44.8
15.9	480.	2.	239.	66.	206.1	1.87	29.7	39.5	-24.8
24.3	160.	4.	723.	108.	484.2	1.63	39.7	47.5	-16.3
44.6	238.	4.	1086.	155.	720.3	1.95	86.8	51.7	68.1
30.4	278.	4.	806.	95.	841.3	1.25	38.1	53.4	-28.6
31.2	69.	7.	332.	108.	1010.5	1.46	45.6	55.5	-17.9
58.6	378.	4.	1292.	175.	1144.0	1.95	114.1	57.0	100.2
23.1	207.	5.	778.	152.	1174.7	1.87	43.1	57.4	-24.9
23.9	960.	3.	515.	124.	1291.8	1.87	44.6	58.5	-23.8
41.9	562.	4.	579.	108.	1700.9	1.15	48.3	62.1	-22.2
91.9	1346.	3.	848.	80.	1811.2	1.32	120.9	62.9	92.1
34.6	720.	4.	736.	155.	2179.0	2.29	79.0	65.4	20.8
46.4	440.	5.	1228.	150.	2497.0	1.63	75.8	67.4	12.5
26.4	551.	5.	1190.	131.	3127.0	1.87	49.3	70.7	-30.2
40.2	1280.	4.	577.	26.	3873.8	1.46	58.7	74.0	-20.6
75.3	716.	5.	902.	134.	4063.4	1.15	86.8	74.8	16.2
121.4	1101.	5.	2214.	300.	6248.3	1.07	129.7	81.9	58.3
60.3	1310.	5.	959.	176.	7434.4	1.46	88.1	85.0	3.6
28.4	1440.	5.	215.	108.	8172.1	1.46	41.5	86.8	-52.2

APPENDIX B—COST INDICES USED IN THE STUDY

COST INDICES USED IN THE STUDY

For each cost function in Part III a particular cost index was chosen to deflate costs (that is, to correct them for inflation). In all, the following 11 indices were used:-

1. New Construction Wholesale Output Price Index (A), (B);
2. Engineering and Allied Industries Wholesale Output Price Index for Home Sales (A);
3. DQSD Building Tender Price Index (B);
4. Construction Materials Wholesale Purchase Price Index (A), (B);
5. Average Earnings of all Employees in Construction Industry Index (monthly enquiry) (A), (B);
6. Basic Weekly Wage Rate of Manual Workers in Construction Industry Index (A), (B);
7. Mechanical Engineering Wholesale Output Price Index (A);
8. Steel Industries Wholesale Output Price Index (A);
9. Chemical and Allied Industries Wholesale Output Price Index (A);
10. Fuel and Light (Electricity) Retail Price Index (A);
11. Basic Weekly Wage Rate of Manual Workers in Gas, Electricity and Water Industry Index (A).

The letters appearing in parentheses after each index title indicate in which of the following publications the index is tabulated:-

(A)	Monthly Digest of Statistics Annual Abstract of Statistics	Central Statistical Office, HMSO;
(B)	Table of Construction Cost Indices, Housing and Construction Statistics (quarterly)	Department of the Environment, HMSO.

Indices 6 and 11 both refer to basic weekly wage rates of manual workers. However, Section 12.9 contains the only references to Index 11. For convenience, therefore, Index 6 has been abbreviated throughout Part III to 'the Basic Weekly Wage Rate Index'.

Table B-1 lists the values taken by the first eight indices over the period 1963 to 1976 Q3. Indices 9, 10 and 11 were used only for updating some of the operating costs, and it was felt unnecessary to list them in detail here. The five most frequently used indices have been plotted in Figure 3-1.

Table B–1. Listing of cost index values

Date	New Construction	Engineering and Allied Industries	DQSD	Construction Materials	Average Earnings	Basic Weekly Wage Rate	Mechanical Engineering	Steel Output
	1.	2.	3.	4.	5.	6.	7.	8.
1963	79	78	76	78	61	70	76	77
1964	80	80	77	80	66	74	78	77
1965	82	82	79	82	71	76	80	78
1966	85	84	82	84	76	79	84	81
1967	85	85	84	84	79	83	84	82
1968	90	88	87	89	86	88	87	83
1969	93	91	89	92	91	90	91	86
1970	100	100	100	100	100	100	100	100
1971	107	110	114	109	110	110	111	109
1972	119	116	139	116	123	126	118	115
1973 Q1	135	120	164	125	138	147	122	117
Q2	141	122	183	131	144	155	124	124
Q3	151	126	214	141	149	169	127	129
Q4	161	130	228	149	154	169	131	134
av.	147	125	197	137	146	160	126	126
1974 Q1	170	137	228	162	153	169	138	146
Q2	180	147	234	176	164	176	148	179
Q3	190	156	230	180	175	198	158	156
Q4	200	165	222	184	185	207	166	190
av.	185	151	229	175	169	187	152	175
1975 Q1	210	177	226	195	195	223	182	220
Q2	220	188	231	204	207	241	193	228
Q3	228	195	229	209	220	263	202	228
Q4	236	202	226	215	228	263	209	231
av.	223	191	228	206	212	248	197	227
1976 Q1	238	210	233	227	227	264	219	237
Q2	246	218	238	242	234	276	226	260
Q3	263	227	246	258	241	300	235	282