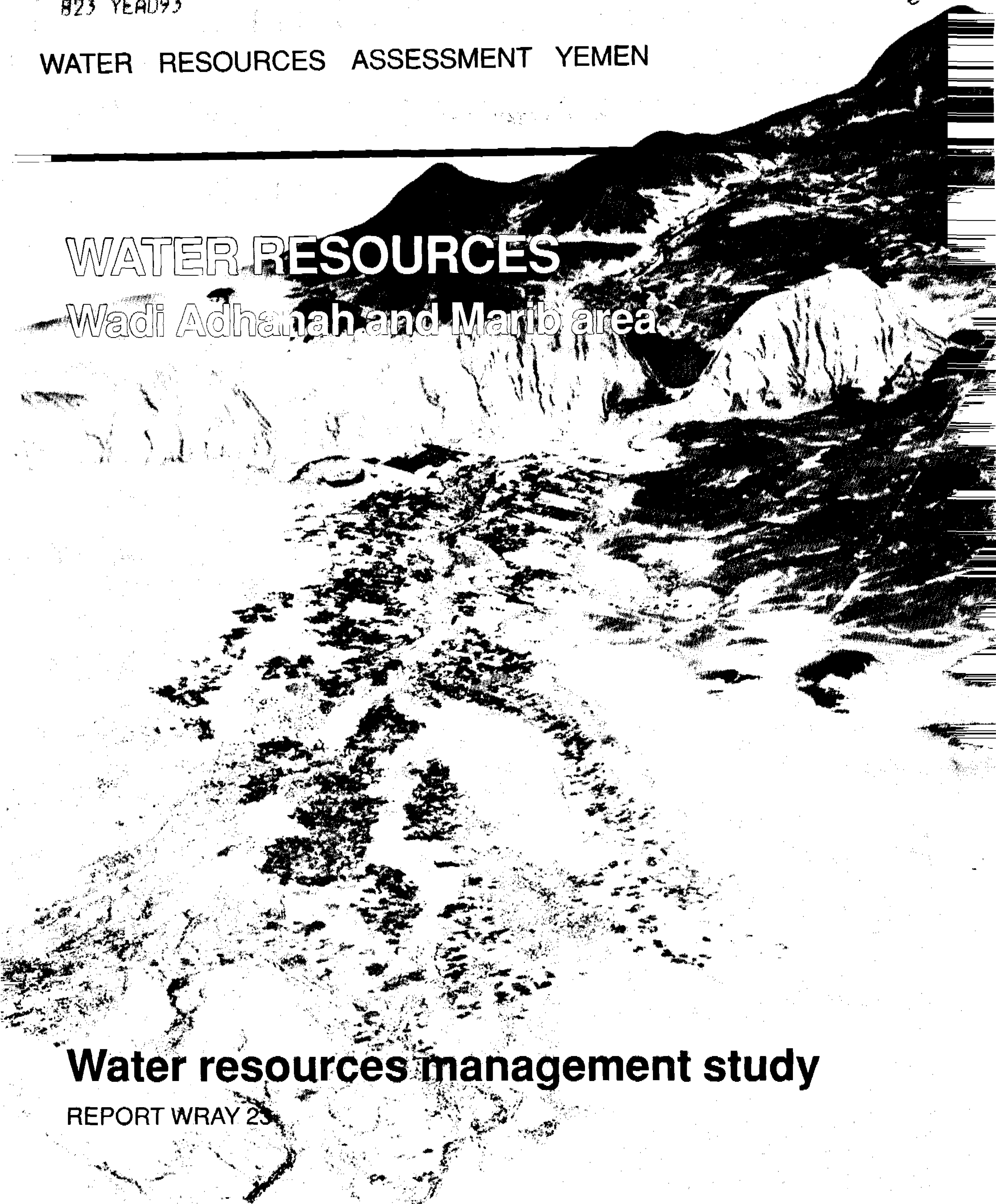
WATER RESOURCES ASSESSMENT YEMEN



WATER RESOURCES

Wadi Adhanah and Marib area

Water resources management study

REPORT WRAY 23

MINISTRY OF OIL AND MINERAL RESOURCES,
GENERAL DEPARTMENT OF HYDROGEOLOGY

TNO INSTITUTE OF
APPLIED GEOSCIENCE

In cooperation with:
MINISTRY OF AGRICULTURE AND WATER RESOURCES,
EASTERN REGIONAL AGRICULTURAL DEVELOPMENT AUTHORITY

WATER RESOURCES ASSESSMENT YEMEN
(WRAY)

The Republic of Yemen
Ministry of Oil
and Mineral Resources

Kingdom of The Netherlands
Ministry of Foreign Affairs
Directorate General of International Cooperation

Water Resources
Wadi Adhanah and Marib area

WATER RESOURCES MANAGEMENT STUDY

by

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In cooperation with:
Eastern Regional Agricultural
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Marib

The Republic of Yemen

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Geoscience
Delft

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AAW	Actual Allocated Water
A.D.	Anno Domini (time reference)
AGRIMAR	agrohydrological/agricultural model developed for the Marib area
A.H.	Anno Hegirae (Islamic time reference)
AWD	Actual Water Demand
CAMA	Civil Aviation and Meteorological Authority
d^{-1}	per day
ECOMARIB	Economic model developed for the Marib area
ERADA	Eastern Region Agricultural Development Authority, Marib, The Republic of Yemen
GDH	General Department of Hydrogeology
GW	Groundwater
GWD	Gross Water Demand
ha	hectare
i	annual rate of discount
kg	kilogram
km^2	square kilometre
m	metre
m^{-1}	per metre
MAWR	Ministry of Agriculture and Water Resources, Sana'a, The Republic of Yemen
m/d	metres per day
m^2/d	square metre per day
m^3	cubic metre
Mm^3	million cubic metres
MODFLOW	Modelcode groundwater model Marib region
MYR	Million Yemeni Riyals
MOMR	Ministry of Oil and Mineral Resources
NB	Net Benefits
PV	Present Value
ROY	Republic of Yemen
SW	Surface Water
SHELL	user interface of the Water Resources Management model developed for the Marib area
TNO	Netherlands Organization for Applied Scientific Research, Delft, The Netherlands[1]
WRAY	Water Resources Assessment Yemen (Yemeni-Dutch cooperation programme started in 1982; executing agencies are GDH and TNO Institute of Applied Geoscience)
WRM	Water Resources Management
YR	Yemeni Riyal
yr	year

1 This organization consists of approximately 30 institutes. One of these, the TNO Institute of Applied Geoscience (P.O. Box 6012, 2600 JA Delft, The Netherlands) has been cooperating with the GDH since 1982 in the WRAY programme.

SUMMARY

Background

Developments during the first half of the 1980s raised the Yemeni Government's concern about the water resources of the Marib area. Therefore, in mid-1986 the second phase of the Water Resources Assessment Yemen (WRAY-2) project started with an investigation of the water resources of the Wadi Adhanah and Marib area; the study was continued during the subsequent WRAY-3 phase (1986-1989). The main objective was to assess the total available fresh groundwater and surface water resources in relation to their use, taking into account the new Marib Dam and Irrigation scheme.

The catchment of the Wadi Adhanah is situated on the Eastern Escarpment of the Yemen mountain belt. The Wadi Adhanah drains into the Marib area, which is a plain at the foot of the Eastern Escarpment. The Marib plain forms part of the Wadi Al-Jawf Basin, which is situated in the headwaters of the Wadi Hadramawt catchment area.

Agriculture is the main economic activity in the Marib area as well as in the catchment area. At present about 8400 ha are cultivated. Although the successful exploration and exploitation of oil and gas in the Marib area is the most important activity from a macro-economic point of view, the local population is hardly involved in these activities.

The intermittent streamflows of the Wadi Adhanah are presently being retained behind the new Marib dam. In addition to the reservoir behind the Marib dam the water resources system comprises the wadi courses, the groundwater system, the irrigation infrastructure and the irrigated land. Water can be released from the dam through the wadi bed to two diversion structures located respectively 10 and 16 km downstream. The primary canals, with a total length of 50 km, are intended to serve 23 irrigation sectors, with a total planned gross area of about 7400 ha. So far, the construction of secondary channels has been completed in only one irrigation sector. Upstream of the first diversion, an area of about 150 ha is irrigated by diverting water by bunds directly from the wadi to the land.

WRAY's investigations have substantially increased the understanding of the area's water resources. The average inflow into the Marib lake observed over the period 1986 to 1991 is much smaller than the average inflow originally estimated during the design phase of the dam, and so is the conveyance efficiency of the wadi between the dam and the diversion works. Because of this, the gross area initially planned to be supplied mainly by surface water in the Marib scheme, may have to be significantly reduced.
Groundwater abstraction has increased dramatically during the last ten years and was approximately 136 million m^3 in 1987. There is evidence of groundwater mining. From a well inventory executed in May 1991 the present yearly abstraction was estimated to be 174 million m^3, which means an average annual increase of 10 million m^3 during the last four years. Taking the Marib area as a whole it is clear that the potential water demand exceeds the average rate of renewal of the water resources. The surface water and groundwater systems in the area are strongly interrelated; any surface water use has direct consequences for the availability of groundwater. Hence, the new dam will have a considerable impact on the

water situation in the Marib area.

The scarcity and the depletion of the water resources and the potential demands for water triggered the need to carefully analyse the water resources of the Marib area and to help the water sector's decision makers develop a consistent water resources management strategy for the development and use of these resources. Therefore, in the WRAY-4 project, which succeeded WRAY-3, a water resources management study was included with the objective to contribute to the development of an adequate water resources management policy for the Marib area. Besides producing concrete results which could be used as a tool for careful water resources management in the Marib area, the study especially aimed at further developing Yemeni capability to formulate and analyse strategies for water resources management. The study concentrated on the evaluation of water resources management options and strategies. It covers economic and socio-economic issues to a limited extent only. The measures that should be taken to implement a selected water resources management strategy need to be elaborated and evaluated during an additional study.

Approach

A Systems Analysis approach was chosen. The study comprised three phases; an Inception phase, a Data Compilation phase and a Systems Analysis phase. During the Inception phase, a problem analysis was done and objectives and criteria for water resources management were defined by the relevant decision makers. During the Data Compilation phase additional hydrological, agricultural, economic and socio-economic data were collected. During the Systems Analysis phase options for water resources management were evaluated according to the predefined criteria. Promising options were grouped into six water resources management strategies. The study was designed at a regional level; spatial variables were aggregated to a certain extent in order to focus on the main issues, interactions and impacts. The Inception phase started in October 1990 and the draft final report was prepared in December 1991.

The study was done by a permanent study team of five persons selected from the General Department of Hydrogeology (GDH), the Eastern Region Agricultural Development Authority (ERADA) and the WRAY-4 expatriate team. The team was integrated into the Studies and Survey Department of the GDH. The management staff of the GDH and ERADA participated in consultative meetings. A large number of staff from several departments from the GDH and ERADA were involved during the data collection in the field. Additional contributions were made by a number of external specialists.

A tailor-made modelling framework was developed to facilitate the analysis. This framework was structured as an integrated simulation model. It comprises four main modules:
a surface water allocation and agricultural model (AGRIMAR);
a groundwater model (MODFLOW);
a cost-benefit model (ECOMARIB);
and a user-interface program (WRMSHELL).
Data files containing data on hydrology, hydrogeology, water use, agricultural and economic parameters are an integral part of the model. The modules and data files can be accessed using the user interface (WRMSHELL). This interface facilitates the formulation of water resources management strategies, ensures communication between the modules, and supplies the

output in a format corresponding to the criteria defined for comparing the impacts of the different strategies.

Objectives for water resources management

The objectives of water resources management as defined by the relevant decision makers were:

- to maximize the economic benefits,
- to maximize the area irrigated by surface water,
- to achieve sustainability of groundwater use,
- to achieve an equitable distribution of water-related benefits.

Analysis of options for water resources management

Several options were evaluated, such as the degree of further development of the irrigation scheme, the construction of a lined conveyance canal from the dam to the diversion structures, different surface water allocation regimes, different groundwater abstraction rates, improved irrigation efficiencies, surface water irrigation in one or more seasons and different cropping patterns. These options were evaluated separately, according to the criteria set for the defined objectives. The evaluation was done for a simulation period of 25 years for three of the four objectives. To evaluate the sustainability of the groundwater resources the Water Resources Management model was run for a period of 100 years.

Groundwater abstraction at present or higher rates will, in the long run, result in extensive areas running dry in the upstream part of the upper aquifer, which will halt groundwater flow to the downstream areas. In order to ensure that at least some groundwater will remain in the upstream part of the upper aquifer within one hundred years from now, in the near future the groundwater abstractions need to be reduced to 70-75% of the present abstraction. This will only slow down the process of losing the resources. If real sustainability of groundwater use is aimed at, reduction to some 35% of the present rate is needed.

In the present situation groundwater recharge from surface water occurs mainly upstream of the diversion structures. When the surface water irrigation system is developed further, there will also be significant recharge from surface water downstream, from 'losses' of irrigation water. So from the point of view of sustainability of groundwater use, further development of the irrigation scheme is a desirable option.

The construction of a lined conveyance canal from the dam to the diversion structures has a positive effect on the groundwater level in the downstream part of the aquifer. It has a negative effect on the groundwater level in the upstream part. Therefore, recharge of the groundwater in the area upstream of the diversion structures should be provided for by means of recharge basins in the wadi, if a lined conveyance canal is constructed.

Further development of the surface water irrigation scheme, including the construction of a lined conveyance canal, may not be economically justified if investment costs of structures are taken into account, but results in a more equitable distribution of benefits.

The analyses further confirmed that improving the surface water irrigation efficiencies has a positive effect on the size of the area that can be irrigated with surface water and on the benefits per hectare, but a slightly negative effect on the sustainability of groundwater use.

When surface water irrigation takes place in the winter season the average annual evaporation from the Marib reservoir is about 30% of the average annual inflow. When surface water irrigation takes place directly after the main inflow period (March and April) the annual evaporation is reduced to about 20% of the average annual inflow. When surface water is released continuously with maximum gate opening the evaporation diminishes to about 10% of the average annual inflow.

The introduction of a cropping pattern with a higher cropping intensity would improve the economic benefits. More groundwater will be needed to meet the greater demand for irrigation water, and therefore this should be integrated into a set of water resources management measures to ensure the sustainability of groundwater use.

Analysis of strategies for water resources management

Promising options were grouped into six strategies, which were evaluated following the same procedure. Full completion of the irrigation scheme is assumed in all strategies, even though economic justification appears weak, because it helps in achieving the other objectives.

Among the six strategies evaluated, one scores comparatively well on all objectives. In this strategy, scheme completion, including the construction of a lined conveyance canal, is assumed between 1994 and 1998. The area of some units is reduced because of migrating sand dunes. Some surface water is allocated to recharge basins in the wadi upstream of the diversion structures, in the near future groundwater abstraction will be reduced to 70% of the average present abstraction, a cropping pattern with a high cropping intensity will be implemented and the irrigation efficiencies will not be improved.

Under this strategy 17% of the upper aquifer will be lost within 100 years. This is only slightly more than aquifer loss under a true sustainable groundwater use strategy, because the aquifer system reacts very slowly to changes. The area irrigated with surface water will increase from around 200 ha at present to around 2100 ha. On average, 40% of the planned net area of each irrigation sector can be irrigated with surface water during the winter season and on average 70% of the area of each sector could be irrigated in the winter season using both groundwater and surface water. On average, 66% of the area now cultivated in the Marib area outside the scheme can be irrigated during the winter season. In the summer season, when no surface water irrigation takes place, 30% of the net area within and outside the irrigation scheme can be irrigated. Even though under this strategy less area will be irrigated than at present, the financial benefits of all units increase, especially in units that show low or zero benefits at present.

Policy analysis for water resources management is an ongoing process

The human resources and the tools developed for this study will enable the responsible Yemeni agencies to investigate a wide range of alternatives for water resources management in the Marib area. The impacts of a suggested strategy can be re-assessed and evaluated continuously, using new data and taking into account certain measures for implementation. As the Water Resources Management model provides much more detail in its output than was used during this study, the impacts of a certain strategy can be evaluated in greater detail too. For instance, the Water Resources Management model can be helpful for evaluating the economic and financial feasibility of constructing a lined conveyance canal and of further developing the scheme, or for assessing the effects of charging a fee for the use of surface water.

1 INTRODUCTION

1.1 Background

In the Marib area in the eastern part of the Republic of Yemen a new dam was constructed in 1986 close to the location of the famous ancient Marib dam. The Wadi Adhanah feeds the reservoir behind the new dam. An irrigation system, to be fed by surface water from the reservoir, is under construction and partly completed. The location of the Marib area is indicated in figure 1.

The actual annual inflow into the Marib reservoir is much less than originally estimated during the design phase of the dam. The conveyance efficiency of the wadi between the dam and the diversion works is also much less than expected. These facts reduce the possibilities to irrigate the originally planned area with surface water.

In the Marib area, groundwater abstraction for irrigation has increased steadily since around 1970 and with a sharp increase in the beginning of the eighties. During the construction of the dam, surface water supply was not possible, so the government supplied free wells to the farmers who could no longer irrigate from surface water. Groundwater levels showed an annual decline of 0.7 to 2 m in large parts of the area in the period of August 1987 to March 1989.

Obviously, the water resources management issues originating from this situation are numerous and complex. Questions arise as how to develop the area, e.g. in such a way that maximum benefit is achieved within the objective of sustainability of the water resources and how these benefits can be distributed fairly over the population.

A systematic approach is needed in order to assess and define these issues in detail and to formulate the objectives and criteria for water resources management. An analysis of several options for water resources management, giving each of them a score according to the extent they meet these objectives will enable the pertinent decision makers to choose an appropriate water resources management strategy.

1.2 Water resources management strategy analysis of the Marib area

The General Department of Hydrogeology of the Yemeni Ministry of Oil and Mineral Resources has been co-operating since 1982 with TNO Institute of Applied Geoscience in the programme 'Water Resources Assessment Yemen Arab Republic' (WRAY).

In the second and third phase (WRAY-2 and WRAY-3) of this programme a water resources assessment study was carried out in the Marib area in the period from 1986 to 1989. Besides assessing the water resources of the area this study produced a brief definition of the most important water resources management issues.

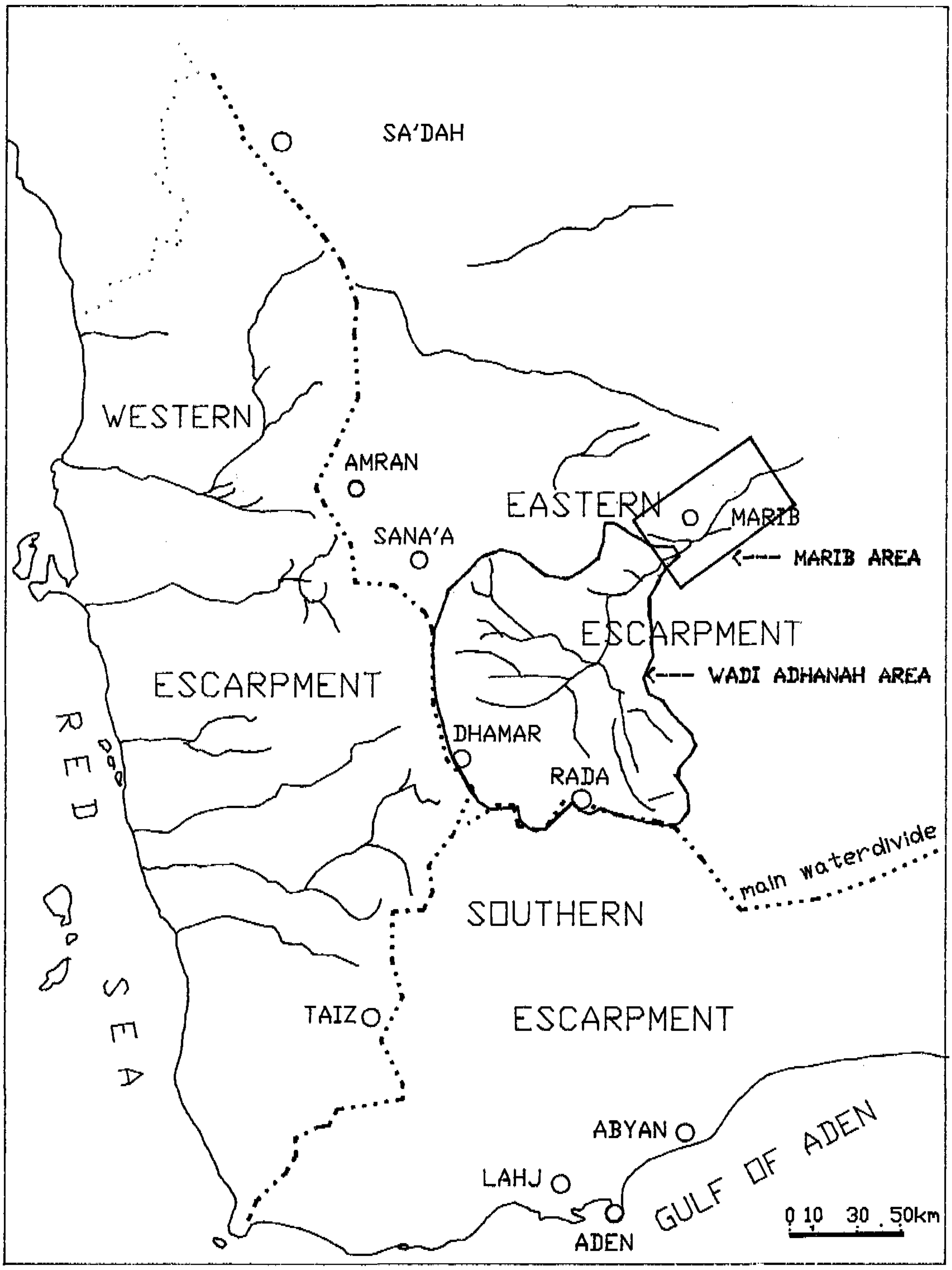

Figure 1. Location of the Marib area.

Within the fourth phase of the programme (WRAY-4) a water resources management study was included with the objectives to contribute to the development of an adequate water resources management policy for the Marib area and to make the Yemeni counterparts in the GDH more acquainted with water resources management.

The approach followed by the WRAY-4 project was to conduct a water resources management study for the Marib water resources system, leading to a set of water management strategies, which could be presented to the decision makers in the area. The study proceeded according to a methodology similar to the one tried out in the Wadi Surdud area (van der Gun and Wesseling, 1991).

The results of the Marib water resources management study are presented in this report. The reader is assumed to have access to previous WRAY reports on the Marib area and therefore the presentation of information about the area has been kept to a minimum.

This study is a water resources management study and as such was limited to formulating inputs for the planning of water resources development and management. It did not address aspects related to the measures which need to be taken to implement the suggested strategies.

1.3 Organization of the study

The study was performed by the General Department of Hydrogeology (GDH) of the Ministry of Oil and Mineral Resources, in close cooperation with the Eastern Regional Development Authority (ERADA) of the Ministry of Agriculture and Water Resources under whose aegis the Marib scheme resorts. The study took place under the supervision of a committee consisting of the management of GDH and ERADA and the World Bank experts to ERADA. For the execution of the study a study team was set up, comprising:

- one member of the Studies and Surveys Department of the GDH,
- one member of Hydrogeology Section of ERADA and
- the WRAY-4 expatriate team of TNO Institute of Applied Geoscience.

The study was integrated within the Studies and Surveys Department of the GDH; the other departments of the GDH and of ERADA supplied services and manpower for various activities such as field surveys (well inventory, socio-economic survey, wadi flow measurements and field check for remote sensing land use map) and data processing. The GDH groups involved were: The Monitoring Department, Geophysics Department, Information Centre and Documentation and Coordination Department. The sections of the ERADA organization involved were the Hydrogeology Section, Dam Operations Section, Agricultural Extension Section, Livestock Section, Dam Maintenance Section, Agro-economics Section and the Horticulture and Crops Section.

Separate studies were performed by: Euroconsult (irrigation study), IWACO (socio-economic survey) and GeoImage, France (remote sensing study). The integrated Water Resources Management model was developed by Delft Hydraulics.

The Yemeni members of the study team were fully involved during the whole study, including the conceptualization, development and operation of the integrated model and the writing of the final report through continuous and intensive coaching by the expatriate staff.

To ensure an intensive use of the Water Resources Management model by professionals from different disciplines from GDH and ERADA, training in the operation of the model was provided after the completion of this study. To ensure the continuation of water resources management activities in the Marib area ERADA established a Water Resources Management Team.

Appendix 1 contains the list of names of persons who participated in the development of the Water Resources Management model, data collection, data interpretation and analysis.

1.4 Acknowledgements

The ERADA provided valuable and substantial contributions during the different phases of the study, especially in the formulation of the objectives for the Marib water resources system, during the execution of the different field investigations and in the formulation of the water resources management strategies to be analysed. The ERADA allowed their professional staff to participate fully in the technical meetings requested by the study team which enabled the approach, scope and context of the study to be delineated realistically. Furthermore, one ERADA staff member was attached full time to the study team during the office activities in Sana'a. This valuable cooperation from ERADA is gratefully acknowledged.

The Ministry of Agriculture and Water Resources and the Ministry of Social Affairs provided four interviewers for the socio-economic survey. Their cooperation is very much appreciated.

Through the Ministry of Agriculture and Water Resources WRAY-4 was able to contract an agro-economist, Mr. Al-Hakimi, whose help and advice proved to be invaluable during and after the socio-economic survey.

The Technical Secretariat of the High Water Council provided comments on the socio-economic study and on this report. Their assistance is also very much appreciated.

Furthermore all members from the GDH and ERADA are thanked for their enthusiasm and perseverance during long hours collecting data in the field and processing data in the National Water Resources Information Centre.

2 OBJECTIVES AND APPROACH OF THE WATER RESOURCES MANAGEMENT STRATEGY ANALYSIS

2.1 Objectives

The overall objective of the water resources management study is to contribute to an adequate water resources management in the Republic of Yemen, and in particular in the Marib region.

The immediate objectives of the water resources management study can be formulated as follows:

(1) to develop and analyse promising strategies for water resources development, use and management for the Marib region;

(2) to develop a Yemeni capability in the formulation and analysis of strategies for regional water resources management;

(3) to develop an integrated Water Resources Management model that may help the Yemeni agencies to improve their understanding of the Marib water resources, and to transfer the model to the Yemeni agencies to enable the development of a water resources management strategy for the area to be continued.

2.2 Approach

A first experience in Yemen with a regional water resources management study was obtained during the pilot study water resources management of the Wadi Surdud (van der Gun and Wesseling, 1990). One of the objectives of that study was to develop methodologies and concepts that might enable comprehensive water resources management plans to be drawn up for other zones.

The systems approach used for the pilot study proved to be a good method of thinking to understand the complexity of the water resources conditions, processes and interactions in the Wadi Surdud area. As a result of the positive experience during the pilot study the systems approach was adopted for the Marib water resources management study. The methodology is briefly described in Chapter 3.

The study was conceptualized and specified during an Inception phase. The Inception phase was concluded with an internal Inception report which gave an overview of existing information, an inventory of water resources management issues, defined water resources management objectives and criteria and gave an outline and workplan for the further execution of the study. In the next phase of the study additional data were collected and a modelling framework was developed. During the final phase options and strategies were analysed. The results of these successive steps are presented in this report.

The modelling framework was structured as an integrated simulation model. A simulation model has the advantage above other modelling approaches that it generates outputs for several optional strategies; this is more attractive to the decision makers than for instance an optimalization approach with a singular option. It is also a more instructive model for resource management because of the user-defined set of values for the model's decision variables for a given strategy.

The model developed for the Marib water resources system simulates water availability, water demands, water flow and water allocation and evaluates the cost-benefit, the sustainability of the developments and the areal distribution of the benefits accruing from water.

2.3 Envisaged achievements

In relation to the objectives of the study the following achievements were planned and realized:

(1) this report which explores options for water resources management in the Marib area;

(2) the enhancement of Yemeni expertise from the GDH and ERADA: specifically by giving the ability to initiate a water resources management study in other zones and by raising the awareness of a larger number of Yemeni professionals of the aspects of water resources management;

(3) an integrated model for the Marib water resources system which can be operated by GDH and ERADA professionals.

3 METHODOLOGY AND IMPLEMENTATION

3.1 Introduction and definitions

As stated above, experience with a water resources management study was gained earlier in the Republic of Yemen, in the Wadi Surdud area (van der Gun and Wesseling, 1991). The description of the methodology given in this chapter is in agreement with the Wadi Surdud report.

The development and sustained use of water resources requires water resources management. Part of the management process is resources development planning, which includes the generation and evaluation of strategies intended to reach the management goals in future situations.

The objectives of water resources management are set by the decision makers. These objectives might reflect a government policy to reach certain goals for society, such as self-sufficiency in food production or adequate and sustained water supply for the population. The degree of compliance with the objectives should be assessable and therefore criteria have to be defined to evaluate the likely contribution of strategies to achieving the objectives, e.g. the level of self-sufficiency or the maximum benefit/cost ratio.

Planning requires decision making, such as choosing the best alternative for resources development. To assist the decision making process, a systematic analysis is carried out, in which alternative strategies are generated and evaluated.

Strategies consist of a combination of options to change the water resources system's performance. They can be implemented by measures which may be physical and managerial (physical structures, operation rules), financial incentives (taxes, subsidies), controlling regulations (licences and restrictions) and institutional measures (responsibilities of agencies, user organizations).

In studies for several countries Delft Hydraulics has shown that Systems Analysis is an efficient approach to the development and analysis of water resources management strategies. Their systems analysis Framework for Analysis will be largely followed here to define a methodology for the Water Resources Management Study Marib. The text of the sections 3.1 and 3.2 draws heavily on a document by Delft Hydraulics (1989).

3.2 A systems approach to water resources management planning

A water resources system can be considered as an input-output system, in which resources are used (inputs) and goods and services are produced (outputs), for example water for irrigation or for a pleasant environment.

Figure 2 shows this in a diagram. 'Natural' refers to the system without human interference; 'infrastructural' to human interference by dams, wells, canals, pipelines and other physical works; and 'institutional' to institutions, laws and regulations required to operate and manage the system.

Water resources management may modify the contents of any of the 'boxes' depicted in figure 2, except the one representing 'scenario conditions'. Hence, the adopted water resources management objectives may be pursued by influencing 'manageable' inputs, changing the characteristics of the system, or modifying the demands or requirements regarding the outputs. These quantities may be called decision variables.

The 'scenario conditions' are assumed to represent a category of inputs that cannot be influenced by water resources management. They are considered as fixed parameters or boundary conditions.

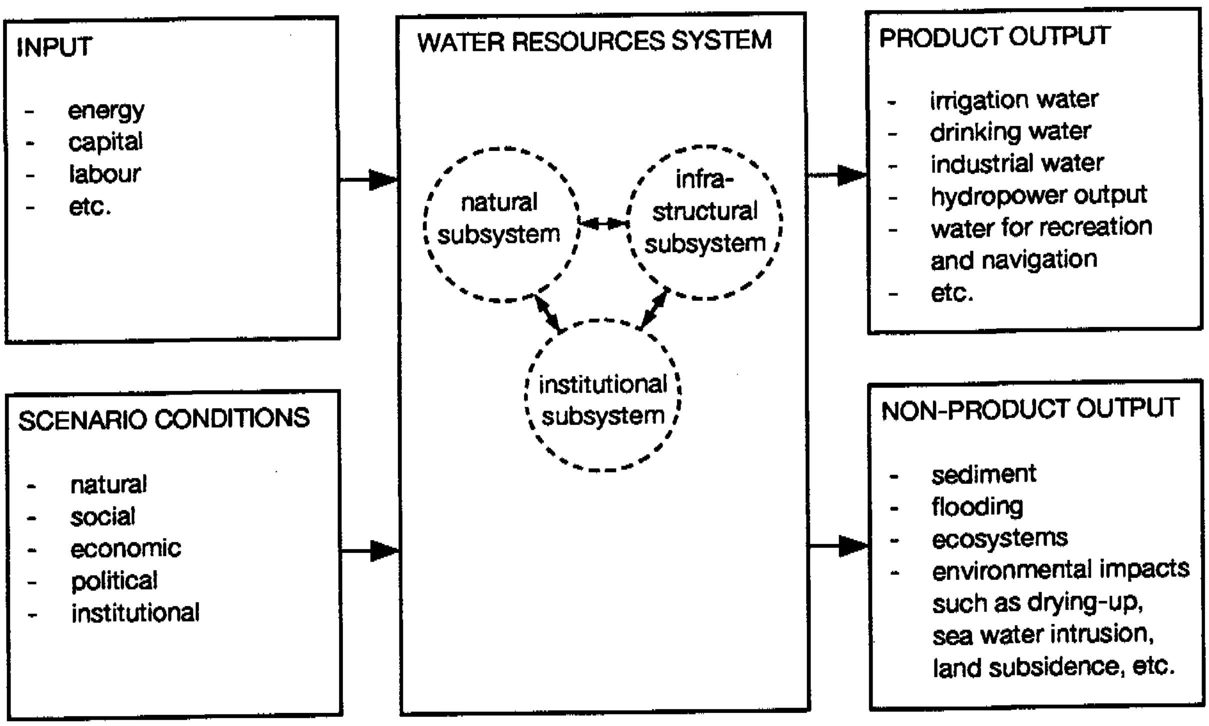

Figure 2. A water resources system as an input-output system (modified after Delft Hydraulics, 1989).

The increasing complexity of water resources systems and the relations and conflicts between the different categories of water use, makes planning a difficult task with many dimensions. The systems to be managed also grow in size due to the increasing interference over larger distances than used to be the case. The management strategies are varied and complex and a systematic procedure is required for the analysis of the system. This analysis has to be quantitative whenever possible.

Systems Analysis can be described as a systematic process of generating, analysing and evaluating alternative strategies to reach the chosen management objectives. It is more a way of thinking than a formal mathematical procedure. Systems Analysis is particularly relevant to Resources Development Planning in view of the growing complexity of management processes today, which include a wide range of aspects (economic, technological, environmental, institutional, social etc.) and of possible development strategies.

The Framework for Analysis structures this process. It comprises a set of consistent steps for the analysis. A set of coherent models for the quantitative analysis of measures and strategies is also used in the analysis. This set of models and related databases, the Computational Framework, varies according to the application.

The Framework for Analysis has three main phases :

(1) Inception phase
(2) Data Compilation phase
(3) System Analysis phase

Figure 3 presents some details on each of these phases.

In Systems Analysis for resources management planning it is essential to:

(a) understand the goals of the decision makers and to translate these goals into measurable objectives;
(b) develop the tools to describe the system;
(c) generate and evaluate options and strategies;
(d) translate and present the results of the analysis to the decisionmakers.

Hence, the whole analysis has to be done in close co-operation with the decision makers, to include a maximum of relevant information, to improve acceptance of the results and to promote an impact of the study on the decision making process. The interaction with the decision maker is emphasized in figure 3.

3.3 Inception phase

3.3.1 Introduction

The Inception phase of the Marib study started in October 1990 with an one week introductory course on the methodology of water resources systems analysis, in which the study team and officials from the GDH and ERADA participated. An inventory was made of problems related to water resources management in the Marib area, and of possible options to solve these during a meeting of decision makers in Marib in December 1990. The objectives for water resources management were formulated during the same meeting, and so were the criteria to evaluate the outcome of the analysis with respect to the defined objectives.

During a workshop in the period February-March 1991 in The Netherlands 4 Yemeni professionals, 2 from the ERADA and 2 from the GDH, were trained. The information available was thoroughly reviewed. Furthermore the scope of the analysis, the analysis conditions and constraints were defined. A workplan was drafted for the next phases of the study, including additional data collection and the development of the Water Resources Management model. The Inception phase was concluded with an internal Inception report.

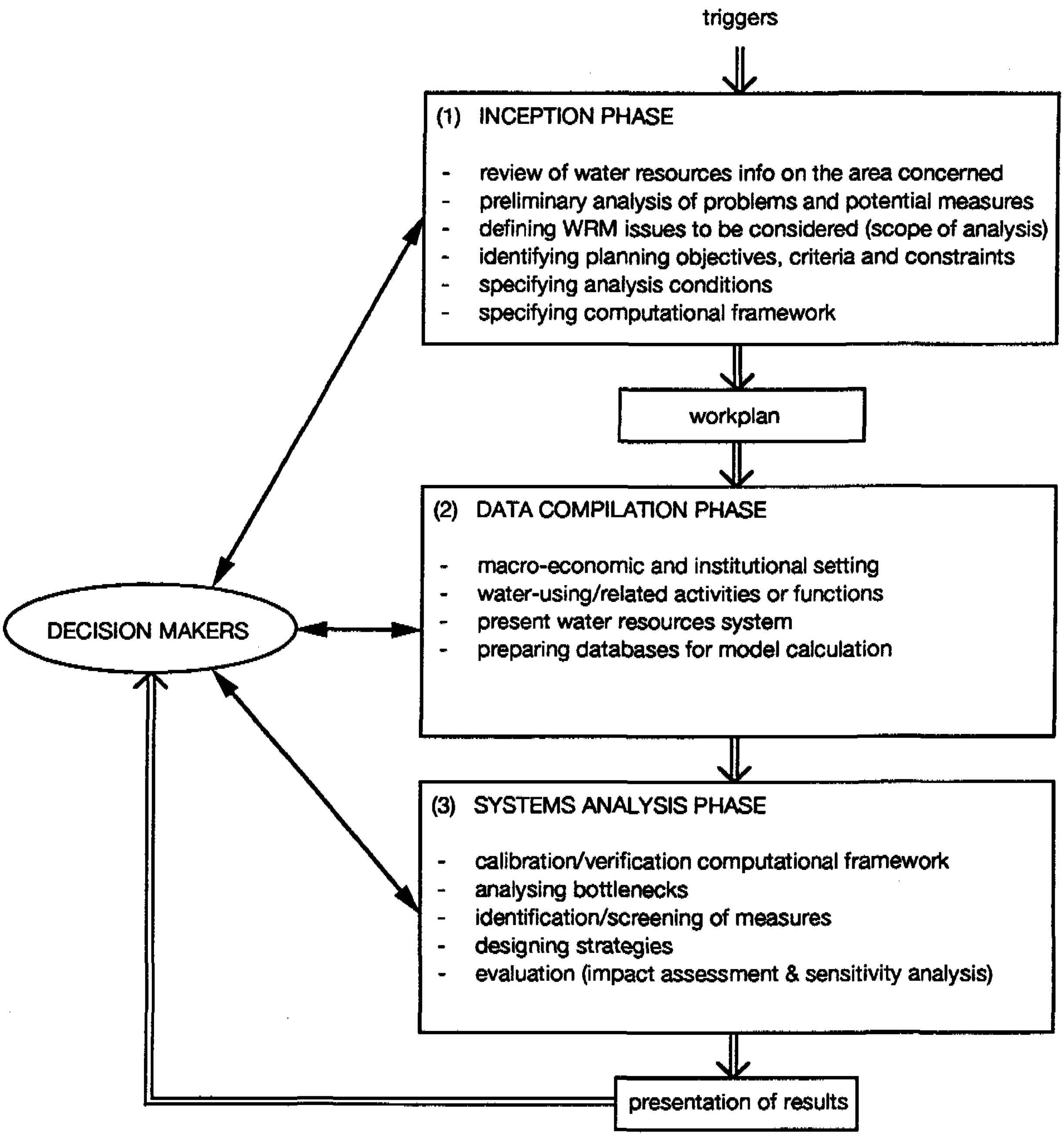

Figure 3. Framework for Analysis (modified after Delft Hydraulics, 1989).

3.3.2 Review of water resources information

For detailed information on different aspects of the water resources of the Marib area, see the reports on water resources assessment of the Marib and Wadi Adhanah area by the WRAY-project (1990). Relevant information collected during WRAY-3 and information collected during the Data Compilation phase have been compiled in chapter 4 of the present report.

3.3.3 Scope of analysis

The study described in this report is a water resources management study. This means that the focus is on the water resources and how to use and manage them adequately. Therefore, although the water sector is intimately connected with other sectors -such as the agricultural and the economic sectors - management options in these latter fields are outside the scope of the study.

The study considered all relevant water-related activities and phenomena in the project area. The degree of attention paid to a particular aspect depends on that aspect's importance for the overall water resources management related development of the area. The ideas expressed by officials of the ERADA during several meetings with the study team helped to reduce subjectivity when deciding how much attention should be paid to a particular aspect of water resources management.

The main focus of the study is on water quantity aspects. The impact of sedimentation of the reservoir was also studied. The potential increase in groundwater salinization in certain areas was not taken into account. This aspect requires more information than is currently available, plus the integration of an additional component in the computational framework. This component was not yet available during the study period, but can be included at a later date.

The degree of detail of the analysis was reduced by aggregating water users into irrigation units that have similar water resources at their disposal and have similar water use conditions and practices.

The study deals with the development, analysis and evaluation of alternative water resources management strategies. The measures and costs required to implement them should be elaborated during a follow-up study.

3.3.4 Water resources management issues

During a special meeting in December 1990 of the study team and management of the ERADA the following problems and possible options were identified:

I **Problems of demand versus supply**

a. The Marib Scheme design was based on an assumed average long-term annual inflow of 148 million m^3 (Electrowatt, 1989). During the period of January 1986 to April 1989 the average annual inflow appeared to be 104 million m^3 (Uil and Dufour, 1990). The total baseline surface water demand for the proposed cropping pattern for the command area of about 6890 ha is 164 million m^3. After improving the field efficiencies of irrigation the total gross water requirement would be 122 million m^3, of which 70 million m^3 should be supplied from surface water (World Bank, 1991). Given the high infiltration rates through the wadi beds and diversion reservoirs it is unlikely that this amount will be available. From these figures it is clear that the surface water demand considerably exceeds possible supply.

b. Preliminary calculations suggest that even if the Marib dam were used only for the purpose of flood control (reducing evaporation losses as much as possible) and maximum recharge of the aquifer, if groundwater continues to be abstracted at the rate of 1988 the annual depletion of groundwater storage will be about 80 million m^3 (Uil and Dufour, 1990). This implies that the present groundwater demand considerably exceeds the recharge of the aquifer.

Options:

a. Adjust irrigation command area relative to smaller inflow in Marib reservoir.
b. Restrict groundwater abstraction.

II Problems related to the efficient and/or economic use of water and sustainability of water resources

a. Groundwater quality. Groundwater with electrical conductivities over 2000 microS/cm occurs on the borders of the cultivated area; this poses limitations for use for drinking and irrigation.
b. Depth of the groundwater level. If groundwater levels drop below the alluvial sediments of the upper aquifer, yields will decrease and abstraction costs will increase.
c. Annual average evaporation losses from the Marib reservoir constituted almost 30% of the average annual inflow during the period of 1986 to 1988.
d. A large amount (estimated at between 25 to 50%) of released lake water infiltrates to the groundwater from the permeable wadi bed upstream of diversion A and the diversion reservoirs. This might be considered acceptable if sufficient surface water remains for irrigation, but could be disastrous in years of little inflow.
e. An estimated amount of 60 million m^3 of groundwater flows out of the area per year.
f. Released lake water is diverted by earthen bunds upstream of diversion A.
g. Reservoir water is lost through seepage and exfiltration underneath the dam.
h. Certain terms of the water balance for the area are unreliable.
i. Field efficiencies of irrigation are low.
j. Some current water use may be giving low economic returns.
k. There is a lack of data on areas under different crops and on crop yields and cost/benefit ratios of crops.
l. Time series of hydrological and meteorological data are short and some show gaps; more detailed information might occasionally be desirable. No direct data is available on evaporation from the reservoir.
m. Fertile soils and irrigation structures are threatened by migrating sand dunes.

Options:

a. Stipulate operation rules for groundwater abstraction, e.g. restrict groundwater abstraction.
b. Stipulate operation rules for groundwater recharge.
c. Operate the dam in such a way that storage is minimized in time and volume, irrigate during different season.
d. Construct an earthen or lined canal from the dam up to diversion A. Control recharge in relation to amount of water available in the reservoir.
e. Suggest ways the pattern of groundwater abstraction could be adjusted.
f. Construct two diversion canals to the area upstream of diversion A.
g. Monitor piezometric levels in and near the dam in order to improve estimates of losses; concentrate and monitor exfiltration water in canal parallel to the dam.
h. Measure unknown terms.
i. Improve field efficiencies.
j. Apply different cropping pattern.
k. Set up a system to collect agricultural data.
l. Install evaporation pan near or in the lake, continue monitoring, apply time series analysis, extend network.
m. Stabilize the sand dunes.

III Problems related to socio-economic aspects

a. Efficient distribution of surface water might be hampered by traditional water rights in the area upstream of diversion A, and possibly also in still uncompleted sectors of the irrigation scheme.
b. A fair distribution of water to the farmers should be attained, especially in periods of water shortage.
c. Land still needs to be acquired for completion of the irrigation canals.
d. Acceptance of government institutions and regulations by the people in the Marib area is low; this is reflected in the resistance of tribes to the construction of secondary canals and their hesitation to become dependent on surface water irrigation.
e. Farmers are unfamiliar with modern irrigation and agricultural techniques.
f. Equitable distribution of benefits to different social groups and to male and female water users should be attained.
g. There is a lack of data on sociological issues in the area.

Options:

a. Define a distribution in this area that is similar to the present distribution but optimizes water use efficiency.
b. Distribute water in proportion to farm size.
c. Acquire finances from government.
d. Define an approach to inform and/or influence inhabitants of the area.
e. Set up demonstration farm.
f. Define an algorithm to calculate benefits to different social groups and male and female water users.
g. Collect sociological data as far as relevant for water resources management.

IV **Problems related to the Marib reservoir**

a. Sedimentation in the Marib lake.
b. Safety of the dam.

Options:
a. Monitor amount of sedimentation, flush sediments out of the lake.
b. Add weight to the foot of the dam (already being done).

Many of the problems are interrelated and can be grouped according to the following water resources management issues:

(a) **Availability of surface water for irrigation in relation to planned capacity of surface water irrigation system, taking into account the actual reduced inflow in the dam reservoir, the high groundwater recharge rates through the wadi bed and the 'spate' irrigation upstream of diversion A.**
(b) Maintaining good relations with farmers living near the constructed surface water irrigation system (secondary canals) who will become resentful if surface water does not reach their fields.
(c) **Timing of allocation of the reservoir water for surface water irrigation and aquifer recharge, in order to improve the efficiency of water use, considering that priority for dry year surface water irrigation is detrimental to groundwater recharge.**
(d) **Groundwater irrigation via wells (within and outside the irrigation command area) versus surface water irrigation in relation to maximizing the irrigated area in a sustainable development.**
(e) **Anticipating negative consequences of excessive groundwater abstraction, such as excessive groundwater level declines and deterioration of water quality.**
(f) Anticipating water quality problems, especially in relation to developing groundwater irrigation units.
(g) Promoting awareness among farmers of water resources management issues and measures and strengthening the authority of ERADA to intervene in these matters.
(h) **Dam safety.**
(i) Environmental protection oriented to the protection of the catchment area and sand dune stabilization in the plain.
(j) **Traditional water rights in the area conflicting with promising options for water resources management.**
(k) Establishment of monitoring networks for meteorology, hydrogeology and irrigation practices.
(l) **Sedimentation within dam reservoir.**

Given the conditions in the Marib area and the scope of analysis described in par. 3.3.3, the water resources management issues under a, c, d, e, j, h and l (bold print) were taken up in the study. The issues under b and g were addressed during a socio-economic survey (IWACO, 1991), see par. 3.4.2.

3.3.5 Water resources management objectives and criteria

The merits of different water resources management strategies can be evaluated and compared if water resources management objectives have been specified. Once these objectives have been stated, the impacts of each of the strategies concerned may be compared using a set of well-defined criteria related to the objectives.

The objectives were adopted in close consultation with officials of the ERADA. Table 3.1 presents these objectives and related criteria.

For ERADA an important objective was to maximize the economic benefits from the irrigated agriculture and as such the criterion of the net benefit of the irrigated agriculture, expressed in YR, was adopted.

The construction of the surface water irrigation system raised the expectations of the surrounding population and was achieved at considerable cost. ERADA identified the maximizing of the area irrigated by surface water via the constructed system as an other important objective. The criterion for this objective is therefore the size of the area (ha) irrigated by surface water.

Table 3.1 Water resources management objectives and criteria adopted for the Marib water resources system.

OBJECTIVES	CRITERIA
1. Maximize economic benefits	* net discounted economic benefit of irrigated agriculture over the period 1991 - 2016 (in YR)
2. Maximize area irrigated by surface water	* average area irrigated by surface water over the period 1991-2016 (ha)
3. Sustainability of groundwater use	* area of upper aquifer lost after 100 years (ha)
4. Equity	* coefficient of variation of the net discounted financial benefits per hectare over the period 1991-2016

Groundwater and surface water irrigation are parallel activities in the area. Because of the interrelation of the groundwater and surface water systems, any option trying to maximize the use of the surface water source, parallel with a certain groundwater abstraction rate, should be checked for its impact on the sustainability of the groundwater resource.

The criterion adopted for the sustainability objective indicates how much of the upper aquifer has dried out after 100 years. The hydrogeology of the Marib area is such that if parts of the aquifer in the south-west of the area fall dry, groundwater flow to the rest of the aquifer is hardly possible anymore. Sustainability in the true sense of the word is achieved only if groundwater levels oscillate around a constant mean. The criterion adopted therefore indicates the extent of damage to the upper aquifer rather than its sustainability.

The opinion of ERADA was further that the benefits generated by the irrigation system should be distributed over the cultivated area as equally

as possible.
The criterion adopted to evaluate the equity objective is the coefficient of variation of the net financial benefits of the irrigation units per hectare. It was decided to use financial prices for this criterion as these reflect the situation from the farmers' point of view (see par. 4.3.3). The coefficient of variation C_v is the standard deviation divided by the mean. This criterion excludes the influence of different means.

3.3.6 Constraints

The range of alternative options for water resources management is limited by political, economic, sociological, financial or technical constraints. During the formulation of the strategies efforts were made to give priority to strategies that in principle seem implementable and that address water resources management issues relevant for the area. Dam safety is a constraint to any option under which the maximum lake level is reached and the spillway is used. Such an option is, however, unlikely to be selected from the point of view of efficient reservoir operation. Socio-economic constraints were investigated during a socio-economic survey (see par. 4.3.4).

3.3.7 Analysis conditions

Areal boundaries

The area studied was the Marib plain, including the Marib reservoir, as indicated in figure 1. This area is 800 km^2.

Scenario conditions

Agriculture plays a dominant role in the development and use of water resources in the Marib area. Although successful exploration and exploitation of oil and gas is the most important activity in the vicinity of Marib in terms of macro-economics, it takes place outside the area, and does not use significant quantities of water from the Marib water resources. Domestic water use involves no more than a few per cent of the total quantity of water used.

Different scenario assumptions can be made about the increase in time of potential yield of crops (by improvement of agricultural production) or about the temporal variation of economic parameters related to irrigated agriculture. Assumptions about the increase in the yield were specified during the Data Compilation phase and have been included in the agricultural model (see par. 4.3.3). For the economic parameters zero growth was assumed. Assumptions regarding the timepath of an possible completion of the irrigation scheme and regarding the year in which certain goals may be reached are listed in par. 4.2.3.

According to information from the Population Studies and Research Centre, Sana'a, the population density was 49 persons per km^2 by 1986. The number of inhabitants was 123 000 in 1986, but continues to grow rapidly. A population growth of 3% is assumed.

Time horizon

Two time horizons were used in the analysis:

- a medium-term horizon of 25 years, to evaluate the results of the calculations under different water resources management options and strategies relative to all objectives, except the sustainability objectives.
- a long-term horizon of 100 years, to determine the sustainability of the groundwater resources under different options and strategies.

Both time horizons start at the same initial year: 1991. This year was adopted as the base year for the analysis, which implies that the data on prices, present cropping patterns, etc. are valid for this year.

Rate of discount

To enable economic data over time to be compared with the present situation, these data have to be discounted. The discount rate includes the intrinsic value of money as a production factor and also the effect of inflation. Inflation is difficult to estimate for a period as long as 25 years ahead. However, the effect of inflation can be eliminated if present values of the successive annual net benefits are being considered. The real rate of discount (rate of discount without inflation) was assumed to be 10% annually for the purpose of this analysis.

During the Systems Analysis phase attention was paid to determining the sensitivity of the computational model for this parameter.

3.4 Data collection and compilation phase

3.4.1 Irrigation

During a six-week mission (May-June 1991) an irrigation expert from Euroconsult, The Netherlands, performed an irrigation study and field survey in the Marib area. Data were collected on irrigation practices, irrigation efficiencies, cropping patterns, cropping calenders and crop yields. The irrigation specialist was further asked to contribute to the formulation of options and targets regarding alternative cropping patterns and calenders, improved irrigation efficiencies and crop yields and different surface water allocation rules. Five members of ERADA participated during the field survey. The findings of the study were documented in a mission report (Neefjes, 1991). The most relevant data have been compiled in chapter 4 of the present report.

3.4.2 Socio-economics

In May 1991 a socio-economic study was carried out in the Marib area to:

- collect information on socio-economic issues related to the objective of a fair distribution of water (equity principle);
- identify possible constraints in relation to identified alternative water resources management strategies;

- design quantitative criteria to measure the equity objective of the strategy analysis.

The study was done by IWACO, the Netherlands. The results of the four-weeks mission, including eight days fieldwork, are presented in a report (IWACO, 1991). During the field survey 8 interviewers from the Ministry of Agriculture and Water Resources, the Ministry of Social Affairs, ERADA and the GDH participated as well as an agro-economist of the Ministry of Agriculture and Water Resources.

During the survey 252 male and female respondents were interviewed. In addition, 'in-depth' interviews were done with some farmers, and information was collected from several resource persons and literature sources. To investigate the importance of the traditional water allocation rules a meeting was held with leaders of several tribes in the area.

Various constraints for further agricultural development were identified: they are summarized in section 4.3.4. Financial and economic costs and revenues of the main crops in the area were determined, and are given in section 4.3.3. Besides these outputs an important conclusion was that for successful implementation of any measure a strategy for communicating with the farmers should be developed.

3.4.3 Land use

A land use map of the summer 1991 cropping season was prepared for the Marib area from SPOT satellite images. For this purpose two multispectral images of 2 May and 18 June 1991 were acquired and two panchromatic images from earlier dates.

The panchromatic images were used to develop a digital elevation model (DEM) for geometrical rectification. The multispectral images were used to classify different land uses. A field check was carried out in June 1991 by three teams of GDH and ERADA. The output of the remote sensing study comprised 4 land use maps at a scale of 1:50 000 and a technical report describing the method of analysis and the areas covered by the different crops and other land uses. The order was executed by GEOIMAGE, France. The results are discussed in section 4.3.1 and appendix 7.

3.4.4 Well inventory

In May and June 1991 a well inventory was performed by four teams of the GDH and ERADA in the Marib area with the purpose of updating the number of existing abstraction wells and to arrive at a good estimate of the total quantity of water abstracted. The outcomes of the survey are presented in section 4.2.1 and appendix 4.

3.4.5 Wadi flow measurements

To estimate the distribution of the wadi losses through the wadi bed between the dam and the first diversion structure the dam was opened for two days in June 1991. The wadi discharge was measured at six crosssections by three teams of the GDH and ERADA. The results are described in appendix 3.

3.4.6 Data processing

To prepare the data sets for the integrated model comprehensive data processing took place at the GDH's Information Centre during and after the additional data collection. A great number of GDH professional participated in the data processing.

3.4.7 Computational framework

During the Data Compilation phase the computational framework was developed, on the basis of the concepts developed by the study team. It consists of three main modules; an agro-hydrological model, a groundwater model and an economic model. These models are connected by a shell. Data can be entered and output can be analysed using the shell's menu's. The shell enables the user to evaluate different water resources management options or strategies by entering different values for the menu items.

The agro-hydrological model and the economic model were tailor-made by Delft Hydraulics, using parts of the Wadi Surdud model. The study team tested the various versions of the model, and supervised the implementation of improvements. The MODFLOW model (McDonald and Harbaugh, 1991) was built in to simulate the groundwater system. The study team extended an existing Modflow-model of the area, prepared additional data sets and calibrated the new model. The graphical programme Surfer (Anonymous, 19..) was used to prepare contour plots of groundwater levels and drawdowns.

The information contained in the data sets of the Water Resources Management model is discussed in chapter 4. In chapter 5 the model is described extensively.

3.5 Systems Analysis phase

In this phase various water resources management options were selected for analysis in cooperation with the ERADA management. They differed in the degree of further development of the irrigation scheme, the groundwater abstraction capacities, the cropping patterns, etc.

These options were evaluated separately, according to the criteria set for the defined objectives. Evaluation took place for a simulation period of 25 years for the economic objective, the equity objective and the objective to maximize the surface water irrigated area. To evaluate the sustainability of the groundwater resources the Water Resources Management model was run for 100 years.

Promising options were grouped into six strategies, which were evaluated according to the same procedure.

The System Analysis and its results are described in chapter 6. In chapter 7 the main conclusions are given.

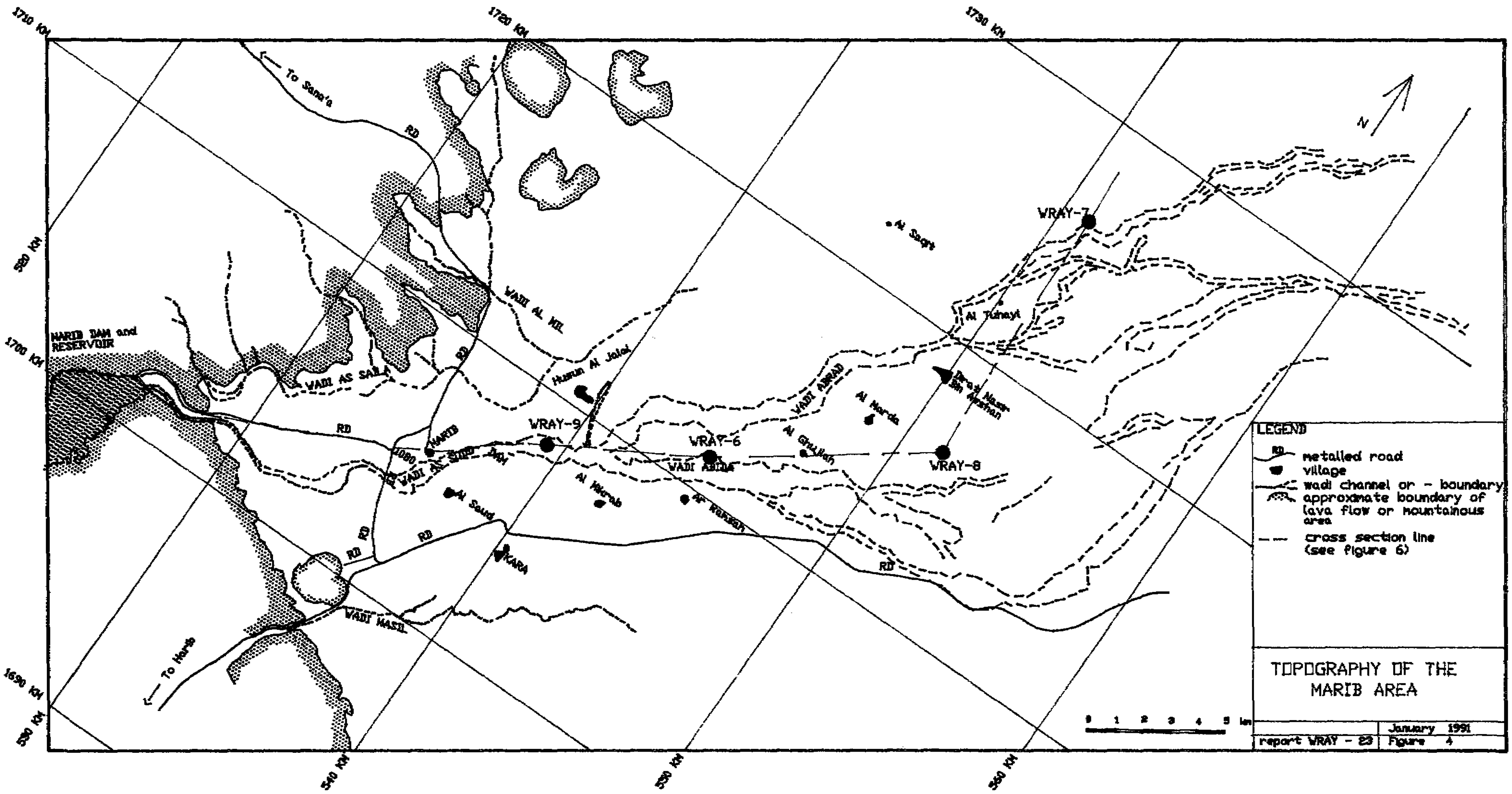

Figure 4. Topography of the Marib area

4 COMPILATION OF INFORMATION ON WATER RESOURCES AND WATER USE

4.1 Introduction

The Marib area (figures 1 and 4) is located at the outlet of the wadi Adhanah catchment area, downstream of the recently constructed Marib dam. In this report the Marib area is assumed to extend from the dam to some 34 km further northeast - where the Ramlat As Sabatayn desert begins - encompassing approximately 1000 km^2.

For detailed information on the area's water resources, see the water resources assessment reports of the WRAY-3 project (Uil and Dufour, 1990; Kool et al., 1990; Uil and Vasak, 1990; Heynert and Uil, 1990; Verbeek, 1990; Gamal and Atrous, 1990; Nio, 1990; Verbeek and Te Stroet, 1990). Data on water use and related agriculture can be found in reports of Electrowatt (1978, 1989) and the World Bank (1988).

This chapter presents in brief the main features of water resources, water use and related agricultural activity in the Marib area, based upon the above-mentioned sources and on various surveys carried out by the WRAY-4 project (see chapter 3). Selection and format of the presented information largely follows the data requirements of the Water Resources Management model (discussed in the next chapter). In some cases, the lack of data made it necessary to estimate values of variables or parameters needed in the model. Some additional information of a more general character is given to make it easier to understand the water resources management analysis reported in chapter 6.

4.2 The water resources system

The water resources system in the Marib area comprises the lake behind the Marib dam, the wadi courses and the interconnected groundwater system which is recharged by the wadi flows and by infiltrating and percolating irrigation water. It also includes the irrigated land, the domestic, public and industrial water users, and the physical infrastructure for controlling and using the water resources (dam, canals, wells, etc.). Figure 5 shows schematically how the main water resource and water use elements are interrelated.

The groundwater system is described first. Next, the meteorological setting, and the surface water system, including the irrigation scheme, will be dealt with. Finally, the agricultural system will be described.

4.2.1 The groundwater system

Aquifer system

The groundwater reservoir is part of the extensive Marib-Al Jawf basin that can be considered on a regional scale as one hydrogeological unit. The general lay-out of the aquifer and the groundwater flow direction are shown in the hydrogeological cross-section presented in figure 6. The crosssection runs approximately through the centre of the project area from southwest to northeast.

Two aquifers separated by the impermeable Azal Formation can be distinguished in the Marib area.

The upper aquifer consists of Quaternary alluvial sediments and semi-consolidated sandstones of the Tertiary/Cretaceous 'Unnamed Unit'. The total thickness of the alluvial ranges from 50 to 70 m; its water-bearing thickness varies from a few tens of metres to a maximum of about 50 m (in the southwestern part). The upper aquifer overlies shales of the Azal Formation which is considered as an almost impermeable aquitard. The Azal

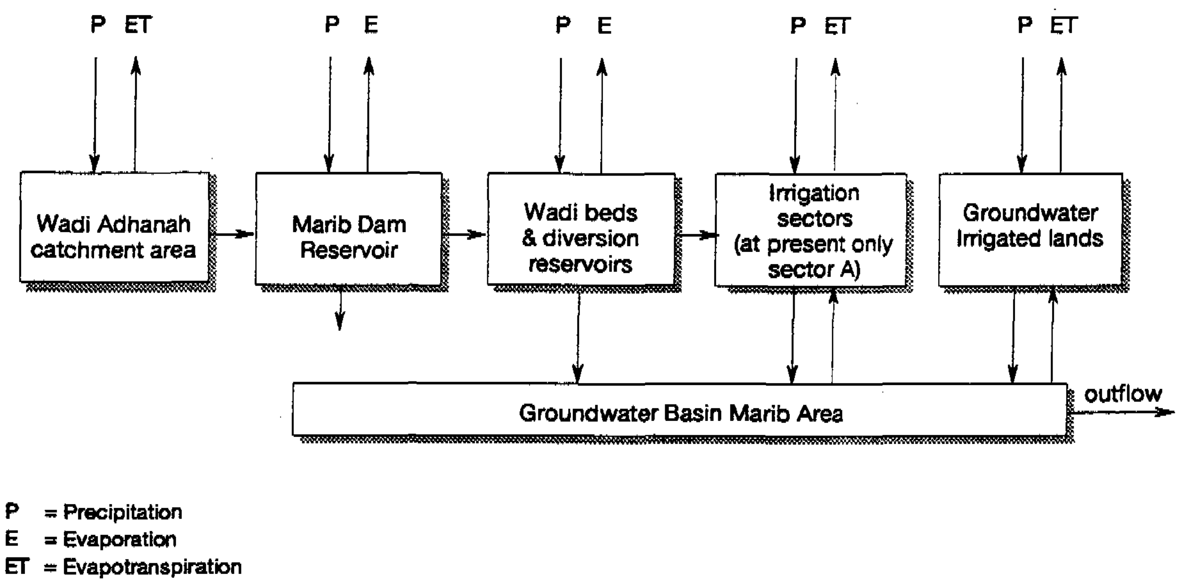

Figure 5. A systems analysis picture of the present water resources system of the Marib area.

Formation dips to the northeast and forms an important barrier to the northeasterly flow of deep groundwater.

The lower aquifer contains sandstone layers of the Safer and Alif Formations dipping northeastwards under the Azal shales. However, these sandstone layers alternate with shales and evaporites, which results in a complex lower aquifer. The Azal Formation is absent from the southwestern part of the area. Since the lower aquifer and the upper aquifer thus unite to form one aquifer there, recharge of the lower aquifer may occur in that area.

The lower aquifer is underlain by the limestones of the Amran Group. These limestones outcrop in the southwest, forming the southwestern boundary of the whole Marib aquifer system.

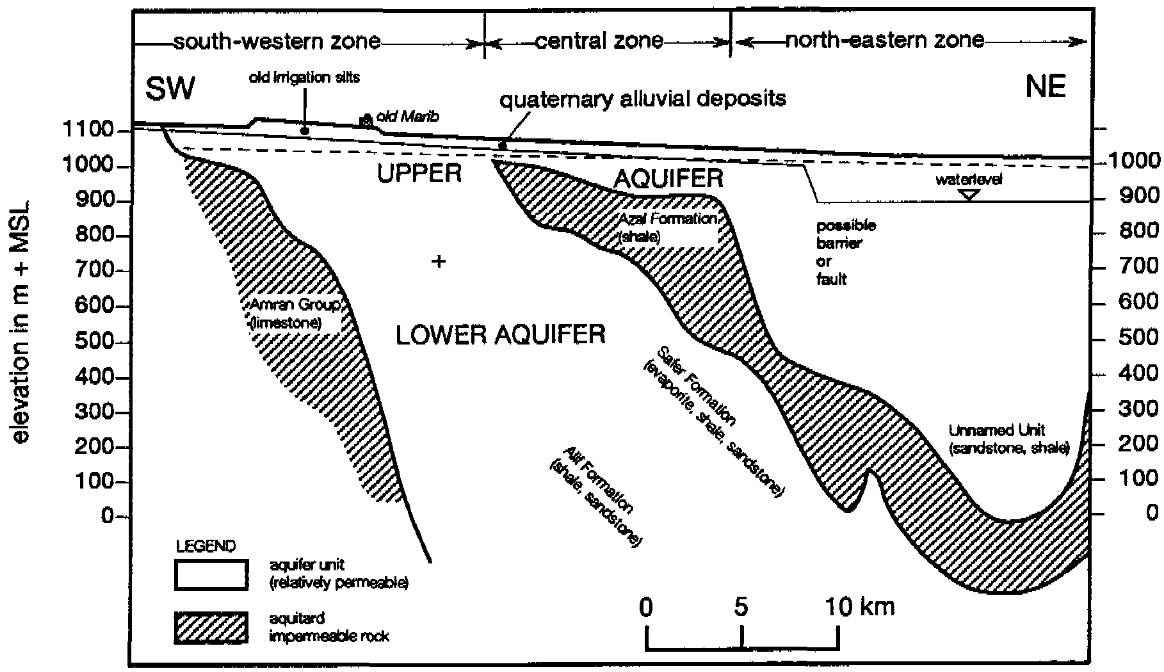

Figure 6A. **Hydrogeological cross-section through the modelled area (see figure 4 for location of profile).**

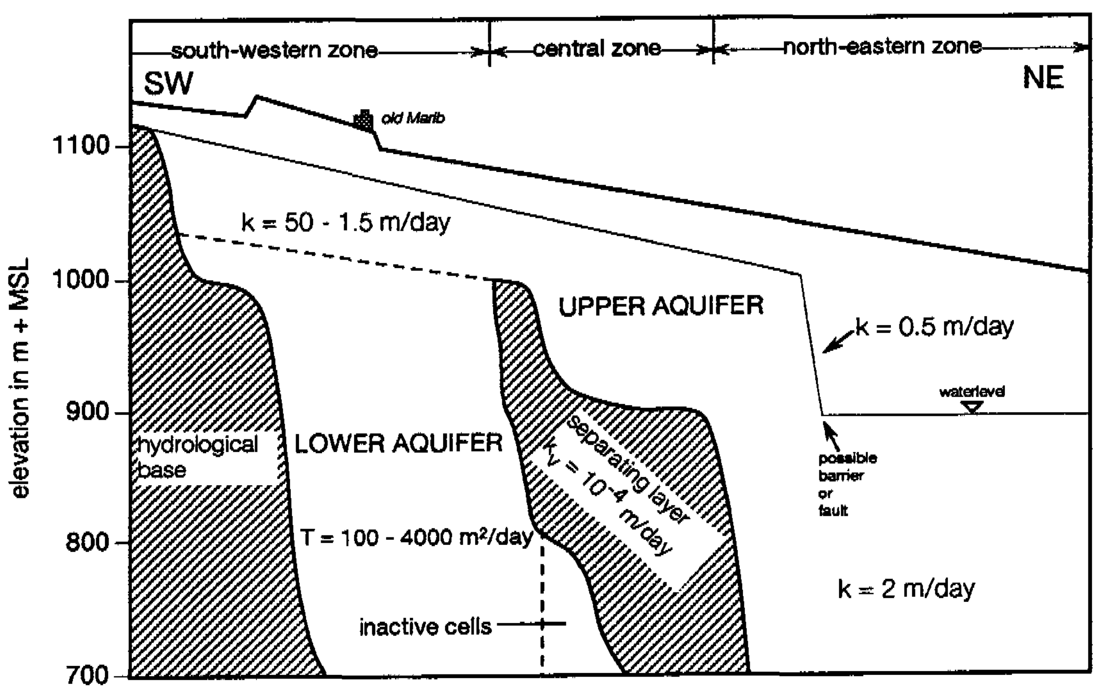

Figure 6B. **Values for the hydrogeological parameters as entered in the model.**

Recharge, discharge and groundwater levels

Recharge of the aquifer is mainly by percolation of surface water through the beds of the wadi system and by downward percolation of irrigation water. Natural discharge does not occur in the area, as groundwater flows northeast to areas outside the Marib area. Artificial discharge, however, occurs via a large number of wells -most of them pumped- scattered over the area.

These groundwater abstractions are steadily increasing. During a well inventory carried out in 1977/1978 (Electrowatt, 1978) approximately 500 wells were counted -400 of them pumped- at an estimated total abstraction rate of 29 Mm^3/year. WRAY-3's well inventory (Uil and Vasak, 1990) resulted in an estimate of 1513 wells with a total abstraction rate of 136 Mm^3/year. A new well inventory in 1991 (see appendix 4) revealed that the total abstraction has since increased to approximately 174 Mm^3/year. In total, 1869 wells were visited; 193 wells were not in use and the average yield of the 1676 used wells was 11 l/s. It appeared that during the winter season the farmers use their pumps for longer than during the rest of the year.

Hence, groundwater abstraction increased between the years 1987 and 1991 by approximately 10 Mm^3/year; the number of wells increased by approximately 90 wells per year. This increase took place all over the Marib area, but is most pronounced in the Al-Shabwan zone, in the zone at the end of the Southern Canal (Al-Tuhyal), around Al-Hunish and Alhany, around Aljithwah, around Al-Alerada and in the zone around the road to the Marib Dam.

As a result of the large and still increasing groundwater abstraction, groundwater levels are falling steadily in the Marib area. Figure 12 shows the position of the groundwater table in 1991.

Groundwater quality

Within a few kilometres from the wadi system, groundwater is almost everywhere in the Marib area relatively fresh (EC_{25}< 1000 microS/cm). There are local anomalies in the pattern (pockets of brackish water), especially at the edges of the fresh groundwater body -which corresponds to the main recharge zone. Further away from the wadi channels, groundwater tends to become brackish (Uil and Dufour, 1990).

4.2.2 The surface water system

The meteorological and hydrological conditions are briefly outlined in subsequent sections on precipitation, evaporation and evapotranspiration and lake inflow, to clarify the meteorological and hydrological boundary conditions adopted in the Water Resources Management model. The information presented below was mainly derived from the hydrological network report of WRAY-3's Marib Water Resources Assessment Study (Heynert and Uil, 1990).

Meteorological data

Meteorological data in the Marib area are collected at the station of the Civil Aviation and Meteorological Authority (CAMA), situated at the airport of Marib town, and at the station of the Ministry of Agriculture and Water Resources (MAWR), which is approximately 1 km from the CAMA station. Some

13 km to the east of these meteorological stations, at Al Ghujlah, GDH operates a rainfall station.

Precipitation

Precipitation in the Marib area is generally low: the average annual rainfall is less than 100 mm per year.

To prepare rainfall time series for the years 1986-1990, the data of two rainfall stations were mainly used:

Marib station (MAWR)	: June 1986 - December 1989
Ghujla (GDH)	: November 1987- December 1990

To produce input data for the Water Resources Management model, daily data were aggregated to decade data[2]. The two time series were completed with time series from the CAMA station: monthly data of this station were split into decade data.

Evaporation and evapotranspiration

As a consequence of the dry and warm climate, evaporation and evapotranspiration are generally high. The annual rates of evaporation and of the reference evapotranspiration are both in the range of 2500-3000 mm/year. For the 5-year period 1986-1990 evaporation and evapotranspiration were calculated on a decade basis according to Penman's formula, using the modified method described by Pruitt and Doorenbos (1984). This formula needs data on wind speed, radiation, temperature and humidity. They were taken from the CAMA station, splitting monthly data into decade data. No correction was applied for energy storage in the lake. Water temperatures are unknown and are assumed to follow closely the average daily air temperature. In general, evaporation from a water body is slightly more than evapotranspiration from a cropped surface.

Hydrological data

Hydrological data were obtained from Lake Marib, where the water level in the lake and the release of water from the lake have been monitored since 1986. It was considered to extend the rather short series of surface water inflow[3], by correlating rainfall stations with a longer record (for instance Sana'a) and rainfall stations in the Wadi Adhanah catchment area, and then using the extended rainfall series in a rainfall-run off model. The correlation coefficients, however, are low, and an accurate rainfallrunoff model for the rather complex and large catchment area may be difficult to establish. These are the main reasons why it was decided to rely solely on the actually measured records only, even though the period of observation is rather short. Consequently, the hydrological and meteorological series used as input into the water resources model (see chapter 5) cover the period 1986-1990 only.

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2 In this report a decade is defined as a period of approximately 10 days. Each calendar month is divided in three decades: the first one encompassing days 1 through 10, the second one days 11 through 20, and the third one the remaining days of that month.

3 or: discharge of Wadi Adhanah at the location of the dam.

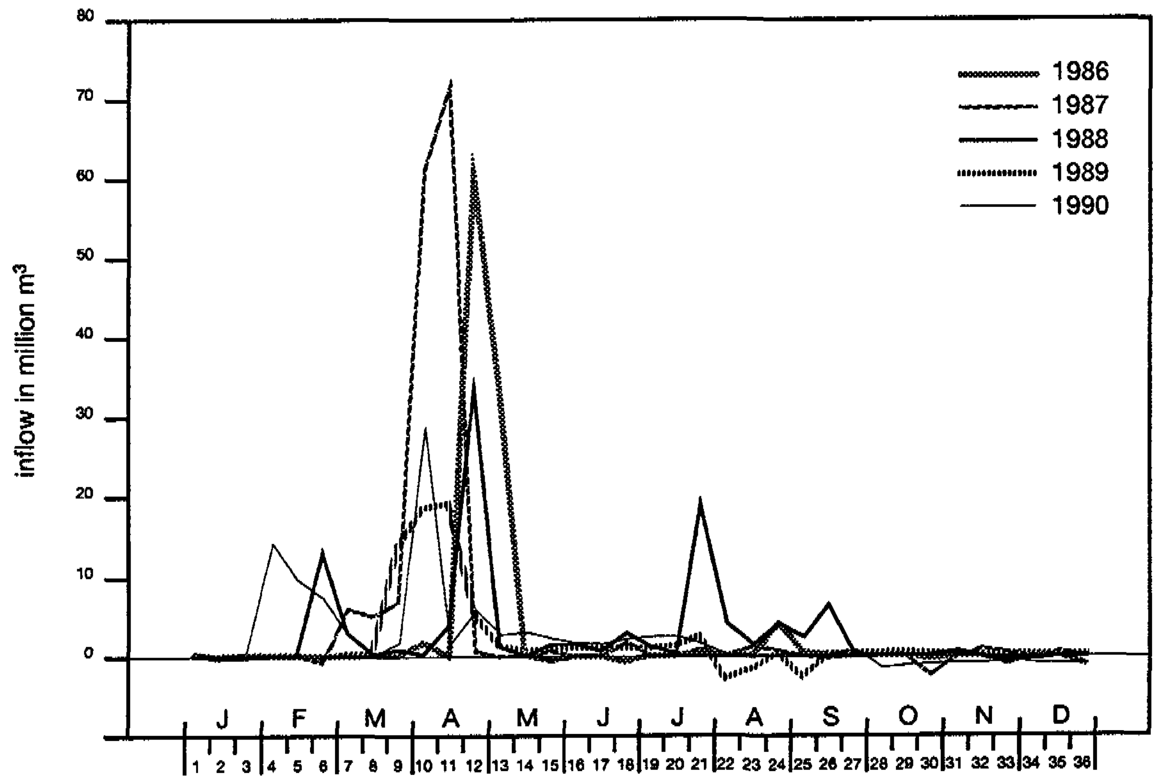

Figure 7. Daily inflow (m^3/year) into Marib lake during 1986 - 1990.

Surface water

The daily surface water inflow into Lake Marib was derived from a water balance for the lake:

$$I = O + A*Eo + \delta S + L - G$$

with:

I	= surface water inflow	(m^3/d)
O	= surface water outflow	(m^3/d)
A	= area of the lake	(m^2)
Eo	= evaporation	(m/d)
δS	= change in stored volume	(m^3/d)
L	= 'losses' (see below)	(m^3/d)
G	= 'gains'(see below)	(m^3/d)

The lake level and outflow from the lake (release) are measured automatically with a scan interval of five minutes. The area and storage of the lake in relation to the lake water level are known from a fitted curve. Details about these and other relations can be found in the hydrological network report of WRAY-3's Marib study (Heynert and Uil, 1990).

Surface water inflow includes the surface runoff from Wadi Adhanah and some local runoff; the latter is considered negligible compared with the former. Surface water outflow takes place by release of water and -in exceptional cases- by spilling.

The volume of water evaporating depends very much on the volume of water stored in the lake, because it is proportional to the area of the lake; during the period 1986-1989 these losses were about one-third of the inflow. The remaining 'losses' in the above water balance are the seepage through the dam and infiltration into the unconsolidated and consolidated rock in contact with the stored water. The first component is clearly visible in the field and is estimated to be 1 Mm^3/year. The losses due to infiltration are estimated to be on average 8 Mm^3 per year. However, this figure was derived on the basis of the water balance during dry periods; verification in the field is not possible and the value might reflect the errors in the other water balance components rather than the physical phenomenon of infiltration.

On the other hand there are some additional 'gains' in the water balance: rainfall on the lake and subsurface inflow, mainly through Wadi Adhanah's stream bed. The subsurface inflow value is unknown although it is considered to be more or less constant throughout the year (Heynert and Uil, 1990). The volume of rainfall is between 1 and 3 Mm^3/year, depending on the rainfall rate and the wet area of the lake during each particular year. Because of their amount and uncertainty, the 'losses' and 'gains' were left out of the above- mentioned waterbalance.

Using the approach and estimates presented, the inflow of surface water into the lake was calculated (figure 7). The error in the inflow thus calculated is estimated to be 10-15%. The calculations show that major inflows tend to occur in spring, especially in the month of April. Annual totals of the surface water inflow are given in table 4.1.

Sediment yield

The runoff from wadi Adhanah's catchment area -which is approximately 10 000 km^2 in extent- carries sediments into Lake Marib, which leads to a gradual decrease of the capacity of this reservoir. Electrowatt (1978) assumed an average annual sediment influx of 2.5 Mm^3/year, while an echo sounding survey on the lake in 1989, carried out by the WRAY-3 project (Nio, 1990) resulted in a preliminary estimate of 1.5 Mm^3/year. The latter value is equivalent to an average annual sedimentation rate of 150 mm if the average wet surface of the lake during the main periods of sediment influx is approximately 10 km^2.

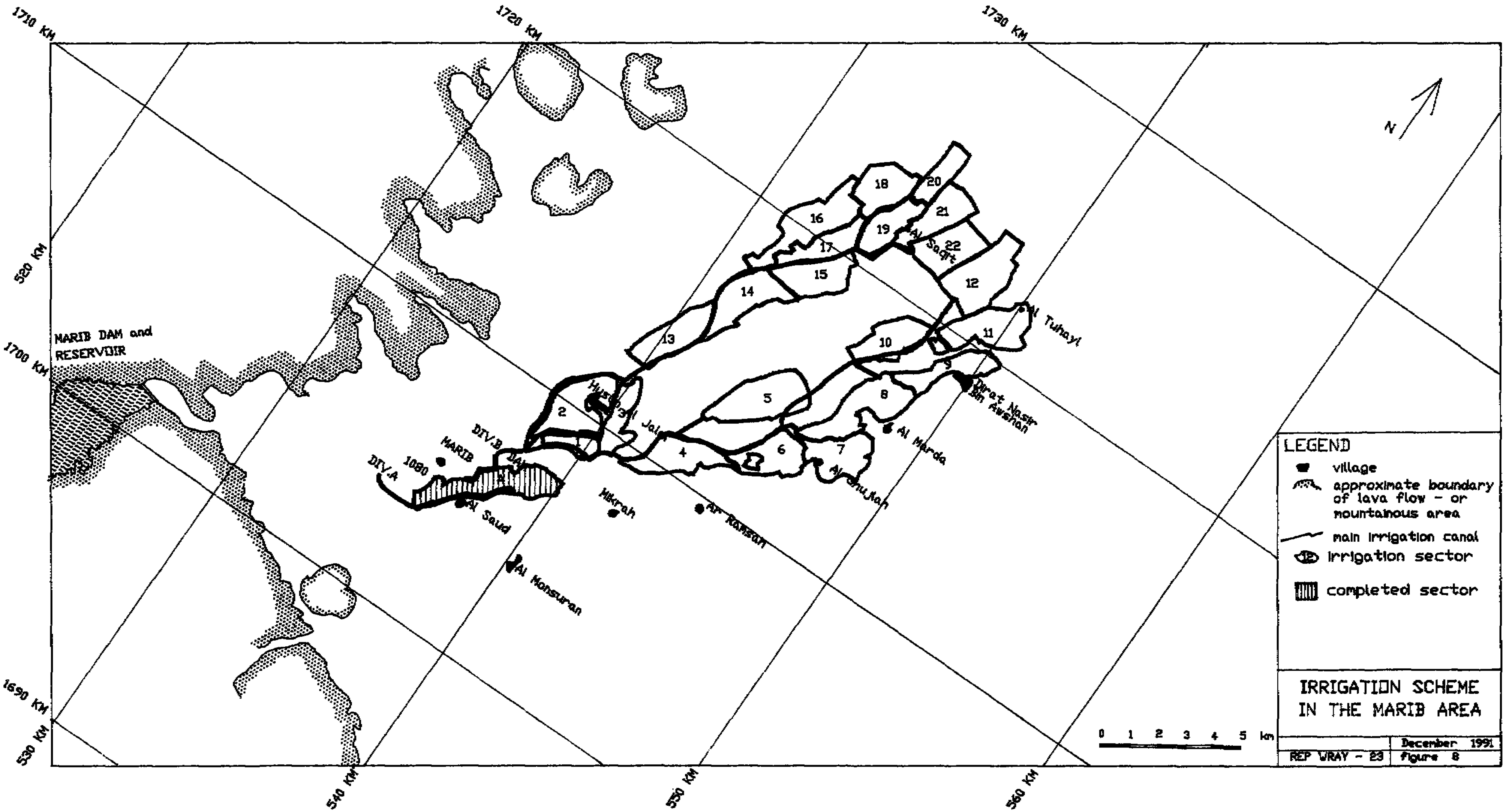

Figure 8. Irrigation scheme in the Marib area

Table 4.1 Yearly inflow in Marib Lake according to the lake water balance.

Year	Surface water inflow (Mm^3/year)
1986	85
1987	136
1988	89
1989	51
1990	70
average	86

Local runoff in the Marib area

Downstream of the Marib dam, additional runoff is generated by occasional rainfalls on the relatively small, but hilly and rocky catchments immediately west and south of the flat alluvial Marib Plain. These are the catchments of Wadi Masil, Wadi As Saila, Wadi Al Mil and others; their total area is approximately 1820 km^2, but average annual rainfall is less than 100 mm.

Hence, the annual volumes of runoff from these areas are only minor, although the floods may be devastating, as was observed in 1988 (Uil and Dufour, 1990). The local runoff was not taken into account for the model.

4.2.3 Irrigation infrastructure in the Marib area

Irrigation in the Marib area

Approximately 2500 years ago, the famous 'Great Dam' was built in the Marib area to control the floods of Wadi Adhanah and facilitate the irrigation of a estimated total area of 9600 ha. In spite of repeated destruction of the dam by floods, the dam functioned for more than a millennium, until it was finally abandoned after being washed away.

For many centuries afterwards, uncontrolled floods of Wadi Adhanah were diverted by earthen diversion dams or cross-dams to the agricultural lands. This spate irrigation system enabled only a fraction of the previous 'Northern and Southern Oases' to be irrigated (approximately 2000 ha).

During the 1970s, groundwater became a significant source of irrigation water as a result of the introduction of diesel-powered pumps; soon the groundwater-irrigated area became larger than the spate-irrigated area.

Implementation of a plan for a new dam and surface water irrigation scheme, developed by Electrowatt, was recently initiated. This scheme has drastically changed the irrigation infrastructure in the Marib area (see figure 8).

The surface water irrigation scheme

The construction of the dam and the diversion structures was completed on 1 April 1986. The construction of the primary canals (a total length of 50 km) was completed in December 1987. Figure 8 gives an overview of the surface water irrigation scheme as it was designed by Electrowatt (Electrowatt, 1978). The main elements of the irrigation scheme are discussed below.

The dam has a maximum reservoir storage capacity of 398 million m^3. The spillway is formed by a natural saddle circa 4 km upstream of the dam, which leads to the neighbouring wadi Masil. The outlet of the dam has a maximum capacity of 35 m^3/s. The water balance for the lake and the sedimentation rate are discussed in section 4.2.2.

At present the released water flows along the wadi bed from the dam to the first diversion structure (diversion A) located 10 km downstream and to the second diversion structure (diversion B) located another 6 km downstream.

From diversion A water is diverted to primary canal A. Downstream of diversion A, the remaining water flows to diversion B, where it is collected in an embanked stretch of the wadi bed which acts as a night storage basin with a capacity of about 1.08 million m3. It is then divided over three primary canals:

(1) Primary canal B-N (north)
(2) Primary canal BB (intermediate)
(3) Primary canal B-S (south)

The primary canals serve 23 irrigation sectors. Sector A is irrigated from primary canal A. The primary canal BB will irrigate three sectors, sector 1, 2 and 3. The primary canal B-N will serve sectors 13 to 22. The primary canal B-S will supply water to sectors 4 to 12.

The capacities of the different primary canals are as follows:

Primary canal:	Maximum capacity (m^3/s)
Canal A	0.84
Connection canal B	15.0
Canal BB	1.5
Canal B-N	6.5
Canal B-S	7.0

The construction of the secondary canals has been completed in sector A only. In this sector irrigation started in October 1989. In the other sectors the construction of the secondary canals has been only partially completed. Options for further development of the scheme are discussed in section 4.2.4.

Other irrigation systems

Upstream of diversion A an area of about 150 ha is irrigated by diverting water from the wadi to the lands by bunds. The infrastructure is similar to that of spate irrigation, but water is no longer diverted from uncontrolled floods, but from flows released from the dam. Groundwater has become a very important source of irrigation water over the last 20 years. The quantities of groundwater abstracted were mentioned earlier in section 4.2.1. The area presently irrigated by groundwater is approximately 8000 ha.

Losses of surface water by infiltration into the stream bed

A significant part of the surface water flows released from the reservoir is lost during conveyance by the wadi: water infiltrates through the stream bed and recharges groundwater. Discharge measurements carried out during 36 days in August and September 1988 between the dam and the diversions A and B (release rates 15 m^3/s to 5 m^3/s) resulted in the following approximative equations for these losses (Verbeek and Te Stroet, 1990):

(a) Losses between dam and diversion A:

$$Q(D\text{-}A) = 0.1620 + 0.3608 * Q(D)\ m^3/s$$

for $Q(D) > 2\ m^3/s$

(b) Losses between diversion A and B:

$$Q(A\text{-}B) = 0.5854 + 0.6431 * Q\ (A)\ m^3/s$$

for $Q(A) > 2\ m^3/s$

The conveyance efficiency of the wadi down to diversion A, as determined during these measurements was on average 61%, the conveyance efficiency of the wadi between diversion A and B had an average value of 13.5%.

Discharge measurements carried out by WRAY-4 on 9 and 10 June 1991 in six cross-sections in the wadi stretch between the Marib dam and diversion structure A produced data consistent with the above-mentioned equations. During these measurements about 20% of the losses occurred over the first 5 km downstream of the dam, about 30% over the next 2.5 km of the wadi and the remaining 50% over the last 2.5 km upstream of diversion A.

Irrigation efficiencies

Irrigation efficiencies were estimated during a field survey in the Marib area during the period May-June 1991 (Neefjes, 1991).

The total efficiency of the surface water irrigation scheme was defined as the product of conveyance efficiency (primary and secondary canals), distribution efficiency (conveyance to the field inlet) and field application efficiency.

For the primary canals a conveyance efficiency of 90% was assumed. Distribution efficiencies for each irrigation sector were estimated on the basis of some field measurements. Values varying from 50% for a sandy soil to 80% for a silty loam were found.

Field application efficiencies were assessed on the basis of field measurements and some computer simulations. They were estimated to be 60% for a sand and a sandy loam, and 75% for a sandy loam and a silty loam. These rather high values are explained by the fact that the irrigation basins are small.

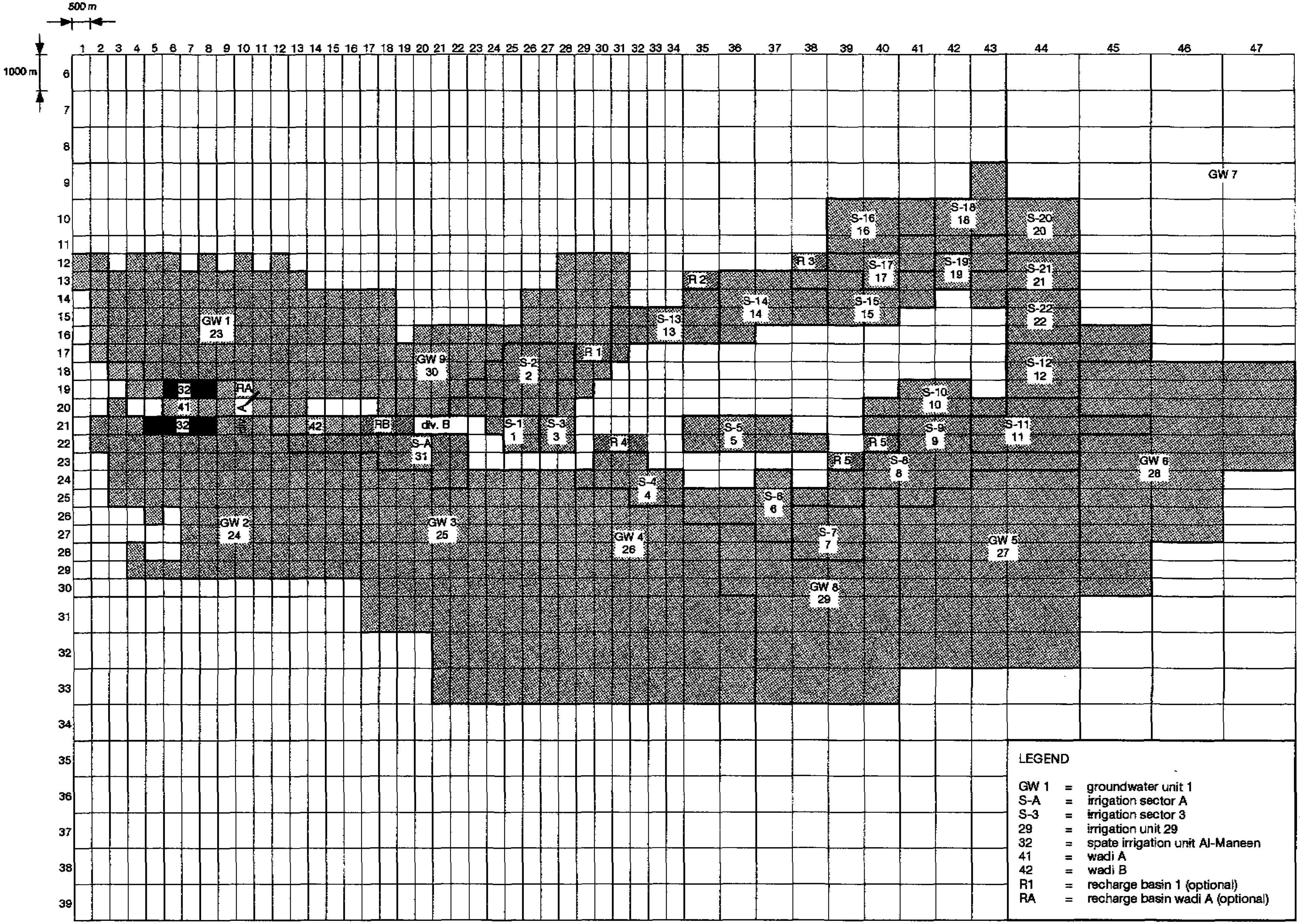

Figure 9: Schematization of the irrigation units in the Marib Area

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For the groundwater-irrigated zones the total efficiency is the product of distribution efficiency and field application efficiency. Because the agricultural lands served by a well are, on average, approximately onequarter the size of the tertiary units of the surface water irrigation system, the distribution canals will be approximately half as long. Hence, in contrast to the report by Neefjes (1991), the distribution losses are estimated as only half those on comparable soils in the surface water irrigation system. Estimates for the groundwater-irrigated zones are an average distribution efficiency of 82.5% and an average application efficiency of 67.5%.

Schematization of irrigated lands to 'irrigation units'

For the purpose of the Water Resources Management model (see next chapter) the total area of irrigated lands was divided into 32 'irrigation units' (see figure 9). Table 4.2 gives some characteristics of the units. They are classified in three categories:

(1) 'groundwater irrigation units', that have access only to groundwater;
(2) 'surface water irrigation units', that have access only to surface water;
(3) 'conjunctive use units', where surface water and groundwater are both available.

For the groundwater units, areas of relative constant depth to groundwater were delineated, because the Water Resources Management model calculates the costs of groundwater per unit (see also section 4.3.3). The location of the groundwater units has been limited to the area where the electrical conductivity is approximately less than 2000 microS.

The conjunctive use units coincide with the sectors of the irrigation scheme. At present these units (except in sector A) only use groundwater for irrigation. The surface water unit upstream of diversion A is called Al-Maneen.

As direct recharge to the groundwater is an option that deserves evaluation some locations for recharge basins were also selected. They are indicated in figure 9.

Further development of the Marib irrigation scheme

As stated above, construction of secondary canals stopped during 1989, and so far only one irrigation sector (sector A) has been completed. Whether and to what extent the irrigation scheme should be completed is still under debate.

A World Bank mission (1991) calculated that a net area of about 1750 ha could be irrigated during the winter season only. The calculations were based on the water requirements for a 5 ha farm model, and on a measured average inflow of 104 Mm^3 -which is the average inflow calculated on the basis of the 1986-1989 observations (Uil and Dufour, 1990)- and 80% losses through the wadi bed as determined by ERADA. The sectors that could be irrigated according to the mission are sectors A, 1, 2, 3, 4, 13 and 14.

The mission proposed a feasibility study for a lined conveyance canal between the dam and the diversion structures. They suggested excluding some

Table 4.2 Characteristics of the irrigation units.

irrigation unit name	no	gross area planned (ha)	net area (ha)	area presently under cultivation (ha)	tot. irr. eff. (%)	1991 GW abstr. Mm³/y	1991 depth to GW (m)
Al-Maneen	32	150	128	128	45	-	30
Sector A	31	405	344	274	54	3.2	28
Sector 1	1	117.6	100	95	47	1.8	22
Sector 2	2	406.6	346	304	32	4.2	20
Sector 3	3	212.2	180	166	32	6.8	20
Sector 4	4	321	272	249	32	5.0	21
Sector 5	5	437	371	277	32	4.4	28
Sector 6	6	292	248	248	47	7.4	30
Sector 7	7	321	273	268	47	4.0	39
Sector 8	8	433.2	368	280	47	3.4	40
Sector 9	9	275.8	234	87	27	2.6	53
Sector 10	10	270	229	102	32	1.0	55
Sector 11	11	383.4	326	94	32	1.6	60
Sector 12[3]	12	458	233	107	32	0.2	65
Sector 13	13	318.8	271	180	27	4.4	23
Sector 14	14	384.1	326	148	27	4.2	32
Sector 15	15	360.2	306	91	27	3.4	53
Sector 16	16	433.3	368	88	56	1.8	70
Sector 17	17	245.1	208	101	56	2.0	75
Sector 18	18	289.9	246	15	56	0.4	75
Sector 19	19	239.2	203	68	32	0.2	75
Sector 20[3]	20	199.3	101	35	54	0.2	95
Sector 21[3]	21	300.1	153	44	27	0.6	80
Sector 22[3]	22	301.6	256	14	32	0.2	70
Gw.unit 1	23	2675	2275	1546	56	18.6	35
Gw.unit 2	24	2700	2300	1170	56	24.0	30
Gw.unit 3	25	2320	1970	812	56	23.8	28
Gw.unit 4	26	2050	1745	727	56	14.0	26
Gw.unit 5	27	740	631	263	56	7.2	40
Gw.unit 6	28	385	326	136	56	4.0	99
Gw.unit 8	29	255	216	90	56	4.2	41
Gw.unit 9	30	610	521	217	56	2.4	21
Total		19289	16,074	8,424		164	

Notes:

1. Irrigation efficiencies for the irrigation units within the Marib scheme are given for surface water irrigation. When groundwater irrigation is applied the irrigation efficiency for these units is 56%.
2. Current abstraction data were obtained during a well inventory in the area (see appendix 4).
3. Net area reduced by 40% because of sand dune movement.

Table 4.3 Assumed timepath for completion of the Marib scheme and for the year of maximum development.

Sector no.	Year of completion	Year of max. Development
S-A	1989	1996
S-1	1994	1996
S-2	1994	1996
S-3	1994	1996
S-4	1994	1996
S-5	1996	1998
S-6	1996	1998
S-7	1996	1998
S-8	1996	1998
S-9	1995	1999
S-10	1995	1999
S-11	1995	2001
S-12	1995	2001
S-13	1994	1996
S-14	1994	1998
S-15	1997	2003
S-16	1997	2003
S-17	1997	2001
S-18	1997	2007
S-19	1998	2002
S-20	1998	2004
S-21	1998	2004
S-22	1998	2008
Al-Maneen	1994	1996

sectors from further development because they are above the level of the primary canal (sectors 16, 17 and 18), and to develop others only partially because they are largely covered by sand dunes (sectors 12, 20, 21 and 22).

Several options for further development were formulated and were subjected to analysis (see chapter 6). As at present there is no time schedule for completion of the secondary canals, assumptions regarding the year of completion of each sector were made based on the status of completion of the units and previous experiences. These assumptions are presented in table 4.3.

Year of maximum development

It will take time to development the irrigation sectors after completion of the secondary canals, especially within irrigation sectors that are at present only partially cultivated.

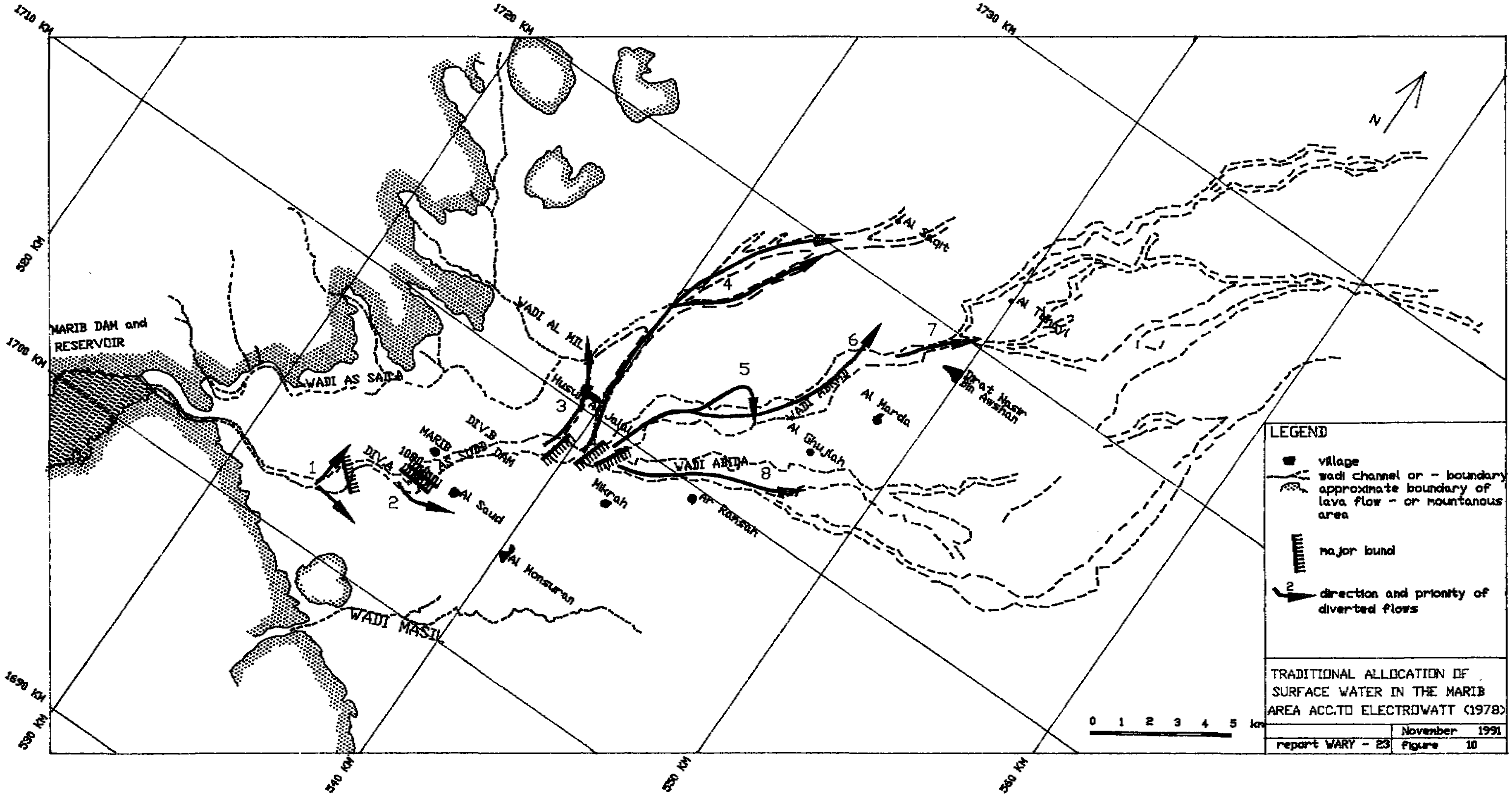


Figure 10. Traditional allocation of surface water in the Marib area according to Electrowatt (1978).

The implementation of the measures necessary after a certain strategy has been selected also takes time. For instance, groundwater abstractions cannot be cut down overnight. Improving crop yield or irrigation efficiencies needs several years of intensive agricultural extension. Assumptions had to be made about the year in which a certain target is reached for each sector: they were based on the ratio between the present cultivated area of the irrigation units and their potentially cultivable area. The assumed 'years of maximum development' are given in table 4.3. As it is obviously unrealistic to assume different target years for every decision variable, the 'year of maximum development' is valid for all decision variables.

4.2.4 Surface water allocation

Spate irrigation

Before the construction of the dam, the spates were distributed to the lands according to traditional rules, making use of diversion bunds constructed in the wadi. The pattern for division of spates by the main diversion bunds as given by Electrowatt, 1978, is presented in figure 10. In table 4.4 the villages and the irrigation sectors are listed in descending order of priority rights regarding spate allocation (Neefjes, 1991).

However, modifications andexceptions could be made to this general order of priority. For instance, areas downstream with a low priority may get water on average once every three years, but if five dry years have occurred, bunds are not constructed upstream and priority is shifted to the downstream areas.

Options for surface water allocation

The gross area to be irrigated from surface water was designed to be 7404 ha, according to an Electrowatt map dated 1990. In Electrowatt's draft final report (1990) a gross area of 6492 ha is mentioned. The average annual inflow into the reservoir was estimated by Electrowatt to be 200 Mm^3, an estimate based on data from Wadi Najran. For their proposed cropping pattern 126 Mm^3 of surface water should be available at the diversion structures in an average year, assuming surface water irrigation during 10 months, and groundwater irrigation during July and August. They assumed that a total amount of 163 Mm^3 could be released annually, apparently taking into account losses of 21% through the wadi bed.

However, the average inflow over this period is 86 million m^3, less than half of the amount estimated by Electrowatt. The annual reservoir inflow from 1986 through 1990 ranged from 51,4 Mm^3 in 1989 to 137 Mm^3 in 1987 (see section 4.2.2).

As it is clear that not enough surface water is available for the area originally planned, a decision must be taken regarding the allocation of surface water for different volumes of water available in the reservoir.

One option is to allocate in proportion to the cultivated area of a sector. Another option is to supply according to the traditional rules that used to be applied before the dam was constructed. If, however, the socio-economic situation of the more downstream areas, where deeper groundwater levels cause higher production costs for groundwater is considered, priority might nevertheless be given to the downstream sectors. Allocation of surface water to one or more recharge basins may also be considered.

Which allocation rule the local inhabitants felt would be the most appropriate was investigated during the socio-economic survey carried out in the framework of this study. Discussions with representatives of some tribes revealed different opinions: some of them expressed preference for a traditional allocation if there was a shortage of surface water; others preferred allocation proportional to area.

Table 4.4 Relative order of priority for spate irrigation allocation before the new irrigation scheme was constructed (after Electrowatt, 1978).

priority level	village names	approximate sector No.
9	Al Haymid	none
8	Al Hayder, Al Saud, Husun Al Raju	A
7	Dirat Al Hada, Husun Al Jalal, Al Qadami	S-1,2,3
6	Al Shabwan, Al Awash, Al Saqit Al Rukzah	S13,14,15,16,17, 18,19,20,21,22
5	Al Hadan	S-5
4	?	S-10
3	Al Tahayl	S-11,12
2	Al Jitwan, Ghujla, Salwah, etc.	S-4,6,7,8,9

Note: Priority levels are given as required by the WRM model, which allows 10 levels of priority (9-0). Priority 9 is the highest priority; the villages under priority level 2 receive water after all others have been served.

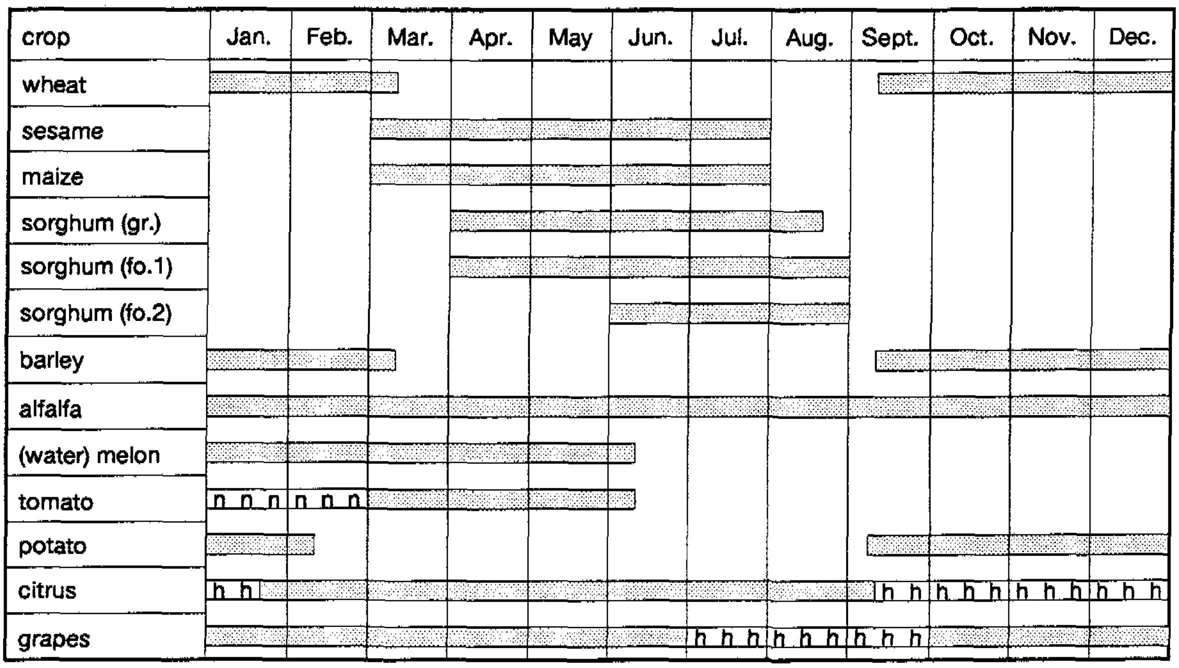
4.3 Agriculture

4.3.1 Land use

Agriculture is the main economic activity in the Marib area. The cultivated area increased rapidly from 3300 ha in 1978 (Electrowatt, 1978) to around 8400 ha in 1991.

The main crops cultivated in the area are: citrus, wheat, sesame, sorghum, maize, tomato, potato, alfalfa and water melon. The cropping calendar for the crops in the Marib area is given in table 4.5. A land use map for the situation of June 1991 was prepared using satellite images of the area (GeoImage, 1991). The areas of the different crops were determined (in ha) for each irrigation unit. In addition, for each irrigation unit the extent of fallow land and of areas covered by natural vegetation, houses, water, sand dunes, alluvial gravels and pediments were determined.

Table 4.5. Present cropping calendar for the Marib area.



Note: Fodder sorghum (1) is cut (ratooned) 2 to 3 times, fodder sorghum (2) is grown after tomato or melon and cut only once, sorghum (gr.) is cut once and than produces grain.; n = nursery and h = harvest.

As only an image of the summer season was acquired, certain assumptions were necessary to arrive at the cropped area and cropping intensities for the winter crops wheat and barley. It appeared possible to distinguish fallow lands that had previously been under wheat from land that had not been cultivated during the previous winter season. To estimate the total area cultivated by wheat it was assumed that all areas classified as sorghum and sesame had previously been under by wheat. As during the field check no field was found that had been cultivated with barley, and as the cropped area of barley is reported to be small and decreasing during the last 5 years (Neefjes, 1991), it was decided to disregard barley.

Cropping intensities were calculated by expressing the number of hectares harvested in a year as percentages of the total agricultural area (cultivated and fallow). For the calculation of the cropping intensity areas of perennial crops were assumed to be double-cropped. The average cropping intensity for 1991 for the whole Marib area was 122%. The cropping intensities range from 17% for sector 22 to 165% for sector 7. A more detailed discussion on the land use study can be found in appendix 7, which also includes the areas and cropping intensities per crop and per irrigation unit.

In table 4.6 the total cultivated area is given per crop for the groundwater units (outside the scheme) and for the irrigation sectors (which are at present also irrigated from groundwater, except sector A), as well as the total cultivated area per crop for the Marib area.

Table 4.6 Crops and cropping intensities in the Marib area.

crop	groundwater units (ha)	irrigation sectors (ha)	total (ha)
citrus	561	410	970
wheat	2235	1724	3958
sesame	953	851	1804
sorghum	380	296	676
maize	284	158	442
tomato	525	403	928
potato	237	101	338
alfalfa	123	116	239
w.melon	54	58	112
fallow	934	388	1321
total cultivated area (ha)	4790	3706	8497

4.3.2 Crop water requirements

When the soil moisture conditions are optimal, the evapotranspiration of crops can be related to meteorological conditions (more specifically: to a reference potential evapotranspiration). The relation is commonly expressed in a crop- specific factor that should be multiplied by the reference potential evapotranspiration to obtain the crop evapotranspiration. The crop factors vary during the growth cycle of the crops, as can be observed in table 4.7.

4.3.3 Agro-economic data

Crop yields

The present average crop yields as well as future yield projections were determined from literature data and field interviews during the Data Compilation phase (Neefjes, 1991). It was assumed that these values are valid for a sandy loam. Yields are assumed to be 20% higher than average for a silty loam, and 10% lower for a sand. In table 4.8 crop yields and crop yield projections are given.

Economic data on crops

The production costs and revenues for the main crops in the Marib area were determined during the socio-economic survey. The survey was based on an enquiry in which 252 respondents participated, some 'in-depth' interviewing and literature data (IWACO, 1991). Financial and economic costs and revenues were calculated. This was done to enable a financial analysis as well as a economic analysis.

Table 4.7 Crop factors for the crops cultivated in the Marib area.

Crop	Crop stage k_c-factor				approximate timing and length of stages (decades 1-36)			
	1	2	3	4	1	2	3	4
wheat	0.25	0.7	1.15	0.2	30	31-32	33-2	3-5
sesame	0.25	0.65	1.05	0.75	8	9-10	11-15	16-17
maize	0.25	0.7	1.15	0.6	8-9	10-12	13-16	17-19
sorghum (gr.)	0.25	0.68	1.1	0.55	10-12	12-14	15-19	20-22
sorghum (fo.1)	0.25	0.68	1.1	0.55	10-11	12-14	15-19	20-24
sorghum (fo.2)	0.25	0.68	1.1	0.55	16	17-18	19-20	21-24
barley	0.25	0.7	1.15	0.2	30	31-32	33-2	3-5
alfalfa	0.90				1-36			
(water) melon	0.6	0.8	1.0	0.75	1-3	4-6	7-12	13-14
tomato	0.6	0.9	1.2	0.65	1-3	4-7	8-11	12-14
potato	0.45	0.8	1.15	0.75	27-29	30-32	33-36	1-3
citrus	0.75	0.70	0.65	0.7	1-6	7-15	16-27	28-36
fallow	0.0				1-36			

Note:
Crop stages are (except for alfalfa and citrus):
1 initial stage (to 10% ground cover)
2 crop development stage (10-80% ground cover)
3 mid season stage (80% ground cover to ripening)
4 maturity or harvest stage (start of ripening to harvest)

A financial analysis assesses the financial viability of a project. The starting point of the analysis are the beneficiaries of the project. In the economic analysis the impact of the investment on the society as a whole is used as perspective. There are two important difference between the economic and financial analysis. First, in the economic analysis transfer payments (such as taxes, subsidies, debt service payments) are omitted. Secondly, in an economic analysis shadow prices are used, while in a financial analysis market prices are taken as a starting point. Market prices reflect the opportunity cost for the individual farmer. Shadow prices are calculated on the basis of the shadow exchange rate and the shadow labour rate. See the report 'Socio-economic study Marib area' (IWACO, 1991) for more information.

In this study an economic analysis is done to assess the net economic benefits of different cases and strategies. A financial analysis is done to assess the equitability of the distribution of water related benefits. The economic and financial analysis are limited to cost and revenues of crops. The investment costs of the Marib dam and irrigation system are regarded as sunk cost. Operation and maintenance cost of the Marib dam and irrigation system are also disregarded.

Table 4.8 Crop yields and future yield projections.

crop	present	future 1-15 y	future 16-30 y	unit of measurement
wheat	1.8	2.5	3.5	ton grain/ha
sesame	0.5	0.7	1.0	ton seed/ha
maize	1.8	2.5	3.5	ton grain/ha
sorghum (gr.)	1.5	2.1	2.9	ton grain/ha
sorghum (fo.1)	16.0	22.0	31.0	ton fresh fodder/ha
sorghum (fo.2)	6.0	8.5	12.0	ton fresh fodder/ha
barley	1.5	2.1	2.9	ton grain/ha
alfalfa	60.0	72.0	85.0	ton fresh fodder/ha
(water) melon	15.0	20.0	25.0	ton fresh prod./ha
tomato	20.0	28.0	39.0	ton fresh prod./ha
potato	12.0	18.0	27.0	ton fresh prod./ha
citrus	13.0	18.0	25.0	ton fresh prod./ha

Table 4.9 gives financial prices of production costs and revenues for the main crops in the Marib area. Production cost in IWACO's survey also included cost of diesel for pumping groundwater. As the groundwater costs are calculated separately by the Water Resources Management model, in the third column of the table the costs for diesel for groundwater pumping were subtracted from the total production costs. Table 4.10 presents similar information but in terms of economic prices.

Table 4.9 Costs and revenues in financial prices for the main crops in the Marib area (YR/kg) in 1991.

Commodity	Crop cost	Crop cost minus fuel costs for pumping	Crop revenue
Wheat	7.09	5.79	9.0
Sorghum	6.33	3.53	9.0
Sesame	26.3	19.9	21.0
Alfalfa	0.3	0.12	1.0
Tomato	0.8	0.62	2.8
Water melon	0.9	0.66	2.7
Potatoes	4.33	4.11	4.7
Citrus	5.99	5.29	21.0
Maize	6.87	4.77	10.2

Table 4.10 Costs and revenues in economic prices for the main crops in the Marib area (YR/kg)in 1991.

Commodity	Crop cost	Crop cost minus fuel cost for pumping	Crop revenue
Wheat	6.48	4.75	5.4
Sorghum	5.83	2.11	4.5
Sesame	22.64	14.1	16.8
Alfalfa	0.31	0.07	0.8
Tomato	0.69	0.45	2.8
Watermelon	0.81	0.49	2.65
Potatoes	3.93	2.30	2.80
Citrus	5.19	4.26	11.0
Maize	6.47	4.37	6.1

Groundwater costs

The cost of groundwater from pumped wells mainly depends on the depth to groundwater, given an annual number of effective pumping hours. Calculations for different depths to groundwater have shown that on average the cost of groundwater can be closely approximated by the following linear relation:

$$\text{Cost (YR per m}^3\text{)} = 0.11 + 0.018 * D$$

where D = depth to groundwater, measured from land surface to static water level in the wells (in m). This estimated cost includes both the fixed cost (well and pump) and the variable cost (fuel and maintenance) of groundwater. Appendix 2 gives more details about the calculations.

4.3.4 Socio-economic constraints to further development

The socio-economic study revealed the following socio-economic constraints that might mitigate the impact of the irrigation scheme:

- High investment cost for land levelling together with a poor access to official sources of credit might hamper the cultivation of additional land. The same applies for the high prices of inputs. A future decline in real market prices and an increase in crop costs is foreseen.
- There is no marketing strategy in the area; the poor distribution of agricultural products has a negative effect on the profitability of the farming.

- Farmers lack sufficient knowledge and inputs to combat plant diseases.
- The agricultural extension services lack an effective communication approach. Agricultural research is absent in the area.
- Migrating sand dunes are a serious problem in the area and might affect the investment behaviour of the farmer.
- Opinions vary regarding the future allocation of irrigation water (see section 4.2.4).
- In the present design of the irrigation scheme the sector boundaries cross the boundaries of tribal areas, which might hamper the efficient distribution of surface water.

4.4 Water demands down-flow of the Marib area

The boundaries of the Marib area as chosen for this study are somewhat artificial, in particular the northeastern and northwestern boundaries (through which subsurface outflow takes place) and the southwestern boundary (which runs more or less parallel to the groundwater flow lines).

In the first place, attention should be paid to the northeastern and northwestern boundaries, as theoretically a possible reduction of outflow might jeopardize other interests related to groundwater. The outflow passing these boundaries consists of groundwater flow only, because the control of surface water by the Marib Dam and Irrigation Scheme will preclude significant amounts of surface water flowing that far downstream. However, beyond these boundaries the area is virtually without sedentary population over very large distances (the Marib area is at the edge of the desert).

Given the slow response of the groundwater system to disturbances far away, it is assumed that measurable impacts at distances of hundreds of kilometres down-flow (where water demands reappear) will not occur within any realistic planning horizon.

The nearest water demands that are supplied from a groundwater system that is probably connected with the Marib system are those of the oil industry in the Marib area. The Alif and Azal fields are located at approximately 40 - 50 km east of the easternmost irrigation units considered. It is assumed that the conditions for groundwater abstraction by the oil industry will not be significantly influenced by water resources management within the limits of the Marib area as adopted in the present study. The validity of this assumption can be verified by running the groundwater component of the Water Resources Management Model (see also chapters 5 and 6).

5 THE COMPUTATIONAL FRAMEWORK

5.1 General features

In order to be able to analyse and compare different water resources management strategies, an integrated Water Resources Management model was developed.

The model simulates in an integrated way the water balance of Lake Marib, the water requirements of the agricultural lands, the allocation of surface water, the abstraction of groundwater, the recharge of the aquifer, the crop yields, the economic benefits obtained by agriculture and the response of the groundwater levels to groundwater abstraction and recharge.

For the purpose of the computations the water resources system was schematized into 32 irrigation units (see par. 4.2.3). A maximum of 5 recharge basins downstream of diversion B may be included to allow the effect of direct recharge to be evaluated. If a lined conveyance canal is constructed it might be desirable to recharge upstream from the diversion structures, and in this case two additional basins may be selected. This schematization is given in figure 11. Input and output of the model is related to the irrigation units.

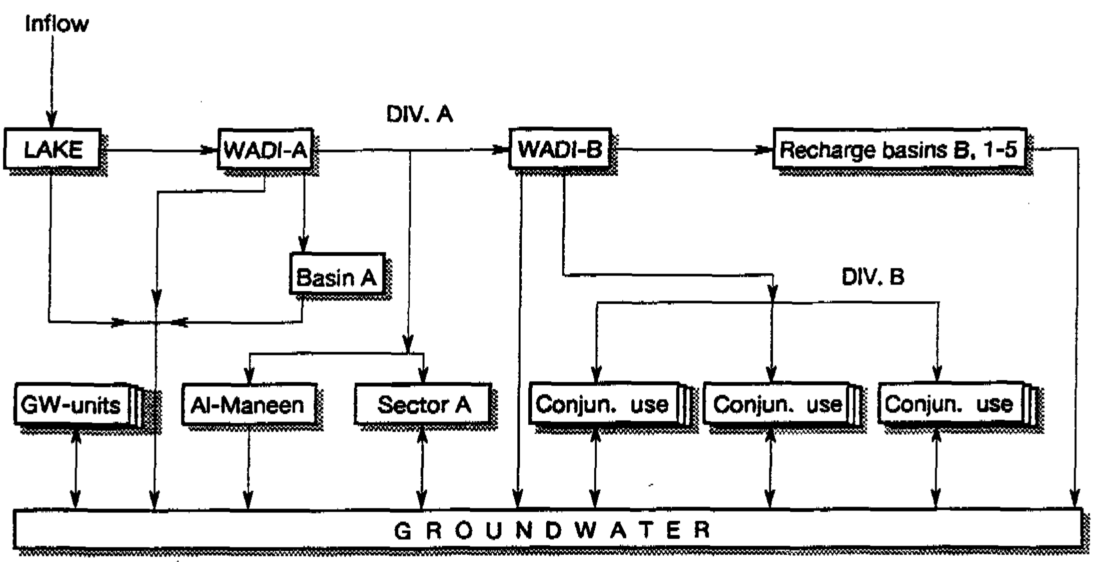


Figure 11. Schematization in computational framework of the Marib water resources system.

Water resources management strategies can be defined by assigning values to the 'decision variables' in the model. Than the model is run for each particular strategy, and the results (in the form of output tables) are evaluated on the basis of the criteria that were formulated for the adopted water resources management objectives (see chapter 3). In this way it becomes possible to identify and select relatively promising strategies.

The time span of the simulations varies: the modules that perform simulations of crop production and related economic calculations cover a 25-year period; to judge the sustainability of groundwater use, however, the groundwater model is run over a period of 100 years. Both standardized simulation periods start in one and the same base year. In the present study 1991 was chosen as the base year.

The computational framework consists of:
- the agro-hydrological model AGRIMAR;
- the post-processing model POSTMAR;
- the groundwater model MODFLOW;
- the economic model ECOMARIB and
- the user interface SHELL

These components are described below.

5.2 The agro-hydrological model

5.2.1 Model tasks

Computations start with the agro-hydrological model AGRIMAR. The output from AGRIMAR is used by the groundwater model and the economic model. AGRIMAR calculates:

- the gross and net water demand in the irrigation units;
- the flows and losses in wadis;
- the 'losses' in the recharge basins;
- the water balance of lake Marib per decade;
- the water balance in irrigation units per year;
- the net groundwater abstraction (abstraction minus return flow);
- the areas irrigated from surface water and from groundwater per irrigation unit per season;
- the yields per crop per irrigation unit per season and per year.
- the non-water costs and revenues of crops per irrigation unit per year.

5.2.2 Algorithms

Simulating water demands and surface water availability

AGRIMAR starts with the computation of the actual water demand (AWD) in each irrigation season. This actual water demand is calculated for each irrigation unit on the basis of the length of the irrigation period, the given crop factors, cropping patterns, crop calendar, areas cultivated and reference potential evapotranspiration, according to:

$$AWD = \Sigma\ t\ \Sigma\ i(A_{max}(i)*k_c(i,t)*ET_o(t))$$

with:

A_{max}	:	irrigable area per irrigation unit (ha)
k_c	:	crop coefficient (-)
ET_o	:	crop reference evapotranspiration (mm/decade)
i	:	irrigation unit index
t	:	decade index (1 - 36)

It is assumed that the crops in the Marib area are using water at a rate equal to potential evapotranspiration. This is a reasonable assumption because farmers' practice is such that under-irrigation in the Marib area is unlikely (Neefjes, 1991).
Depending on the strategy chosen, additional water may be allocated to the five recharge basins in the area and/or to the two basins in the wadi.

Losses are calculated in accordance with the assumptions made (see chapter 4). If the scheme's irrigation sectors are supplied by surface water, then the irrigation losses and the wadi losses are accounted for in the calculation of the irrigation requirement and gross water demand. If they use groundwater only (which is the present situation for most of them), only irrigation losses have to be taken into account. The volume of losses is calculated over the length of the irrigation season. Note that because of irrigation losses and wadi losses the gross water demand (GWD) is always larger than the actual water demand. The intake for the surface water unit Al Maneen is assumed to be situated at diversion A.

Next, the volume of water available in the lake (V_{lake}) is calculated. This is done at the beginning of each season on the basis of the lake water balance. From the wadi inflow data, the evaporation from the lake, and seepage through the dam and through the adjoining rocks the volume of water in the lake is calculated (rainfall is ignored). From the relation between lake level and volume in the lake, the lake level can be derived. This relation between lake level and volume contained in the reservoir is updated annually on the basis of the annual sedimentation rate specified in the model (see section 4.2.2).

Matching supply and demand of water

In the groundwater irrigation units the amount of groundwater abstracted is always equal to the gross water demand of these units, unless the userdefined maximum groundwater abstraction is reached. In the latter case the area irrigated will be less than the user-specified 'input-area'.

The way supply and demand are matched in the other irrigation units depends on the operational rules chosen for the release of surface water from the surface water reservoir. In the model, basically two options exist for the conjunctive use units: (a) surface water is the primary source of water; (b) groundwater is the primary source of water. The matching procedure will vary accordingly as is explained below.

If surface water is considered to be the primary source, the procedure is as follows. The volume of water stored in the lake at the beginning of the irrigation season minus the sum of minimum active volume desired at the end of the surface water irrigation season (V_{min}) and the volume to be allocated to the recharge basins (V_{rech}), is assumed to be available for irrigation. It will be called V_{avail}. The value for V_{min} includes the 'dead storage'. Two situations can occur:

if GWD = or < V_{avail} : AAW = GWD
if GWD > V_{avail} : AAW < GWD

where: $V_{avail} = V_{lake} - (V_{rech} + V_{min})$

AAW = water actually allocated

The solution in the first case is straight forward: the amount of water released from the reservoir is equal to the gross water demand and the irrigated area is equal to the input area. In the second case (GWD is larger than V_{avail}) the available volume of water will be allocated according to the preset priority level for the irrigation units. If all priority levels are equal, then water is allocated proportional to the gross water demand of the surface water and the conjunctive use units; otherwise it is allocated to the units in the order indicated by the priority levels. In the surface water units this might result in a smaller area being irrigated than the original 'input-area'. In the conjunctive use units additional irrigation takes place from groundwater up to the predefined maximum. If shortages still occur the area being irrigated will be smaller than the 'input-area'.

If groundwater is considered to be the primary source in the conjunctive use units, then the gross irrigation water requirement for the groundwater units and the conjunctive use units is assumed to be abstracted from the groundwater basin, up to a predefined maximum for each irrigation unit. The remaining part of the gross water demand will be satisfied by surface water, according to the rules as explained for the case of surface water as the main source.

Outside the specified surface water irrigation season(s) the irrigation water requirement is abstracted from groundwater.

Computation of costs and revenues

AGRIMAR computes the non-water costs for each irrigation unit per year by multiplying the area under each crop by the production costs in YR per hectare. Crop yields for each irrigation unit are computed by multiplying the area under each crop by the crop yield per hectare. Revenues are computed by multiplying the latter figure by the crop revenues in YR per kg.

5.3 The post-processing model POSTMAR

POSTMAR is a post-processing module that prepares input data for the MODFLOW-model from output data of AGRIMAR. Amongst other data, AGRIMAR produces mean annual groundwater abstraction and recharge data. These are processed by POSTMAR to generate an input file for the MODFLOW WELL package.

5.4 The groundwater model

5.4.1 Model tasks

The groundwater model has two tasks:

- To compute the drawdown in each irrigation unit after the 25-year simulation period; these are input to the economic model to calculate the groundwater costs.

- To compute the groundwater levels after the long-term simulation period to evaluate the sustainability of the groundwater resources under a certain strategy.

After each model run a postprocessing module called POSTMOD is automatically run to transform the binary drawdowns and groundwater heads computed by MODFLOW into ASCII values. An additional conversion program has been written to convert the format of the ASCII file that contains the groundwater drawdowns to the format required by the economic model.

5.4.2 Hydrogeological schematization

Discretization

Since one of the adopted water resources management objectives is sustainability of the groundwater resources, simulations have to be extended over a long period. A period of 100 years was chosen.

In order to model the study area an existing MODFLOW model developed for part of the Marib area by Verbeek and te Stroet (1990) was extended. For long-term simulations the model had to be extended to allow the reduction of storage of groundwater to be spread over a large area, and to be able to describe the unknown vertical boundary conditions at sufficient distance from the stressed area.

The size of the modelled area in the original model is 34*24 km^2. This area coincides with the study area defined for the present study. In the new model the area has been enlarged to 222*116 km^2. It has been verified that at large distances fixed head boundaries are realistic.

The extended model consists of 44 rows and 53 columns and two layers. The total number of nodal points in the middle of the cells amounts to 4664 nodes. The spacing of these cells is related to the availability of data and to the desired accuracy.

In the study area the discretization of the existing model was maintained. The grid size is 500*500 m^2 cells in the southwestern part of the model. Moving northeast from there, the grid spacing increases gradually to a maximum cell size of 1*2 km^2 (see figure 9). Outside the study area the cell size increases gradually towards the boundaries to reach a maximum of 32*128 km^2.

Hydraulic parameters

The area has been discretized vertically into two aquifers separated by an impervious layer as shown in figure 6.

The hydraulic conductivity in the upper aquifer varies between 0.5 m/d (in a zone where a 'barrier' to groundwater appears to be present) to 50 m/d elsewhere. The unconfined storage coefficient was assumed to be 0.2. For the impervious layer the vertical hydraulic conductivity was taken as 10^{-4} m/d (Verbeek and te Stroet, 1990).

Transmissivity in the lower aquifer has been derived on the basis of an estimated hydraulic conductivity of 2 m/d and the aquifer thickness

(Verbeek and te Stroet, 1990, appendix 2.1). The confined storage coefficient was estimated to be 10^{-4}.

The external boundaries of the modelled area for the two aquifers were defined as inactive in the areas where Amran limestone and basaltic cones outcrop and further as constant head boundaries. The internal cells and the cells in which the wadi enters the modelled area were defined as cells with variable head. The second aquifer is made inactive where the base of the Azal Formation aquifer is deeper than 300 m below surface, because it is unlikely that deeper wells will be drilled.

5.4.3 Description of model code

A MODFLOW PC-EXT version (McDonald and Harbaugh, 1991) was used in order to restrict computation time for the several thousands of groundwater nodes and the maximum stress periods of 100 years. The model was run on a Toshiba T2000SX portable computer with 2 Megabytes extended memory and a mathematical co-processor.

Basically the groundwater flow in discretized rectangles is calculated, while the water balance of each rectangle is assumed to obey the law of continuity, the groundwater flow is Darcian and boundary conditions are met.

The partial differential equation for movement of groundwater with constant density may be described as follows:

$$\frac{\delta}{\delta_x}\left(K_{xx}\cdot\frac{\delta_h}{\delta_x}\right)+\frac{\delta}{\delta_y}\left(K_{yy}\cdot\frac{\delta_h}{\delta_y}\right)+\frac{\delta}{\delta_z}\left(K_{zz}\cdot\frac{\delta_h}{\delta_z}\right)-W=S_s\cdot\frac{\delta_h}{\delta_t}$$

where:

K_{xx}, K_{yy} and K_{zz}	:	hydraulic conductivity along the x, y, z coordinate axes (m/d)
h	:	potentiometric head (m)
W	:	volumetric flux per unit volume (d^{-1})
S_s	:	specific storage (m^{-1})
t	:	time (d)

From the modular MODFLOW package specific modules were used as indicated in table 5.1.

5.4.4 Stresses

Groundwater abstraction and recharge are the main stresses on the aquifer system.

Groundwater abstraction

Well inventories were done in 1978 by Electrowatt (1978), in 1987 by WRAY-3 and in 1991 by WRAY-4 (see appendix 4). The estimated annual groundwater abstraction rates were 29 Mm^3 in 1978, 136 Mm^3 in 1987 and 174 Mm^3 in 1991. In order to calculate the net groundwater abstraction the irrigation efficiency was assumed to be 56% (see also chapter 4).

To obtain annual abstraction rates for the period of 1978 to 1987 the abstraction was assumed to increase in three steps (1978 to 1980, 1981 to 1983 and 1984 to 1986). In the first step the net abstraction rate of 1978 was repeated where in the second and the third steps a net abstraction of one-third and two-thirds of the difference between abstraction rates of 1978 and 1987 were entered. For the period from December 1987 to November 1988 monthly net abstraction data were available from the existing model (Verbeek and te Stroet, 1990).

Table 5.1 MODFLOW modules used in the WRM model.

module abbreviation	meaning	main function
BAS	BASIC	administrative
BCF	Block Centred Flow	calculation of conductance terms
WEL	WELL	input of wells
SIP	Strongly Implicit Procedure	solving sets of mass balance equations
OC	Output Control	output control

The well screens are assumed to be above the Azal Formation (where present). In the remaining area the well screens are assumed to be positioned in the second aquifer to allow maximum drawdown for analysis of the sustainability of the aquifer.

Recharge

Recharge through the wadi bed in the period 1978-1986 can only be approximated. It was assumed that in the beginning of the seventies there was more or less an equilibrium (steady state) between recharge and discharge of the groundwater. It was assumed that recharge took place from the main wadi course, which ends several kilometres outside the study area, and from a major branch south of the main course. The amount of recharge was assumed to decrease gradually in northwards.

From 1986 onwards the amounts of water released from the lake are known. The losses through the wadi bed up to diversion B were estimated from wadi discharge measurements done in 1988 (Appendix 3). During WRAY-3 the distribution of the losses over the wadi was determined by model simulations.

The recharge through the wadi bed was modelled by the WELL package; this is possible because the recharge is independent of the groundwater head.

Figure 12 CALCULATED AND MEASURED GROUNDWATER LEVELS NOV. 1987

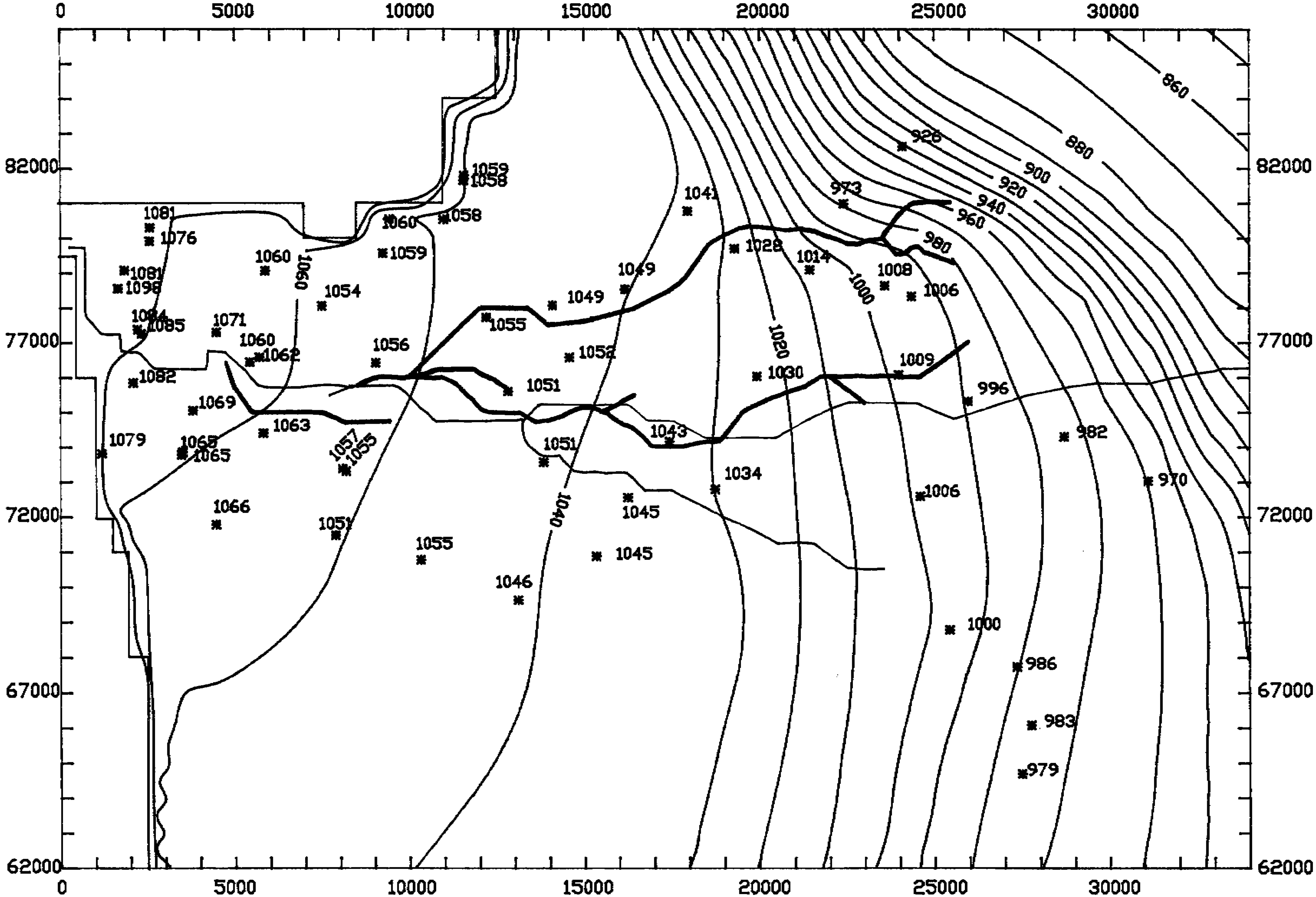


Figure 12. Calculated and measured groundwater levels November 1987

Recharge from rainfall was ignored because of the low rainfall intensity in the area (less than 100 mm per year, Heynert and Uil, 1990). This rainfall evaporates and is lost to the atmosphere.

5.4.5 Calibration

Groundwater levels in the Marib area were measured for the first time in 1978 (Electrowatt, 1978). Monthly groundwater levels are available from 1987 onwards. Initial calibration of the MODFLOW model concentrated on the period 1978-1987. This enabled the slowly reacting groundwater system to be calibrated over a relatively long period. The model was verified with heads measured in 1988, 1989 and 1990.

Initial heads

For the initial heads the 1978 piezometric levels were entered. The data were corrected for the different reference level used by Electrowatt. As these heads cover only the central part of the study area, the initial heads in the outer parts were calculated as follows. First the 1987 heads were used as an indication for the initial heads in 1978. Applying the above-mentioned stresses (groundwater abstraction and recharge) the heads in 1987 were calculated and compared with measured heads. The difference in head between the calculated heads and the measured heads was added to the initial heads.

No information is available on the groundwater levels in the lower aquifer. For the initial heads in the lower aquifer those of the upper aquifer were entered, as there is no layer separating the upper aquifer and the part of the lower aquifer that is assumed to be 'active'.

Calibration on 1987 heads

Stress periods of one year were chosen for the model calibration. After several runs of the model 73 Mm^3 was found to be a reasonable estimate for the natural recharge of the aquifer. This amount was divided over the wadi nodes as described above. The value of 73 Mm^3 was derived from the assumption that in 1978 the aquifer was in steady state and consequently the long-term recharge of the aquifer amounts to the sum of the aquifer discharge (60 Mm^3 per year, Heynert and Uil, 1990) and the annual net abstraction in 1978 of 13 Mm^3. After the closure of the dam in April 1986 and until December 1987 hardly any water was released and recharge from the wadi bed was taken as zero.

Basically the calibration concentrated on the permeability values of the upper aquifer. After approximately 30 runs with various recharge rates and k-value distributions a satisfactory result was obtained. It appears that there is a more or less sectoral division of k-values. High values are found in the southeastern area (35-50 m/d), intermediate k-values in the central part and very low values of 0.01 m/d in the assumed barrier in the northeastern part of the study area.

Figure 12 shows the isohypses derived from the calculated heads in November 1987 and also the measured heads. In general the agreement between calculated heads and measured heads is satisfactory. There are major discrepancies near the dam.

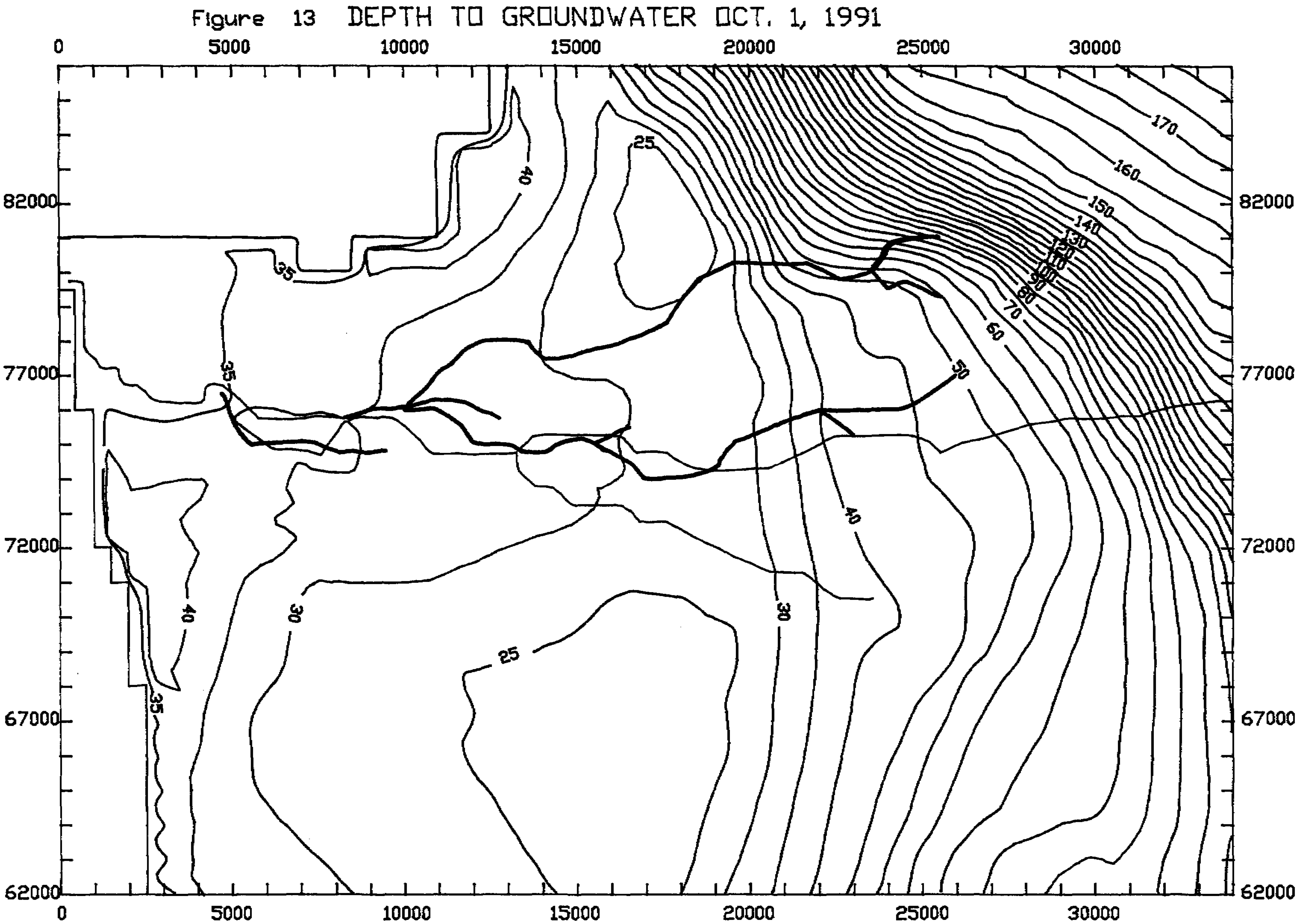


Figure 13. Depth to groundwater (in metres below ground surface) October 1, 1991.

Here the impermeable boundaries probably make the model very sensitive to the actual recharge rate (which is unknown).

Verification using 1988, 1989 and 1990 heads

Large amounts of lake water were released from December 1987 until November 1988. In this period a stress period of one month was chosen, because of the availability of detailed data (Verbeek and te Stroet, 1990). The measured heads of the recharge mound near diversion A were compared with the calculated heads at the end of the recharge period. It appeared that the extension and the maximum height of the recharge mound is reasonably well simulated.

The groundwater heads were also calculated for December 1989 and 1990 and compared with measured data. The calculated isohypses and point measurements agree reasonably. It should be stressed, however, that in the area where no groundwater levels are available, the model is approximate and consequently results are not reliable for remote areas.

5.4.6 Base year and initial conditions

Using the calibrated model the initial heads were calculated for the beginning of the base year October 1, 1991. The depth to groundwater is relevant for pumping costs and is shown in figure 13.

5.4.7 Graphical presentation

The Surfer program (Anonymous,199..) was used to present groundwater level contours and drawdown patterns graphically.

5.5 The economic model

The tasks of the ECOMARIB are:
- to compute the groundwater costs;
- to compute the net economic or financial benefits per irrigation unit;
- to compute the net economic or financial benefits per hectare of 'input' area for each irrigation unit.
- to discount the net benefits over the simulation period to the present value.

ECOMARIB computes the net economic or financial benefits in each year of the simulation from the difference between the revenues and the costs. Revenues and non-water costs are read from the AGRIMAR output files. The cost of pumped groundwater is computed by ECOMARIB by multiplying the total quantity of pumped groundwater by the cost per m^3 which is calculated from the depth to groundwater (see appendix 2). The depth to groundwater at the end of the simulation period is calculated from the initial depth to groundwater for each irrigation unit and from the average drawdown after 25 years calculated by the MODFLOW-model. Linear interpolation between the depths is done by ECOMARIB to estimate the average groundwater depth for a specific year.

The flow of net benefits (NB) over 25 years is converted to a single present value (PV), using an estimated discount rate i. The discounting procedure is as follows:

$$PV = \sum_{n=1}^{n} (NB_n * (1+i)^{1-n})$$

The present value of the total net economic benefits is used to compare the strategies in relation to the objective of maximum economic benefit.

Furthermore ECOMARIB calculates the net benefits per hectare of input area of each irrigation unit, to enable the equity criterion to be calculated. For this calculation financial prices are used.

5.6 The shell

The user interface WRMSHELL was developed to control the different models of the framework and to enter and edit input data and analyse the output data. The WRMSHELL model is menu-driven and uses pull-down menus.

The WRMSHELL model enables the user to:

- enter and edit input data;
- view the fixed input data;
- start the AGRIMAR, MODFLOW and ECOMARIB models;
- analyse the output data.

Furthermore it takes care of:

- the data communication between the different models;
- some error checking of the input data

A normal sequence is to run the AGRIMAR model first, than the MODFLOW model and then the ECOMARIB model. The complete sequence can also be run automatically. For sustainability analysis the long-term option in the geohydrological model has to be chosen.

5.7 Operation of the Water Resources Management model

5.7.1 Fixed and variable input data

The purpose of the Water Resources Management model is to analyse different options for water resources management or development. The model is operated for a specific case, characterized by its input data. The model makes a distinction between fixed data and variable data. Fixed data are the same for all cases and consist of: time series of inflow into the lake, rainfall and evaporation and reference potential evapotranspiration; the crop factors; and the hydraulic parameters of the aquifer. Variable data can be changed depending on the water resources management option(s) to be evaluated or on the availability of information.

The variable data belonging to one case are stored in a case-specific directory. The fixed data are stored in the FIXED directory. The fixed and variable data files are described below. A list of file names with a brief description is shown in table 5.2.

Fixed input data

The crop factor file (CROPFACT.DAT) contains the crop code, the standard length of the growing season in decades and the crop factor in each decade for the main crops in the area. The crop code is a number specific for each crop.

The inflow file (INFLOW.DAT) contains the series of daily surface water inflow into Lake Marib from 1 January 1986 to 31 December 1990.

The rainfall file (RAINFALL.DAT) contains data per decade on precipitation for Al-Gujlah and Marib stations, evaporation from Lake Marib and evapotranspiration in the Marib plain for the period from 1986 to 1990.

Three different hydrological sequences can be selected, an average hydrological sequence, a dry sequence and a wet sequence. The average hydrological sequence file (HYSEQAVE.DAT) consists of the five years for which measured data is available. In the dry hydrological sequence file (HYSEQDRY.DAT) the wettest year (1987) of the five-year series is replaced by the driest year. In the wet hydrological sequence file (HYSEQWET.DAT) the driest year is replaced by the wettest year. To generate a 25-year series the resulting sequences are repeated five times.

Agro-economic data is stored in two files:
The financial file (FINANCE.DAT) contains the present crop yields and the future crop yield projections in tons per hectare for three different soil types. It also contains the current (1991) financial prices in YR per ton and costs in YR per ha for each crop. Besides this it contains data on water costs; the parameters for the groundwater cost calculation and the price of surface water charged to the water users in YR per m^3. Also the cost of structures like secondary canals can be entered, expressed in YR per m^3.
The economic file (ECONOMIC.DAT) contains the same data as the financial file except for the prices and costs for which economic values are entered. Note that these data are fixed in the sense that they are the same for all cases evaluated during this study. However, if new data become available, these files can be edited from the shell menus by the user.

The irrigation units, the wadis and the recharge basins are connected to the groundwater model by 'groundwater nodes', consisting of the layer, row and column numbers of the corresponding grid cells of the groundwater model. The groundwater nodes are stored in the groundwater nodes file (GWNODES.DAT). For each groundwater node the fraction of the total abstraction for the unit or the total recharge from the wadi or in the recharge basin should be given. This enables the distribution of abstraction or recharge to be controlled. The user could change these data from the shell, e.g. if a different location of a recharge basin should be selected, or a different distribution of the wadi losses is assumed.

Variable input data

The irrigation unit file (IRRUNIT.DAT) contains the present and future type of irrigation, the priority level for surface water irrigation and the present depth to groundwater. The present and future values for the area of the unit, the groundwater abstraction capacity, the irrigation losses and the cropping pattern should also be entered. The 'year of completion', in which the irrigation unit changes from 'groundwater unit' to 'conjunctive use unit' should be specified. The file also contains the 'year of maximum development' for each irrigation unit, in which the projected future values for the above- mentioned variables are reached. Present values increase or decrease linearly to the future values.

The calendar file (CALENDER.DAT) contains the crop pattern number, the crop codes sequences and start and end decade of the crop's growing season. A sequence of no more than three crops can be entered for each pattern number.

The fields file (FIELDS.DAT) contains for each irrigation unit the crop pattern number, a soil index indicating the soil type, and the present and future area cultivated by each crop as a percentage of the total unit area.

The reservoir file (RESERVR.DAT) contains the initial, minimum (dead storage) and maximum volumes of the lake, the desired volume (V_{min}) in the lake at the end of each season, the sedimentation rate in mm per year and the infiltration rate in mm per day. The fraction of the available lake volume to be allocated to recharge is also stored in this file, as well as the season in which recharge takes place.

The agricultural option file (AGRIOPT.DAT) contains the start year for simulation, the number of years to be simulated, the start and end decade for the surface water irrigation seasons and the primary source for irrigation in the conjunctive use units (groundwater or surface water). It also contains the parameters indicating the wadi losses. The fraction of the recharge water to be assigned to each of the recharge basins is also stored in this file.

The user selects which fixed hydrological sequence file is to be copied to the case-specific sequence file (HYSEQ.DAT). The same applies to the economic or financial files, which are copied to the case-specific economic file (ECOBEN.DAT).

5.7.2 Description of output

The output data from the Water Resources Management model are stored in the case-specific directory in eleven different files as described below. A list of file names with a brief description is shown in table 5.3.

In the irrigation area file (AGRIAREA.TAB) the areas irrigated with surface water and groundwater per unit for season one and two, and if existing, an intermediate period are summarized. The input area per unit is given, as well as the maximum area that could be cultivated under the selected cropping pattern. Per season the percentage of the input area actually irrigated is also given. Totals per agricultural year and for the simulation period are given, as well as the averages over the simulation period.

In the irrigation units water balance file (AGRIBAL.TAB) the water balance parameters for the irrigation units in Mm^3 are given; rainfall, evapotranspiration, surface water use, groundwater use, irrigation losses and evaporation losses. Totals per agricultural year and for the simulation period are given, as well as the averages over the simulation period.

In the wadi flows and losses file (AGRIFLW.TAB) the discharge in wadi A and B in m^3/s and the losses in both wadis in Mm^3 per decade are stored, as well as the average recharge for each recharge basin for the simulation period. The average flow and the total losses per agricultural year and for the simulation period are given.

Table 5.2 Overview of input files.

Data type	Input file	Description
V	AGRIOPT.DAT	Control data for the AGRIMAR model
F	INFLOW.DAT	Daily lake inflow in m^3/s
F	HYSEQAVE.DAT	Sequence of hydrological years: average
F	HYSEQDRY.DAT	Sequence of hydrological years: dry
F	HYSEQWET.DAT	Sequence of hydrological years: wet
V	HYSEQ.DAT	Sequence of hydrological years as selected by the user
V	RESERVR.DAT	Reservoir operation data of Marib lake
V	IRRUNIT.DAT	Irrigation unit data
V	FIELDS.DAT	Cropping pattern for each irrigation unit
F	RAINFALL.DAT	Rainfall, evaporation and evapotranspiration data per decade
V	CALENDAR.DAT	Cropping calendar
F	CROPFACT.DAT	Crop evapotranspiration data
F	FINANCE.DAT	Financial data on crops and water
F	ECONOMIC.DAT	Economic data on crops and water
V	ECOBEN.DAT	Economic or financial data as selected by the user
A	AGRIMAR.FNM	Description file for AGRIMAR
A	POSTMAR.FNM	Description file for POSTMAR
A	ECOMARIB.FNM	Description file for ECOMARIB
V	GWNODES.DAT	Groundwater nodes connecting AGRIMAR and MODFLOW
M	MODFLOW100.BAS	Basic input file MODFLOW 100 years
M	MODFLOW25.BAS	Basic input file MODFLOW 25 years
M	MODFLOW.BCF	MODFLOW file with hydrogeological parameters
M	MODFLOW25.OC	Output control file 25 years
M	MODFLOW100.OC	Output control file 100 years
M	MODFL.SIP	MODFLOW iteration package

Note: F - Fixed data files (FIXED directory), V - Variable data files (CASE-specific directory), A - Administrative files (CASE-specific directory), M - Modflow files (MODFLOW directory).

In the groundwater abstraction file (AGRIGRW.TAB) the groundwater abstraction, return flow and surface water used in Mm^3 per decade for each unit are stored, as well as the losses in the wadi, the recharge from the recharge basins and the infiltration from the lake.

In the reservoir water balance file (AGRIRES.TAB) the water balance parameters for the lake per decade are stored: the release, the infiltration, rainfall, evaporation, the amount released for recharge and the lake volume. The surface area of the lake and the water level in the lake per decade are also stored. For each agricultural year the sedimentation rate and the spilling volume are given. Totals and averages are given per agricultural year and for the simulation period.

In the revenue file (AGRIYLD1.TAB) the revenues in thousand YR for the summer and winter season and the total annual revenue per unit are stored. Totals are given per agricultural year and for the simulation period.

In the yields per crop file (AGRIYLD2.TAB) yields per crop in tons for the irrigation units are stored. Totals are given per agricultural year and for the simulation period. Average yields per crop and the average revenues per crop for the simulation period are also given.

The revenues, non-water costs and 'input' areas are stored per unit in an administrative file (AGRIYLD3.TAB). This file is not accessible from the shell.

The MODFLOW.WEL file contains the yearly groundwater abstraction and recharge data per groundwater node as computed by POSTMAR from AGRIMAR output data. It is an input file to the MODFLOW model.

The DRAWDOWN.TAB file contains the groundwater drawdowns after the 25 years simulation period. To obtain these data MODFLOW output is read by the postprocessing module POSTMOD and converted to the format needed by ECOMARIB by a small program called CONDD.EXE.

Table 5.3 Overview of output files.

Output file	Description
AGRIRES.TAB	Water balance of lake per decade and yearly summary
AGRIFLW.TAB	Wadi water flows per decade and yearly summary
AGRIBAL.TAB	Water balance per sector and yearly summary
AGRIYLD1.TAB	Revenues in thousand YR per irrigation unit per season and per year
AGRIYLD2.TAB	Yields in tons per crop per year
AGRIYLD3.TAB	Revenues, non-water costs and input area per irrigation unit
AGRIAREA.TAB	Area distribution per year and simulation year
AGRIGRW.TAB	Groundwater abstraction rates
MODFLOW.WEL	Abstractions and return flows per groundwater node
DRAWDOWN.TAB	Drawdowns at the end of a simulation period per node
ECOMARIB.TAB	Economic analysis of the case

The costs and benefits results from the economic model ECOMARIB are stored in the economic file (ECOMARIB.TAB). The costs and benefits will be either financial or economic depending on the user's choice. In this file the input area, the revenues, the non-water costs, the groundwater costs, the surface water costs, the net benefits and the discounted net benefits are given per irrigation unit for the simulation period. The same variables are given per hectare of an irrigation unit. Totals for all irrigation units are also stored.

The MODFLOW.WEL file is the output file from POSTMAR which contains abstractions from and return flows to the groundwater nodes. This file is used as input file by the well package of MODFLOW.

The DRAWDOWN.TAB file is an output file from MODFLOW which contains groundwater level drawdowns at the end of a simulation per node. This file is used by ECOMARIB to determine the costs of pumping groundwater.

6 ANALYSIS OF ALTERNATIVE WATER RESOURCES MANAGEMENT STRATEGIES

6.1 Introduction

In this chapter different water resources management options and strategies are analysed. During the Inception phase the objectives for water resources management were determined and an inventory was made of water resources management options (chapter 3). These options were incorporated in the Water Resources Management model. Before the different strategies were selected a preliminary analysis was done on the main options to assess the effect of each option separately.

6.2 Water resources management options

The main options for water resources management are the following:

6.2.1 Development of the Marib irrigation scheme

The Marib scheme is far from completed. Of the net planned area within the scheme of 6090 ha, only sector A, with a net area of 344 ha, has been completed. Within the scheme area at present 3060 ha are irrigated with groundwater (compared with 4960 ha outside the scheme area). The Al-Maneen area upstream of diversion A, about 128 ha, is irrigated by surface water. For net cultivable areas and areas presently cultivated per irrigation unit see table 4.2.

Several options for further development of the Marib scheme can be considered:

1. No further development. The present cultivated area in sector A (274 ha) is irrigated with surface water in the winter season. The Al-Maneen area is also irrigated with surface water. The remaining cultivated area (at present 8020 ha) is irrigated with groundwater.
2. A partial development of the scheme, including only the sectors that can be irrigated from surface water without any improvement of the wadi and the Al-Maneen area. The World Bank mission (World Bank, 1991) calculated that in a year with an inflow of 104 Mm^3 to the Marib lake, sectors A, 1, 2, 3, 4, 13 and 14 can be irrigated from surface water during the winter season. The net area within these sectors is 1840 ha. The remaining cultivated area (6880 ha) is irrigated with groundwater.
3. A partial development of the scheme, as under 2, while the conveyance efficiency is improved by constructing an earthen canal in the wadi bed. As the improvement is only minor (maximum around 5%), this option was not evaluated.
4. Development of the sectors that can be irrigated by gravity. These are all the planned sectors, except sectors 16, 17 and 18, which are above the level of the primary canal. This option is realistic only if a lined conveyance canal is constructed between the dam and the diversion structures to reduce the wadi losses. The 'spate irrigation unit' Al-Maneen will be served by two branches leaving from the lined conveyance canal between the dam and diversion A. Sectors 12, 20, 21

and 22 are partially covered by sand dunes, and cannot be developed fully. The net area within the scheme will then be 5270 ha. The remaining area to be irrigated solely by groundwater is 5165 ha.

5. Development of the irrigation scheme as planned by Electrowatt, which means that for sectors 16, 17 and 18 the water has to be pumped from the primary canals into the secondary canals.

6.2.2 Development of groundwater abstraction

From the socio-economic survey it became clear that about 40% of the respondents expect to increase the area of their farms. However, they said they had not done so during the last five years, because of the high production costs. This situation could improve, e.g. if less costly surface water becomes available, or if farm revenues increase because of better marketing facilities, or more successful agricultural extension. Additional cultivation of land will lead to increased groundwater abstraction. Several situations will be evaluated:

1. Abstraction capacity within the scheme will remain the same because surface water will be available, but will increase in the area outside the scheme, assuming a linear increase in groundwater abstraction, similar to the increase that occurred from 1987 to 1991. With an annual increase in abstraction of 10^6 m^3/yr the abstraction after 25 years will be 2.4 times the present abstraction. The development of the irrigated area of the groundwater units has also been limited to 2.4 times the present cultivated area. The groundwater-irrigated area will then almost double to 10 440 ha.
2. Abstraction capacity both within and outside the scheme will remain the same as at present. The present abstraction capacity for each irrigation unit is assumed to be twice the present average groundwater use of the unit. The cultivated area will increase within the irrigation scheme only.
3. Abstraction will be restricted to a level that allows sustainable development of the groundwater. This implies that the areas of most irrigation units will also decline. A reduction of the abstraction capacities to 50% of the present capacities (which results in an average abstraction of 70% of the present abstraction) was tested as well as a reduction to 25% (the resulting average abstraction was 35% of the present abstraction).

6.2.3 Type of crops cultivated

During the socio-economic survey most farmers said they had changed their cropping pattern during the last five years, and those located within the irrigation scheme expected to change their cropping pattern in the future, as an increased water availability is foreseen. For initial evaluation with the Water Resources Management model only the following changes in cropping pattern were considered:

1. The present cropping pattern will not undergo any changes.
2. The cropping intensity of the more profitable crops will increase, the cropping intensity of less profitable crops will decrease. For this option the cropping pattern proposed by the World Bank mission (1991), with a cropping intensity of 186%, was entered (see table 6.4).

6.2.4 Surface water allocation within the irrigation scheme

As described in section 4.2.4 several options exist for the allocation of surface water within the scheme if insufficient water is available to irrigate all sectors. Within the Water Resources Management model priority levels can be given to each sector, ranging from 9 to 0, where 9 indicates the highest priority. Numerous combinations are possible. For evaluation the following options were selected:

1. The available water is allocated in proportion to the size of the farms, which in the context of the Water Resources Management model is translated into an allocation proportional to the gross water demand of the irrigation sector.
2. Allocation according to the traditional rules (see table 4.4 and figure 10).
3. Priority to the more downstream sectors, to arrive at a more equitable distribution of benefits. Sectors 7 to 12 and 15 to 22 were given the highest priority level (level 9), followed by sectors 1 to 6, 13 and 14 (level 8). The lowest level was given to sector A and Al-Maneen (level 7).

6.2.5 Surface water allocation to recharge basins

In the present situation the groundwater is recharged upstream of the diversion structures, and by irrigation return flow. As the regional groundwater gradient adjusts very slowly to stresses, the groundwater in the downstream area will for a very long period not 'benefit' from the recharge upstream. Therefore in the Water Resources Management model the option of recharge basins was built in. Many options are possible; between 0 and 5 recharge basins downstream of diversion B can be selected in addition to two recharge basins in the wadi upstream of each diversion structure; the fraction of water to be allocated to each of the basins can be varied; and the amount of surface water in the lake allocated to recharge can be defined as 25, 50, 75 or 100% of the available lake volume.

The irrigation season in which recharge will take place can also be selected, and the presence or absence of a lined canal will affect the location of recharge too. For preliminary evaluation with the Water Resources Management model the following option was selected:

1. Recharge of all of the available lake volume throughout the year, assuming the presence of a lined canal with two recharge basins and 5 recharge basins downstream. 10% of the water to be recharged will be allocated to the basins in the wadi. 10% will be allocated to the basins close to diversion B and 20% to the basins further downstream. In this case the only source of irrigation water is groundwater. Recharge will take place directly after the main inflow periods.
2. Maintain the present situation; recharge of the groundwater resources by infiltration of surface water through the permeable wadi bed.

6.2.6 Length and timing of season(s) in which surface water is allocated for irrigation

Surface water can be allocated during a specific period, e.g. the period in which wheat, potato and barley are grown (winter season), and/or the period in which vegetables are grown (intermediate season), and/or the period in which the other cereals are grown (summer season), or the entire year. The following options were selected for preliminary evaluation:

1. Surface water irrigation in the winter season only.
2. Surface water irrigation during the winter season and the summer season.

6.2.7 Irrigation efficiencies

Irrigation efficiencies can be improved in several ways, varying from a better levelling of the land or using pipes or hoses, to applying drip or sprinkler installations. Several levels of improvement are suggested in the mission report on irrigation and crop aspects (Neefjes, 1991). For evaluation the following options were selected:

1. An improvement in distribution efficiency within the scheme to the distribution efficiency assumed for groundwater irrigation (82%) and a 5% improvement of the field application efficiency for the whole area. Irrigation losses differ under surface water irrigation and under groundwater irrigation, so a weighted average is entered for the conjunctive use units.
2. Maintain the present situation; not improving the irrigation efficiencies favours recharge of the groundwater resources from surface water irrigation 'losses'.

6.2.8 Primary source of irrigation water

The Marib lake or the groundwater reservoir can be selected as a primary source of irrigation water for the irrigation units within the scheme (see section 5.2.1). Using groundwater as a primary source, however, is only realistic in relation to the recharge option mentioned above, in which all surface water is allocated to recharge. No separate option was therefore analysed for this decision variable.

6.3 Scenario conditions

Although, strictly speaking, the time schedules mentioned below for completion of the irrigation scheme and for 'maximum development' of the irrigation sectors are not scenario conditions as defined in subsection 3.2, they were used as such during the strategy analysis.

6.3.1 Year of completion of the irrigation scheme

As nothing is known yet about a time schedule for further development of the irrigation scheme, assumptions had to be made. These assumptions were based on the status of completion of the different irrigation sectors and previous experiences, and are listed in table 4.3.

6.3.2 Year of maximum development

The model allows the values for certain variables to increase linearly from their present values to a certain target value in the 'year of maximum development'. These variables are the net cultivable area (input area), the groundwater abstraction capacity, the irrigation efficiency, the cropping intensity and the crop yield. The year of maximum development can be entered for each irrigation unit, but is similar for all variables mentioned. Assumptions are based on the present state of development of the units and are listed in table 4.3.

6.3.3 Crop yields

Crop yields may improve in the future, e.g. when different varieties of the crop become available or as a result of more successful agricultural extension. In his mission report Neefjes (op.cit.) presents future yield projections for two periods, from 1 to 15 years and from 16 to 30 years (see table 4.8). As the improvement of crop yields is considered to be independent of water management measures, future yield projections are regarded as scenario conditions. The following scenario conditions were tested during the preliminary analysis:

1. Crop yields do not improve.
2. The crop yields projected for 16 to 30 years from now are reached at the end of the simulation period.

6.4 Preliminary analysis of the decision variables

6.4.1 Introduction

The effect of each option should be investigated separately. Therefore for a preliminary analysis, cases were formulated for which only one decision variable is analysed at a time.

6.4.2 Description of the cases

The base case is, by definition, the present situation. In case 1 the development of the irrigation scheme is assumed to be partial, and the conveyance efficiency of the wadi is not improved (option 6.2.1-2). In case 2 the development of all irrigation sectors that can be irrigated by gravity is analysed (option 6.2.1-4).

Case 2 will serve as reference case for evaluating the other options. In the description of the cases given below only the decision variable that is changed with respect to case 2 is discussed. In case 3 to 13 development of the scheme as in case 2 is assumed.

In the first versions of the Water Resources Management model the option to enter a year of maximum development was not yet available. Therefore in the cases where the effect of a different groundwater abstraction, an increased irrigation efficiency or a different cropping pattern were evaluated, these values were entered as if they had been valid from the base year. The only exception is case 11, which was added later, where the input areas of the irrigation units increase linearly from their present values to their maximum values in the year of maximum development. In earlier versions, however, it was possible to enter present and future crop yields, and so the future yields were reached at the end of the simulation period. Most cases were run using this scenario (6.3.3-2), except the base case and case 13, where crop yields were assumed to maintain their present values (6.3.3-1).

The option to enter the year of completion of an irrigation sector was not available until the final version of the Water Resources Management model, and therefore calculations for cases 1 to 13 took place with a year of completion equal to the base year.

Table 6.1 presents the options selected for the different decision variables for each case. In this table the option that is analysed in each case appears in bold print.

BASE CASE
The base case is an extension of the present situation to the entire period of analysis, so for all decision variables the present situation is entered (see table 4.2). Surface water irrigation will take place in the winter season only. The maximum capacity of groundwater abstraction has been determined in such a way that for every hydrological year the present cultivated area can be irrigated fully.

Note that a medium amount of recharge is allocated to the wadi. This is done to simulate the irrigation practices of ERADA. The gross water demand in the present situation is so small that a release of less than 1 m^3/s is required. At present ERADA releases about 2 to 2.5 m^3/s during the winter season.

CASE 0.
As the base case, but with modified scenario conditions. In this case the effect of an increase in crop yields on the benefits is evaluated, while all other variables remain the same as in the base case. A linear increase is assumed from the present values to the values projected for the period of 16 to 30 years from now, which are reached at the end of the simulation period (scenario 6.3.3-2).

CASE 1.
In case 1 a partial development of the irrigation scheme is assumed, with no improvement in conveyance efficiency of the wadi (option 6.2.1-4). Sectors A, 1, 2, 3, 4, 13 and 14 are assumed to be completed in the base year. For the sectors irrigated by surface water, development of the total net area is assumed. The irrigation losses for the conjunctive use units are a weighted average of the losses under surface water irrigation and under groundwater irrigation. All other decision variables have present values. Irrigation with surface water takes place during the winter season only.

Table 6.1 Main features of the defined cases.

CASE no.	Development of irrigation scheme	Net input area irrigation units	Groundwater abstraction capacity (Mm^3/year)	Irrigation losses	P[1]	R[2]
BASE	**no**	**sector A 275 ha, rest 8060 ha**	present	sector A[3] rest 0.44	S	2
CASE 0	no	see base case	present	sector A[3] rest 0.44	S	2
CASE 1	**partial**	**sector A,1,2, 3,13,14 1840 ha; rest 7000 ha**	present	sector A,1,2, 3,4,5,13,14[3] rest 0.44	S	-
CASE 2	**full minus sectors 16/17/18**	**sectors 5270 ha; rest 5200 ha**	present	sectors[3] rest 0.44	S	-
CASE 3	see case 2	**sectors 5270 ha; rest 10 440 ha[4]**	**sectors pres.; rest max.[4]**	see case 2	S	-
CASE 4	see case 2	see case 2	present	see case 2	S	-
CASE 5	see case 2	see case 2	present	see case 2	S	-
CASE 6	see case 2	see case 2	present	see case 2	S	-
CASE 7	see case 2	see case 2	present	see case 2	G	4
CASE 8	see case 2	see case 2	**50% of present**	see case 2	S	-
CASE 9	see case 2	see case 2	present	see case 2	S	-
CASE 10	see case 2	see case 2	present	**improved[3]**	S	-
CASE 11	**no**	**start: pres. then linear to 15 190 ha[5]**	**unlimited**	see case 2	G	4
CASE 12	see case 2	see case 2	**25% of present**	see case 2	S	-
CASE 13	see case 2	see case 2	present	see case 2	S	-

Notes:

1. Primary source; S - surface water, G - groundwater
2. Recharge during winter season:
   2 = 50% of available lake volume
   4 = 100% of available lake volume
3. Weighted average of surface water irrigation losses and groundwater irrigation losses;
4. Area and abstraction capacity increased to 2.4 times the present value;
5. Area increase linear to 2.4 times the present value in the 'year of maximum development' (YMD);
6. Year of maximum development is given in table 4.3.

Table 6.1 (continued)

CASE no.	Conveyance	Priority of allocation	Season with surface water irrigation or recharge	Cropping pattern	Crop yield	Year max dev.
BASE	**wadi**	equal	winter	present	start: pres. end: pres.	1991
CASE 0	wadi	equal	winter	present	**start: pres. end: future**	1991
CASE 1	wadi	equal	winter	present	see case 0	1991
CASE 2	**lined canal**	equal	winter	present	see case 0	1991
CASE 3	lined canal	equal	winter	present	see case 0	1991
CASE 4	lined canal	equal	winter	**'World Bank'**	see case 0	1991
CASE 5	lined canal	**first-first**	winter	present	see case 0	1991
CASE 6	lined canal	**last-first**	winter	present	see case 0	1991
CASE 7	lined canal	equal	**whole year**	present	see case 0	1991
CASE 8	lined canal	equal	winter	present	see case 0	1991
CASE 9	lined canal	equal	**winter and summer**	present	see case 0	1991
CASE 10	lined canal	equal	winter	present	see case 0	1991
CASE 11	lined canal	equal	winter	present	see case 0	**YMD**[6]
CASE 12	lined canal	equal	winter	present	see case 0	1991
CASE 13	lined canal	equal	winter	present	**start: pres. end: pres.**	1991

CASE 2 : REFERENCE CASE
Full development of the irrigation scheme is assumed, excluding sectors 16, 17 and 18 (option 6.2.1-4). For all sectors, development of the total net area is assumed. Sectors are assumed to be completed from the base year. Irrigation losses for all sectors are entered as weighted averages of surface water irrigation losses and groundwater irrigation losses. All other decision variables have present values, surface water irrigation takes place during the winter season only.

CASE 3.
As case 2, except that in this case the effects of increased groundwater abstraction are evaluated. Groundwater abstraction capacity remains at present values for the completed irrigation sectors, but has maximum values in the groundwater units. These maximum values are based on the measured annual increase, but cannot be more than 2.4 times the present values (option 6.2.2-1). The maximum values are valid from the base year.

CASE 4.
As case 2, except that here the effects of a more profitable cropping pattern are analysed. The cropping pattern entered is the one proposed by the World Bank mission (1991) (option 6.2.3-2). For the purpose of this analysis this cropping pattern was entered from the base year onwards.

CASE 5.
As case 2, except that in this case the effects of surface water allocation according to traditional rules is evaluated (option 6.2.4-2).

CASE 6.
As case 2, but with the modification that downstream irrigation sectors have highest priority for surface water allocation (option 6.2.4-3).

CASE 7.
As case 2, but modified such that the effects of allocating all surface water to the recharge basins (option 6.2.5-1) can be evaluated. The recharge takes place during throughout the year. As the Water Resources Management model requires that 'seasons' are selected and because the major inflow into the Marib lake occurs during February, March and April, the first 'recharge season' starts on 10 May and ends on 9 September. The inflow that occurs during the summer months is released during the second 'recharge' season which covers the remainder of the agricultural year. All irrigation units use groundwater only.

CASE 8.
As case 2, but the groundwater abstraction capacity is reduced to 50% of the present abstraction capacity (option 6.2.2-3), so that the effects of reduced groundwater abstraction can be analysed.

CASE 9.
As case 2, except that surface water is allocated both in the winter season and in the summer season (option 6.2.6-2).

CASE 10.
As case 2, but irrigation efficiencies are improved (option 6.2.7-1). Distribution efficiency is assumed to be 82% and all field application efficiencies are increased by 5%. For the present values of the irrigation efficiencies see table 4.2.

CASE 11.
In this case the effect of allocating all surface water to recharge is evaluated. The scheme is not further developed, but to allow for allocation to the downstream recharge basins a lined canal is assumed to be present. All irrigation units use groundwater only. The cultivable areas of the irrigation units increase linearly from their present values to their maximum values in the year of maximum development. Groundwater abstraction capacity is unlimited.

CASE 12.
As case 2, except that groundwater abstraction capacity is reduced to 25% of the present capacity (option 6.2.2-3).

CASE 13.
As case 2, but crop yields remain at present values (scenario 6.3.3-1).

6.4.3 Analysis of the cases

The main results of the cases are summarized in Appendix 7, tables A7.1, A7.2 and A7.3.

Total benefits, irrigated areas and water balance terms

In the first section of table A7.1, the total discounted net economic benefits and the net economic benefits divided by the total irrigable area (the input area) of the irrigation units are given per case. Note that costs of structures and of operation and maintenance of the scheme have not been included in any of the cases that assume completion of the irrigation scheme.

In the second section the input area is given (the total area cultivated at present and/or the total net cultivable area, depending on the case in question), as well as the total area cultivated (the sum of the areas irrigated in both seasons), the areas irrigated with surface water and with groundwater for each season, and the percentage of the 'input' area irrigated for each season.

In the third section of table A7.1 the main components of the water balance for the irrigation units have been given, as well as the evaporation from the Marib lake. Except for the 'input' area the figures in the second and third sections are mean values for the total simulation period.

Distribution of benefits

In order to analyse the distribution of net financial benefits over the irrigation units, table A7.2 gives the discounted net financial benefits per hectare for each irrigation unit, as well as the coefficient of variation of the financial benefits for each case. Investment costs and recurrent costs of operation and maintenance of the scheme have been ignored.

Sustainability

To evaluate the sustainability of the groundwater resources for the different cases, the drawdown over a period of 100 years starting with the base year was calculated for all cases. The areal distribution of drawdown was plotted and the area with drawdown values exceeding 50 m was computed. The value of 50 m was selected because the water-bearing thickness in the upstream area, where the Azal formation is absent, and in the central area, where the Azal formation is relatively close to the surface, is currently a maximum of 50 m. When drawdowns of more than 50 m occur in these areas the groundwater can no longer flow downstream, and the groundwater flow system is severely disrupted.

For cases 3, 4 and 11 the MODFLOW iteration procedure did not converge within 100 years, not even for various acceleration parameters (McDonald and Harbaugh, 1988), because the area where the upper aquifer fell dry became too big before the end of the simulation period. So for these cases of large abstraction the drawdown could only be calculated after a restricted period. A period of 50 years was selected. In table A7.3 the area with a drawdown of more than 50 m is given for both periods (50 and 100 years) in ha as well as a percentage of total area of the aquifer. The total study area is 81 600 ha. About 8850 ha is occupied by impermeable hardrock, leaving a total area of aquifer of 72 750 ha. This area contains mainly fresh groundwater, except for the part south of wadi Masil.

6.4.4 Discussion of results

To facilitate analysis of the results according to the criteria defined for the adopted objectives (see section 3.3.4) the results for each objective were ranked in 5 classes, and a score table was prepared (see table 6.2).

Benefits

The total discounted economic benefits per case mainly depend on the total area cultivated, the crop yields and the cropping pattern.

A comparison of the base case and case 13 (whose crop yields remain at present values) with cases 0 and 2 (whose crop yields increase linearly to projected future values) clearly shows the effect of the crop yields on the benefits. The discounted economic benefits over the simulation period are 2 to 3 times higher when crop yields are assumed to increase.

The economic effect of implementing a cropping pattern with a higher cropping intensity on the benefits is clearly visible if case 4 is compared with case 2. In case 4, the cropping pattern as suggested by the World Bank was entered, with a cropping intensity of 186%, while case 2 was run with the present cropping pattern with an average cropping intensity of 122%. The total discounted benefits in the 'World Bank case' are almost double those in case 2.

The economic effect of enlarging the total irrigated area can be seen when case 2 is compared with case 3, which has a larger irrigated area. The benefits of case 2 have been classified as moderate, those of case 3 as high. Total benefits for case 10 are slightly higher than for case 2 because a larger area is irrigated with surface water due to improved irrigation efficiencies.

Table 6.2 The scores assigned to the cases analysed on the basis of their results.

CASE	Benefits	Surface water irrigated area	Equity	Sustainability
BASE	--	--	--	-
CASE 0	0	--	-	-
CASE 1	0	-	-	-
CASE 2	0	+	-	-
CASE 3	+	+	-	--
CASE 4	++	+	++	--
CASE 5	+	+	-	-
CASE 6	+	+	-	-
CASE 7	0	--	-	--
CASE 8	0	+	0	0
CASE 9	0	0	-	--
CASE 10	+	++	-	-
CASE 11	+	--	-	--
CASE 12	--	+	0	++
CASE 13	--	+	--	-
criterion	10^6 YR	ha	coeff. of variation	% of aquifer lost
--	<1000	<500	>1.0	>40
-	1000-1500	500-1000	0.8-1.0	10-40
0	1500-2000	1000-2500	0.6-0.8	5-10
+	2000-3000	2500-3000	0.4-0.6	
++	>3000	>3000	<0.4	<5
-- = very low - = low 0 = moderate + = high ++ = very high				

Completing the Marib irrigation scheme has less impact on the benefits than the above-mentioned factors. This can be seen by comparing case 13 with the base case, or case 2 with case 0. In case 13 and case 2 completion was assumed from the base year, and investment costs and costs of operation and maintenance were not taken into account. The increase in the economic benefits due to completion of the scheme over the 25-year simulation period after discounting is 109 million YR for case 13 and 156 million YR for case 2. The difference in financial prices is respectively 225 and 316 million YR. Rough estimates show that the investment required to complete the secondary canals that have not yet to be completed and to construct a lined conveyance canal exceeds 300 million YR.
The operation and maintenance costs during 1992 were about 1.3 million YR (financial prices) which is about 0.45 YR per cubic metre of surface water. If this value is entered in the model it calculates discounted costs of operation and maintenance of about 185 million YR over the 25-year

simulation period. This indicates that even if all investment costs yet to be incurred for completion of the scheme are regarded as sunk costs, the costs of operation and maintenance exceed the economic benefits of the irrigation scheme and are only slightly less than the financial benefits.

Area irrigated

For each irrigation unit and for each season the Water Resources Management model calculates the areas that can be irrigated with surface water and/or with groundwater. The extent of the area that can be irrigated depends on the input areas (the net planned areas), the cropping pattern and the availability of irrigation water.

The groundwater abstraction capacities were selected such that in the present situation (the base case) the present cultivated area would receive sufficient irrigation water during both seasons throughout the whole simulation period of 25 years (the capacities turned out to be about twice the average present groundwater use).

During the winter in most cases the area planned for this season is irrigated fully, using surface water and groundwater. In case 7 (where all available surface water is allocated to the recharge basins) 90% of the planned area is irrigated and in case 12 (for which the average groundwater abstraction over the simulation period is 35% of the average present abstraction) the corresponding figure is 80%. In case 4, with the 'World Bank' cropping pattern the figure is 91%. The area that can be irrigated with surface water is, on average, about 3000 ha. If irrigation efficiencies are improved (case 10) this area can be slightly increased to about 3300 ha.

In the case of partial development of the irrigation scheme, conveyance of released water through the wadi, and present cropping patterns (case 1), about 65% of the net area of the completed sectors (sectors A, 1 to 4, 13, 14) can be supplied with surface water during the winter season.

In the cases where all irrigation sectors are developed (except for sectors 16, 17 and 18), and a lined conveyance canal is constructed, with the present cropping patterns, on average about 88% of the area of the sectors can be irrigated with surface water in the winter season. If irrigation efficiencies are improved (case 10), this figure is 97%.

If, however, the more water demanding 'World Bank' cropping pattern is implemented (case 4), the area that can be irrigated during the winter season with surface water decreases to around 57% of the area planned for cultivation. In the latter case in the downstream sectors the present groundwater abstraction capacities are insufficient to supplement the additional demand for water, and the area that can be irrigated with both surface water and groundwater is only 80% of the planned net area.

In case 5, where priorities for surface water allocation were entered according to the traditional water rights, and in case 6, with priorities shifted to the downstream sectors, the area irrigated during the winter season as a percentage of the net planned area per irrigation sector obviously depends on the priority level (see table 4.4 and figure 10). In case 5 the sectors with priorities 9 to 6 are irrigated with surface water only. For the sectors with priorities 5 to 3 the surface water irrigated area is about 95% of the net area. Only 65% of the area in the sectors with priority level 2 can be irrigated with surface water. In case 6 the gross water demand of the downstream sectors is fully satisfied, while in the sectors with priority level 8 the surface water irrigated area is 84% of the net area and in the sectors with priority level 7 it is 54%.

During the summer season in most cases (except the base case) the gross crop water demand exceeds the groundwater abstraction capacities entered. With the present cropping pattern, on average only 80% of the planned summer area can be irrigated. A slightly higher percentage is achieved (85% of planned summer area) if the irrigation efficiencies are improved (case 10). With the cropping pattern proposed by the World Bank the area irrigated during the summer season will be only 54% of the area planned for this season (case 4). In cases 8 and 12, with average groundwater abstractions of respectively 70% and 35% of the average present abstraction, respectively 52% and 26% of the planned summer area obtains sufficient irrigation water.

Equity

To evaluate the distribution of the benefits over the irrigation units the discounted net financial benefits per unit were calculated per hectare of their input areas. It appears that the irrigation units further upstream have much higher benefits than the downstream units. Several aspects influence the costs and benefits:

Revenues depend on the crop yields, the cropping pattern and the irrigated area. As well as depending on the assumptions regarding the future yields, the crop yields depend on the soil type in the irrigation unit. In general the soil in the upstream area is better than further downstream. In the downstream units the cropping intensity is often low, and profitable crops like citrus are hardly grown. The importance of this aspect can be seen by comparing case 4 (a uniform cropping pattern and cropping intensity) with the other cases with the present cropping pattern. The extent of the irrigated area in the downstream units is influenced by the assumptions about the groundwater abstraction capacities; when the gap between the present cultivated area and the net planned areas (the input area) is big, as it is in most downstream units, the area that can be irrigated is limited because the abstraction capacities are limited to present or lower values.

Non-water costs per irrigation unit depend on the cropping pattern and the irrigated area.

The groundwater costs in the irrigation units are related to the initial depth to groundwater and the drawdown during the simulation period and to the amount of groundwater abstracted. Although groundwater abstractions and drawdowns are greater in the upstream part of the area, the groundwater costs here are less than downstream because of the smaller initial depth to groundwater. For instance, under case 2 the drawdown in groundwater unit 2 at the end of the short-term simulation period is about 40 m, while in groundwater unit 6 it is only 9 m. With an initial depth to groundwater of 30 m in unit 2 and of 99 m in unit 6 this results in the cost of groundwater increasing from 0.58 to 1.32 YR/m^3 in unit 2 and from 1.8 to 1.96 YR/m^3 during the simulation period.

It is important to note that although the total benefits increase if an increase in input area and groundwater abstraction is allowed (as in case 3), the benefits per hectare decrease, because of increasing groundwater costs (compares case 2 and 3 in table A7.2). The opposite is true in the units with deep initial groundwater levels, where groundwater abstraction is decreased; units 15 to 21 have the highest (or least negative) benefits in case 8, where abstraction capacities are cut to 50% of their present values.

It was beyond the scope of this study to evaluate the development of costs and benefits for the different units in the different cases in detail. The equitability of the distribution of benefits was evaluated by calculating the coefficient of variation of the net financial benefits per irrigation unit for each case. None of the cases appear very equitable, except case 4 and - to a lesser extent - cases 8 and 12. The uniformity of the cropping pattern in case 4 levels out the variability caused by the present different cropping patterns. In cases 8 and 12 the reduction of groundwater abstraction favours the conjunctive use units within the irrigation scheme. The effect of different priority levels for surface water allocation as entered in case 5 (priorities according to traditional rules) and in case 6 (priority for the downstream sectors) on the benefits per hectare is minimal; the differences in groundwater costs are virtually overruled by the variability in the revenues.

Sustainability

In most cases after 50 years about 3% of the upper aquifer has fallen dry. However, this occurs in areas at the southeastern boundaries of the aquifer, where the Amran limestones are close to the surface. In cases 3 and 11, which allow increase of groundwater abstraction, respectively 13% and 29% of the aquifer will fall dry. The large groundwater abstraction in the 'World Bank' case (40% more than the present average abstraction) causes 20% of the upper aquifer to fall dry. For the latter cases the MODFLOW model could not calculate the results after 100 years, as the extent of area falling dry prevented the model from converging. For most other cases between 30% and 40% of the upper aquifer is lost after 100 years.

In case 8, where the average groundwater use is 70% of the present average use, 8% of the aquifer falls dry. In case 12, where abstraction has been reduced to a sustainable level in the sense that groundwater abstractions are equal to groundwater recharge, in most of the aquifer drawdowns stabilize at circa 25 m below the present groundwater level.

The location of the areas fallen dry should also be taken into consideration. In the cases where irrigation water takes is conveyed through the wadi (base case and case 1) drawdowns in the upstream part of the aquifer range between 20 and 40 m. In these cases parts of the aquifer run dry in the downstream part of the study area. All cases where a lined conveyance canal is assumed (cases 2 to 13), excluding case 12, show drawdowns between 60 and 100 m in the upstream area, which means that in all these cases no groundwater flows downstream anymore.

Allocating all surface water to recharge basins does not have a positive effect on the sustainability (case 7). Although the water balance for the whole aquifer for this case indicates that the excess of groundwater abstraction over recharge is similar to e.g. case 2, in the latter case 36% of the upper aquifer is lost after 100 years, whereas in case 7 the figure is 49%. The reason is that recharge through recharge basins is a very local phenomenon in a slowly reacting groundwater system, and is less effective than recharge from irrigation losses spread out over the entire irrigation scheme.

It should be re-emphasized that sustainability in the true sense of the word is only achieved in case 12, where the average groundwater abstraction is equal to the groundwater recharge. The approach to evaluating 'sustainability' in this study is pragmatic, aiming at highlighting the effect of different water resources management options on the groundwater resources, and at enabling the effect of different options to be compared.

Additional remarks

An indication of the efficiency of reservoir operation can be obtained from the amount of evaporation that occurs in different cases. Over the whole simulation period on average $29*10^6$ m^3 evaporates per year, which is 34% of the average annual inflow over the simulation period. In the base case and in case 10 the average annual evaporation is slightly higher (39% of the average annual inflow), as in these cases less surface water is used. In case 9, where surface water irrigation takes place in two seasons the average annual evaporation is 29% of the average annual inflow. In case 7, where all surface water is released directly after the periods in which inflow occurs, the average annual evaporation from the lake is $15*10^6$ m^3, which is 15% of the average annual inflow. The Water Resources Management model is set up such that surface water is released evenly over the defined season. Evaporation will decline even more when all surface water is released as soon as possible (with maximum gate opening). It is not possible to evaluate this option with the Water Resources Management model (see section 5.2). Spreadsheet computations show, however, that in this case the average annual evaporation is circa $8*10^6$ m^3, which is 9% of the average annual inflow.

In the present situation the model calculates that about one-third of the irrigation units have negative financial benefits. This raises the question of whether the farmers themselves experience these negative benefits. From the socio-economic survey it appeared that many farmers are dissatisfied with the benefits they gain from their work. Most of the farmers interviewed complain about diesel prices and the cost of spare parts. They do not seem to feel they are loosing so much that they should stop farming. There is possibly a subjective reason for this; they do not take the depreciation of their investments into account.
The model does not include a water quality module. However, a simple water balance calculation shows that the volume of fresh groundwater that can be abstracted is about $6 * 10^9$ cubic metres. With an annual overabstraction of about 60 million cubic meter this indicates that within 100 years fresh groundwater resources will be depleted. Locally, fresh groundwater may be replaced by brackish groundwater much sooner.

Table 6.3 Effects of different water resources management options on objectives.

objective / option	maximize benefits	maximize surface water irrigated area	maximize equity	maximize sustainability
no development of irrigation scheme	-	-	-	-
partial development of irrigation scheme	+	+	0	+
full development of irrigation scheme	+	+	+	+
lined conveyance canal (no recharge basins)	+	+	+	-
recharge to downstream basins	-	-	-	-
recharge to upstream basins	-	-	-	+
increased groundwater abstraction	+	0	-	-
decreased groundwater abstraction	-	0	+	+
increased crop yields	+	0	+	0
more profitable cropping pattern	+	0	+	-
improved irrigation efficiencies	+	+	+	-
allocation according to traditional rules	0	0	0	0
allocation priority to downstream sectors	0	0	0	0
surface water irrigation in winter and summer seasons	-	-	-	0
+ = positive effect	0 = no effect		- = negative effect	

Conclusions

The effect of the different water resources management options on the objectives have been summarized in table 6.3.

- In the case of a partial development of the scheme, with conveyance through the wadi bed, about 1000 ha can be irrigated with surface water. The total irrigated area hardly increases (by 200 ha only) with respect to the present cultivated area.

- In case of full development of the scheme, with the construction of a lined conveyance canal, about 3000 ha can be irrigated with surface water. The total irrigated area in both seasons increases by 1200 ha when present groundwater abstraction capacities are maintained, because in the summer season the present groundwater abstraction capacity is less than the gross water demand. The economic gains do not seem to exceed the estimated construction costs of the remaining secondary canals and the lined conveyance canal, nor the estimated recurrent costs of operation and maintenance. Thus, full development of the scheme can only be justified by reasons that are other than economic.

- The construction of a lined conveyance canal has a positive effect on the groundwater level in the downstream part of the aquifer, as the water 'lost' under surface water irrigation will recharge the aquifer. In the upstream area the effect of a lined canal is negative in this respect, as hardly any upstream recharge occurs. Conveyance through a lined canal should therefore be accompanied by recharge in the wadi upstream of the diversion structures.

- If abstraction rates remain at current levels and a lined conveyance canal is constructed, after 100 years large areas in the upstream part of the upper aquifer will be dry. In cases with abstraction rates higher than present, such as case 4, with the 'World Bank' cropping pattern, or cases 3 and 11, where an increase in groundwater abstraction is assumed, large areas in this part of the aquifer fall dry within 50 years of the base year.

- The effect of local recharge through recharge basins located downstream of diversion B on the sustainability is negative, compared with the recharge over the entire area of the irrigation scheme from surface water irrigation losses.

- Although an increase in groundwater abstraction at the rate of recent years results in higher total benefits, because the irrigated area increases, the benefits per hectare decrease, because of increasing groundwater costs. For example in case 3, with an increase in groundwater abstraction to 150% of the present average abstraction, the benefits per hectare fall to about 90% of their values under case 2.

- If the aim is a 'sustainable' development of the groundwater resources - in the sense that in the upstream part of the first aquifer at least a few metres of groundwater are left in the long run - the groundwater abstraction will have to be reduced to about 70% of the present average use in the near future. A sustainable development in the true sense of the word (case 12) requires a reduction in groundwater abstraction to about 35% of the present average use.

- A reduction in groundwater abstraction has a negative effect on the total benefits, but a positive effect on the benefits per hectare in the downstream units, and therefore a positive effect on equity. A comparison of case 2 (present average abstraction), case 8 (abstraction 70% of present average) and case 12 (abstraction 35% of present average) indicates that this effect is greatest under the greatest reduction.

- Improving crop yields increases the total benefits significantly. It also has a positive effect on equity, as the increase in the groundwater cost component is smaller than the increase in revenues.

- Improving the cropping pattern has a positive effect on the total benefits. As implementing a similar cropping pattern also rules out the present variation, this scores high on equity too. Implementing the 'World Bank' cropping pattern has very negative effects on sustainability, because of its high water demand.

- Improving surface water irrigation efficiencies has a positive effect on the amount of area that can be irrigated with surface water and on the benefits per hectare, but a negative effect on the sustainability of the groundwater resources, because there is less recharge.

- Evaporation from the lake decreases only slightly, from 34% to 29% of the average annual inflow, if surface water irrigation takes place during two seasons, but decreases to 15% if all surface water is allocated to recharge during two seasons. If all surface water is released at maximum gate capacity the average evaporation decreases to 9% of the average annual inflow.

- Different priorities for surface water allocation, whether according to the traditional rules or with higher priorities for the downstream sectors, hardly affect the distribution of benefits. The effect on the groundwater costs is overruled by the variability in revenues because of different cropping patterns, different yields from different soil types, and different groundwater levels.

6.5 Strategies

6.5.1 Introduction

Five strategies were formulated according to the adopted objectives, taking into account the results of the preliminary analysis of the decision variables. The preliminary analysis indicates that the evaporation from the Marib reservoir can be reduced to about 15% of the average annual inflow, if the water is allocated directly after the main inflow season. Therefore one strategy was added, with the objective of improving the operation of the Marib reservoir.

Strategy 1: Maximizing the sustainability of the groundwater resources.
Strategy 2: Maximizing the benefits.
Strategy 3: Achieving a more equitable distribution of benefits.
Strategy 4: Satisfying both the objective of maximizing benefits and the objective of sustainability.
Strategy 5: Maximizing both equity and sustainability.
Strategy 6: Decreasing evaporation from Marib reservoir.

6.5.2 Description of the strategies

Further development of the Marib irrigation scheme is assumed in all strategies, even though there may be no economic justification for this.

This is done because the decision-makers want to complete what has been started and meet the expectations raised among the farmers in the Marib area, which is reflected in their objective of maximizing the surface water irrigated area. Furthermore, further development favours a sustainable development of the groundwater resources and a more equitable distribution of water-related benefits. The assumed timepath for further development of the scheme is described in section 4.2.4 and presented in table 4.3. All sectors of the irrigation scheme are included in all strategies, because the distribution of the benefits is fairest if all irrigation sectors receive surface water and the sustainability of the groundwater resources is most assured if recharge is spread over the entire area of the irrigation scheme. Investments and the costs of operation and maintenance of the irrigation scheme have not been included in the calculations.

Another water resources management measure included in all strategies is a reduction in groundwater abstraction capacity in order not to exhaust the upper aquifer. Reductions range from 25% (strategy 1) to 50% (strategies 2 and 3) of the present capacities (which are estimated to be about twice the present average groundwater use, see table 4.2).

In strategies 1 to 5 surface water irrigation will take place during the winter season, from 20 September to 20 February. In order to allow for recharge of the upstream part of the aquifer in these strategies a 'small' or 'moderate' amount of surface water (25% or 50% of the lake volume available at the beginning of a season respectively) is allocated to two recharge basins in the wadi, upstream of the two diversion structures. In strategy 6 surface water is allocated to irrigation directly after the main inflow season, starting 1 May. It is assumed that sesame, sorghum and tomatoes are grown from 1 May instead of earlier in the year, in addition to the perennial crops citrus and alfalfa. During the winter season, defined from 20 September to 30 April in this strategy, all surface water is allocated to the recharge basins in the wadi, and wheat, potato and watermelon, as well as citrus and alfalfa, are irrigated from groundwater.

To arrive at a cropping pattern that is more beneficial than the average present cropping pattern, but less water-consuming than the one proposed by the World Bank, an 'improved' cropping pattern has been selected. This cropping pattern is given in table 6.4 with the other cropping patterns mentioned. Its implementation is assumed in all strategies except those aiming at maximizing benefits (the second, fifth and sixth strategies), where the 'World Bank' cropping pattern is applied.

Improvement of irrigation efficiencies is opted for only in the strategies where sustainability of the groundwater resources is not a major objective (second and third strategies). Field application efficiency is assumed to increase by 5% and distribution efficiency to 82.5%. The present irrigation efficiencies are given in table 4.2. As surface water and groundwater irrigation efficiencies are different, a weighted average of both is entered for the completed irrigation sectors.

Table 6.4 Average present cropping pattern, 'World Bank' cropping pattern and 'improved' cropping pattern in%.

crop	average present cropping pattern	'World Bank' cropping pattern	'improved' cropping pattern
citrus	9	30	15
wheat	48	50	50
sesame	26	8	10
sorghum	7	8	10
maize	4	--	4
tomato	10	26 (tomato and watermelon)	10
watermelon	2		5
potato	3	6	5
alfalfa	3	14	2

All decision variables have present values in the base year and increase or decrease linearly to their future value in the 'year of maximum development'. Surface water irrigation in each irrigation sector starts in the 'year of completion' (see table 4.3). The values for the main decision variables for each strategies are presented in table 6.5.

STRATEGY 1: 'Maximize sustainability'

In strategy 1 'true' sustainability of the groundwater resources is aimed at; groundwater abstraction is equal to groundwater recharge. To achieve this, groundwater abstraction has been reduced to about half of the present average use (see table 4.2). This has been done by reducing the present abstraction capacities to 25%. Furthermore the following water resources management measures are assumed:

- Irrigation efficiencies are not improved, to allow for maximum recharge.
- The 'improved' cropping pattern is implemented.
- A 'small' amount of the available lake volume is allocated to the recharge basins in the wadi during the irrigation season, to sustain the upstream part of the upper aquifer.

STRATEGY 2: 'Maximize benefits'

Strategy 2 consists of measures aiming at maximizing benefits. For this the present cropping pattern is assumed to change gradually to the cropping pattern as proposed by the World Bank mission (1991), which will be fully implemented in the 'year of maximum development' for each sector. The reduction in groundwater abstraction capacities is less than in the other strategies; 50% of the estimated present groundwater abstraction, resulting in an average groundwater abstraction that is 85% of the present abstraction. Furthermore:

- Irrigation efficiencies will be improved, to increase the surface water irrigated area, which will have a positive effect on the

groundwater costs.
- Recharge during the winter season is 'small'.

STRATEGY 3: 'Maximize equity'

From the preliminary analysis it appeared that in most cases the downstream sectors have low or negative benefits. In order to increase their benefits these sectors are given the highest priority for surface water allocation. In addition to this:
- Groundwater abstraction capacities are reduced to 50% of the estimated present capacities, resulting in an average groundwater abstraction that is 78% of the present abstraction, as a reduction in groundwater abstraction proved to have a positive effect on the benefits in the downstream sectors.
- Irrigation efficiencies will be improved, to reduce groundwater costs.
- The 'improved' cropping pattern will be implemented.
- A 'small' recharge is applied.

STRATEGY 4: 'Maximize equity and sustainability'

In order to satisfy both the equity and the sustainability objectives the priority for surface water allocation is similar as in strategy 3, but groundwater abstraction capacities in the year of maximum development will be 42.5% of the estimated present capacities (which results in an average groundwater abstraction of 75% of the present average groundwater abstraction), and the improved cropping pattern is selected. It is also assumed that:
- The irrigation efficiencies will not be improved.
- A 'moderate' amount of the available lake volume will be allocated to the recharge basins in the wadi sustain the upstream part of the aquifer.

STRATEGY 5: 'Maximize benefits and sustainability'

The cropping pattern as proposed by the World Bank is selected for this strategy, but to provide for a sustainable development of the groundwater resources the groundwater abstraction capacities are reduced to 35% of the present estimated abstraction capacities, resulting in an average groundwater abstraction that is 70% of the present groundwater abstraction. Furthermore:
- The irrigation efficiencies will not be improved.
- Recharge during the surface water irrigation season will be small.

STRATEGY 6: 'Decrease evaporation from Marib reservoir'

This strategy is similar to strategy 5, except that surface water is allocated directly after the main inflow period, in order to reduce the evaporation from the Marib reservoir.
- Surface water irrigation starts on 1 May. The cropping calendar is adjusted so that from this date sesame, sorghum and tomatoes are grown in addition to the perennial crops citrus and alfalfa.
- All surface water available at the beginning of the winter season is allocated to the recharge basins in the wadi from 20 September to 30 April. Wheat, potatoes, watermelon, citrus and alfalfa are irrigated with groundwater.

Table 6.5 Main features of the defined strategies.

Strategy	Objective[1]	Development of scheme	Area at maximum development	Groundwater abstraction capacities	Irrigation efficiency	Recharge to basins A and B[2]	Allocation priority	Cropping pattern	Season with surface water irrigation[2]
STRATEGY 1	S	full	sectors: 6090 ha GW units: 4970 ha	25% of present capacities	present	small in season 1	equal	improved	1
STRATEGY 2	B	full	sectors: 6090 ha GW units: 4970 ha	50% of present capacities	improved	small in season 1	equal	'World Bank'	1
STRATEGY 3	E	full	sectors: 6090 ha GW units: 4970 ha	50% of present capacities	improved	small in season 1	priority: 11,12,15, 16,18,19, 20,21,22	improved	1
STRATEGY 4	E+S	full	sectors: 6090 ha GW units: 4970 ha	42.5% of present capacities	present	moderate in season 1	see 3	improved	1
STRATEGY 5	B+S	full	sectors: 6090 ha GW units: 4970 ha	35% of present capacities	present	small in season 1	equal	'World Bank'	1
STRATEGY 6	O	full	sectors: 6090 ha GW units: 4970 ha	35% of present capacities	present	all in season 2	equal	'World Bank'	1

Notes:

[1] S = maximize sustainability
B = maximize benefits
E = maximize equity
O = maximize operation efficiency

[2] Strategies 1 to 5: season 1 from 20 September to 20 February, season 2 from 20 February to 20 September.
Strategy 6: season 1 from 1 May to 20 September, season 2 from 20 September to 1 May.

Table 6.6 The scores assigned to the strategies analysed, on the basis of their results in terms of adopted objectives.

strategy	total discounted economic benefits	surface water irrigated area	equity	sustainability
STRATEGY 1	--	+	+	+
STRATEGY 2	++	++	+	--
STRATEGY 3	+	++	+	--
STRATEGY 4	-	-	+	-
STRATEGY 5	+	+	+	+
STRATEGY 6	++	--	-	-
criterion	10^6 YR	ha	coeff. of variation	% of aquifer lost
--	<1000	<1500		>40
-	1000-1250	1500-2000	>0.5	20-40
+	1250-1500	2000-2500	0.4-0.5	<20
++	>1500	>2500	<0.4	
-- = very low - = low + = high ++ = very high				

6.5.3 Results

The main results are summarized in Appendix 7, tables A7.4, A7.5 and A7.6 and in figure 14. In the first section of table A7.4 the total discounted economic net benefits and the discounted economic net benefits per hectare of input area are presented for each strategy. In the second section the total irrigated area, the input area, the areas irrigated per season and the percentage of input area irrigated per season are presented. In the third section of the table the water balance terms for the study area are given, as well as the evaporation from the lake.

In table A7.5 discounted net financial benefits per hectare per irrigation unit are given for all strategies.

Table A7.6 presents the percentages of aquifer lost after 100 years. In figure 14 drawdown plots are given for each strategy. The results will be discussed per objective.

A score table has been prepared to facilitate evaluation of the degree to which the adopted objectives are satisfied for the different strategies (see table 6.6).

Benefits

Highest discounted economic net benefits are achieved in strategy 2, where the cropping pattern proposed by the World Bank is implemented. High economic benefits are also achieved in strategy 6, because the area

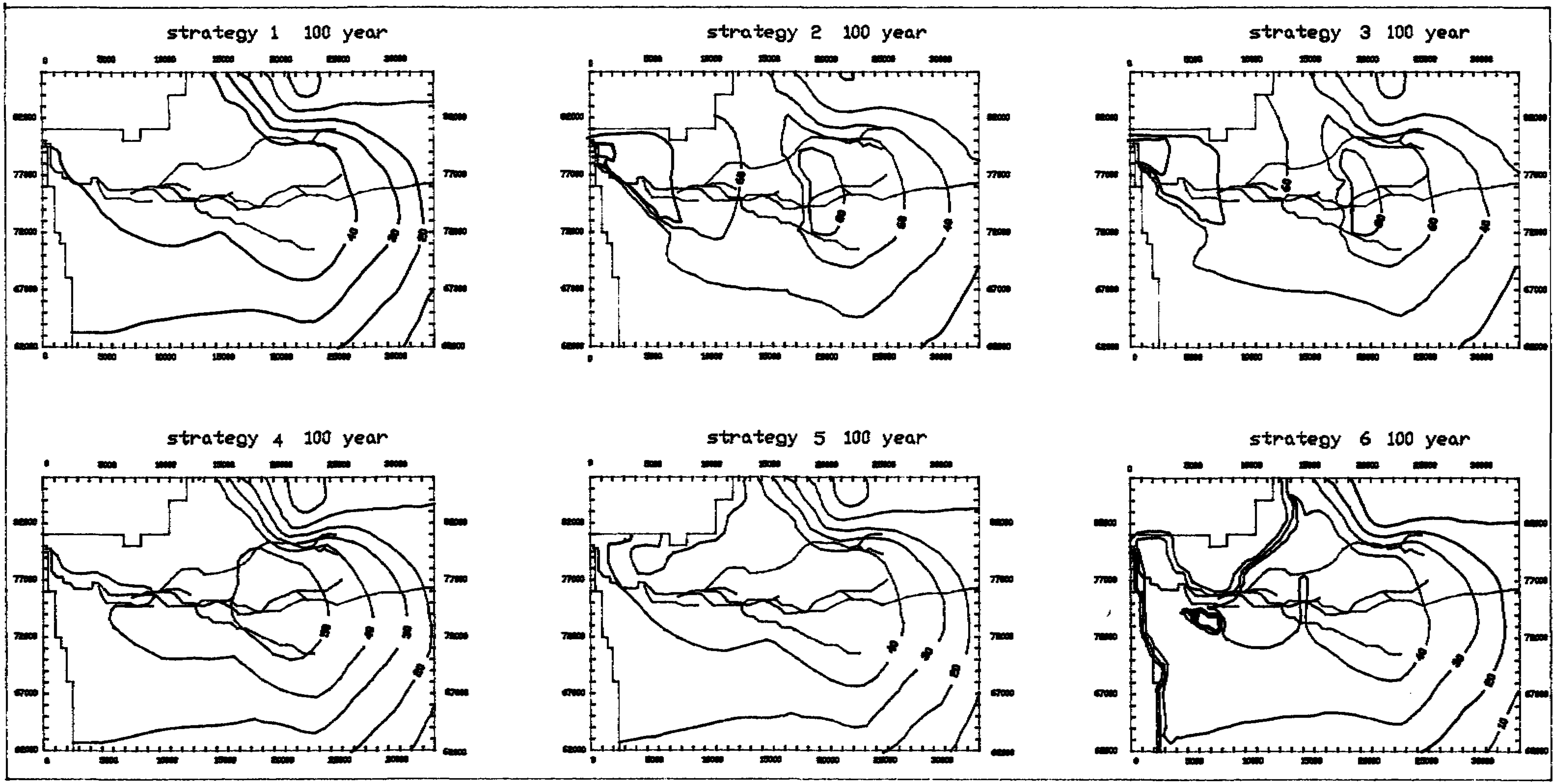


Figure 14. Drawdown (in m below ground surface) after 100 years for the six strategies.

cultivated with summer crops, which have a higher margin of profit than the winter crops, is relatively large. Strategies 3 and 5 also score relatively high on 'benefits'. In strategy 3 the assumed reduction in groundwater abstraction capacities is relatively small, which allows a larger area to be irrigated. In strategy 5, the profitable 'World Bank' cropping pattern causes the 'high' score, in spite of the relatively small groundwater abstraction capacities. Strategy 4 scores poorly on economic benefits because less surface water is available, as half of it is allocated to the recharge basins in the wadi, which boosts groundwater costs. Also, the reduction in groundwater abstraction capacities in this strategy reduces the area that can be irrigated. Strategy 1 shows the lowest economic benefits, as abstraction capacities are the lowest of all strategies and this results in the smallest cultivated area.

Area irrigated with surface water

The size of the area irrigated with surface water depends on the amount of surface water available, on the net water demand and on the irrigation efficiencies. In strategy 4 50% of the available lake volume at the beginning of the winter season is allocated to recharge, and irrigation efficiencies are not improved. Because of this, only 27% of the net planned area within the irrigation scheme can be irrigated during the winter season. In the other strategies the surface water allocated to recharge is 25% of the available lake volume. If irrigation efficiencies are not improved (strategies 1 and 5) about 35% of the planned net area within the irrigation scheme can be irrigated with surface water. When the irrigation efficiencies are improved (strategies 2 and 3) this figure is 40%. The area irrigated with surface water is smallest in strategy 6, because the net water demand during the summer season is high.

Equity

In all strategies the equitability of the distribution of financial benefits over the irrigation units is improved compared to the present situation (the base case). The coefficient of variation ranges from 0.45 (strategy 3) to 0.53 (strategy 6), while in the present situation this value is 1.2. In strategy 3 the financial benefits per hectare of - say - the 5 'richest' irrigation units are 4 times higher than those of the 5 'poorest' units. In strategy 6 this ratio is circa 6.

Sustainability

As a result of the measures assumed in strategies 2 and 3, after 100 years groundwater levels drop by 60 to 100 m in the upstream part of the aquifer. This means that even with an average groundwater abstraction of 80 to 85% of the present abstraction, the upstream part of the upper aquifer will fall dry before the end of the long-term simulation period. In the downstream area drawdowns of 60 to 80 m occur.
In strategy 1 groundwater abstraction is in balance with groundwater recharge. Groundwater levels stabilize at about 30 m below the present groundwater levels. Strategies 4, 5 and 6 are relatively sustainable in the respect that after 100 years some groundwater flow can still occur in the upstream part of the upper aquifer. The groundwater declines of 40 to 50 m are, however, important, and under these strategies the upstream part of the upper aquifer is close to falling dry too.

Evaporation from the Marib reservoir

The evaporation from the lake gives an indication of the efficiency of the operation of the Marib reservoir. In strategies 1, 2, 3 and 5 the average evaporation is about 31% of the average annual inflow. In strategy 4, where more surface water is allocated to recharge, the evaporation is about 28% of the average annual inflow. In strategy 6 the evaporation is 20% of the average annual inflow.

Conclusions

Strategy 1 is the only 'sustainable' strategy in the true sense of the word. It scores low on all other objectives. The total discounted economic net benefits are about the same as in the present situation (the base case). The area that can be irrigated with surface water is about 2210 ha, 35% of the net planned area. About 75% of the total input area can be irrigated during the winter season using surface water and groundwater and about 35% in the summer season.

Strategies 2 and 3 score high on benefits, surface water irrigated area and equity, but very low on sustainability. The area that can be irrigated with surface water is just over 2500 ha, 40% of the net planned area of the irrigation scheme. The total area that can be irrigated during the winter season is 80% under strategy 2, and 95% under strategy 3. In the summer season the figures are respectively 46% and 45%.

Strategy 4 scores low on all objectives, except equity. The surface water irrigated area is about 1500 ha, 25% of the planned net area, because a relatively large amount of surface water is allocated to recharge. Irrigated areas in the winter and summer seasons are respectively 85% and 52% of the input area.

Strategy 5 scores high on all objectives. The area that can be irrigated with surface water scores lower than in strategies 2 and 3 because no improvement of the irrigation efficiencies was assumed, and is about 2140 ha, 35% of the planned net area. About 70% of the planned net area within the irrigation scheme can be irrigated during the winter season, using groundwater and surface water. In the groundwater units only 50% of the present cultivated area can be irrigated. In the summer season only 30% of the present area of the groundwater units and of the planned net area within the scheme can be irrigated.

Strategy 6 scores high on benefits. It scores low on the other objectives. The area that can be irrigated with surface water is about 1400 ha only, 23% of the planned net area, because the net water demand of the irrigated crops during the summer is high. The average annual evaporation from the reservoir is reduced to 20% of the average annual inflow.

Which water resources management strategy is selected depends on how the decision makers rank the relative importance of each objective. However, inferior strategies can be eliminated if the actual values are considered (see table 6.7). No matter how the objectives are weighted relative to each other, strategy 4 is always inferior to strategy 5. Strategy 1 scores less than strategy 5 on all objectives except for surface water irrigated area. This latter difference is only small, so it is highly improbable that strategy 1 will be preferred over strategy 5. The same is true for strategy 3 with respect to strategy 2; strategy 3 scores significantly worse for economic benefits, while the differences between the scores for the other objectives are rather small. This leaves the production-oriented strategy 2, the sustainability-oriented strategy 5 and the 'mixed' strategy 6.

Table 6.7 The WRM Model's results for each objective.

strategy	total discounted economic benefits (10^6 YR)	surface water irrigated area (ha)	equity (coefficient of variation)	sustainability (% of aquifer lost)
STRATEGY 1	843	2278	0.5	16
STRATEGY 2	1876	2518	0.46	52
STRATEGY 3	1374	2583	0.45	51
STRATEGY 4	1127	1514	0.5	24
STRATEGY 5	1384	2142	0.49	17
STRATEGY 6	1500	1440	0.53	28

6.6 Sensitivity analysis

To analyse the sensitivity of the simulations for the 'fixed' hydrological input data and the discount rate, strategy 5 was run for two different hydrological sequences and for a different discount rate.

Hydrological input data

All cases and strategies were run with an 'average' hydrological sequence for the 25-year simulation period, which consists of a repetition of the hydrological data for the period 1986 to 1990. The effect of a different hydrological sequence was tested by running strategy 5 for a 'wet' hydrological sequence and for a 'dry' hydrological sequence. The wet sequence was prepared by replacing the driest year in the 1986-1990 sequence by the wettest year. To obtain a 'dry' hydrological sequence the wettest year was replaced by the driest year.

Under the 'wet' sequence the average inflow to the lake is $103*10^6$ m^3 per year. The 'dry' sequence results in an average inflow of $69*10^6$ m^3 per year. The effect on the average area irrigated during the winter season is relatively small; under a 'wet' sequence the average irrigated area increases by 130 ha, under the 'dry' sequence the average irrigated area decreases by 210 ha. Average economic net benefits per hectare increase by about 2000 YR in a 'wet' sequence and decrease by the same amount in a 'dry' sequence. The effect on the sustainability of the groundwater resources is appreciable; the 'wet' sequence results in 0% of aquifer lost, the 'dry' sequence results in 25% of aquifer lost. Under strategy 5, 17% of the aquifer is lost after 100 years. It is assumed that the relative ranking between the strategies will not change.

Discount rate

To evaluate the effect of the discount rate that rate was reduced from 10% to 5%. The discounted benefits obviously increase; from $117*10^3$ YR per hectare of input area to $213*10^3$ YR. The relative ranking of the strategies will not be affected by a different discount rate.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

1. The Marib Dam and Irrigation Scheme improve the control of the surface water of wadi Adhana significantly. However, the available quantity of water is reduced because there is appreciable evaporation from the Marib lake.

2. Decisions still have to be taken on the final extent of the surface water irrigation scheme; should it be completed as originally planned or should some sectors be excluded? Should a lined conveyance canal be constructed up to the diversion structures? The following remarks are relevant here:
   a. A lined conveyance canal is inevitable if a further development of the scheme is desired; if conveyance takes place through the permeable wadi bed, only about 1000 ha can be irrigated with surface water (which is less than the 1840 ha of the six most upstream sectors proposed by the World Bank as a first stage in further development). If a lined canal is constructed on average about 2200 to 2500 ha can be irrigated by surface water.
   b. Although the study did not aim at assessing the economic feasibility of completing the irrigation scheme, it showed that there may be no economic justification for fully implementing the scheme. The greatest increase in benefits will occur when the cropping pattern and the crop yields are improved.
   c. Full development of the scheme maximizes the surface water irrigated area, and it favours an equitable distribution of water-related benefits. Full development also favours sustainability of the groundwater resources, although care should be taken to facilitate recharge upstream of the diversion structures.

3. Evaluation of different possible future groundwater abstraction rates showed that:
   a. If groundwater abstraction in the area increases at the rate observed during 1987-1991, there will be higher overall economic benefits in the short to medium term (within 25 years) as more land will be cultivated, but net benefits per hectare will fall and in the long run (100 years period) there will be very large declines of the groundwater levels. Apart from their direct economic effects, such declines may halt groundwater flow from the upstream to the downstream part of the area, which greatly endangers the physical sustainability of groundwater use in the long term.
   b. Maintaining groundwater abstractions at their present rate will still cause dramatic declines of the groundwater levels.
   c. Reducing the groundwater abstractions uniformly to 70% of their present rates will prevent dramatic declines such as those mentioned above from occuring within 100 years from now, and favours a more equitable distribution of profits from groundwater-irrigated agriculture. The price to be paid for this is a reduction of the overall net economic benefit in the

short and medium term.

d. A 'true' sustainable groundwater development in the area - in which groundwater abstractions are balanced by groundwater recharge minus natural outflow - is only possible if groundwater abstractions are reduced to no more than 35% of their current rates.

3. It is less effective to recharge the groundwater resources through local recharge basins than through irrigation losses spread out over the scheme area, because the water takes a long time to spread laterally in the aquifer.

4. A cropping pattern with a higher cropping intensity and more profitable crops with a high water demand, such as citrus, will increase the net benefits, and will improve equity if it is implemented in the whole area, but will greatly reduce the sustainability of groundwater use.

5. Improving the irrigation efficiencies increases the area irrigable with surface water, but diminishes the recharge of the groundwater through irrigation 'losses'. The overall economic effect, however, is slightly positive.

6. If, instead of the current practice of irrigating with surface water in the winter season, surface water irrigation is practised directly after the main inflow period in March and April, the evaporation losses from the Marib reservoir decrease. This advantage is virtually cancelled by the higher water demand of the crops, which then have to be grown during the hot summer months.

7. The impact of different surface water allocation rules on the distribution of net benefits over the various sectors is insignificant.

8. The economic results of the six strategies analysed range between 843 million YR and 1876 million YR discounted economic benefits, if the investment costs and costs of operation and maintenance are ignored. The area irrigated with surface water under the different strategies ranges between 1440 and 2583 ha. The six strategies result in 16 to 52% of aquifer lost within 100 years. The strategies do not differ much in their effect on equity; the coeffient of variation of the financial benefits per irrigation unit varies between 0.45 and 0.53.

9. Which strategy is chosen depends on the relative importance accorded to each objective by the decision-maker. Three strategies can most probably be discounted immediately. The remaining strategies aim at maximizing economic benefits, maximizing both benefits and sustainability, and at maximizing the operation efficiency of the Marib reservoir. The most sustainable strategy has the following elements:
   - full completion of the irrigation scheme,
   - construction of a lined conveyance canal,
   - reduction of groundwater abstraction to 70% of its present rate,
   - allocation of about 25% of the surface water to recharge basins in the wadi upstream of the diversion structures,

- implementation of a more profitable cropping pattern.

10. The predicted results regarding sustainability of the various strategies evaluated are very sensitive to the assumptions about the future inflow into the lake. However, this will not affect their relative scores. The predicted economic benefits of the different evaluated strategies are very sensitive for assumptions on the discount rate to be applied. This does not affect their relative scores.

11. Water quality aspects were not included in the study. Changes in groundwater quality, however, are to be expected as a result of infiltrating mineralized irrigation water and of lateral movement of brackish groundwater towards the main agricultural area. Rough calculations indicate that fresh groundwater will be exhausted between 50 and 100 years from now.

7.2 Recommendations

1. Water resources management is an ongoing process. It is very important that the activities in this field continue, and that statistics on land use, crop yields, crop costs and revenues are updated yearly, trends in groundwater abstraction are monitored and strategies are adjusted in accordance with new insights.

2. One of the adjustments to be considered is the present design of the irrigation scheme, as the surface water irrigable area is much smaller than estimated during the planning stage. For example, planned area of sectors that are currently hardly cultivated could be adjusted.

3. A water resources management strategy should be selected and, the measures needed to implement it should be developed. Attention should be paid to the following points:

   - The area must be surveyed and a more detailed cadastral registration has to be done, to avoid the problems encountered earlier during the construction of the primary and secondary irrigation canals and to achieve an efficient distribution of surface water.

   - Measures for reducing groundwater abstraction need careful study and must be supported by the national government. These measures could include an awareness-raising campaign among the farmers, regulations, taxes and incentives. The administrative power of the regional authorities needs to be strengthened.

   - Intensive agricultural extension is needed to help farmers achieve better crop yields, a more profitable cropping pattern and higher irrigation efficiencies.

   - As the poor distribution of agricultural products is a major problem in the area, development of a marketing strategy by ERADA is recommended.

- The need for effective communication within the Marib irrigation scheme was recognized by a World Bank mission (FAO/World Bank, 1988), which recommended setting up Water Users Groups at tertiary level and a Water Users Association at sectoral level. The Water Users Association should consist of tribal leaders or representatives, the governor and ERADA management.

- In addition, ERADA should develop a communication strategy that also includes farmers and their leaders or representatives outside the scheme area.

4. It should be noted that the Water Resources Management Model has a level of detail that was not addressed fully in this study. For example, it allows the development of costs and revenues over time to be assessed for individual irrigation units. Other options include charging for surface water, and including the investment cost of structures in the economic analysis. These options can be useful during the process of further analysis and implementation.

5. The streamline module MODPATH should be incorporated in the Water Resources Management model, and water resources management options should then be analysed for their impacts on groundwater quality. Annual monitoring of the groundwater quality in the area is recommended as well.

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CALCULATION OF GROUNDWATER COST

Mining groundwater for a certain period will cause the groundwater level to fall. The groundwater will have to be pumped from increasing depths and therefore the costs of groundwater will increase.

An equation was developed to relate the costs of groundwater abstraction to the depth to groundwater. The procedure to calculate the cost of abstracting groundwater is explained below.

Total annual groundwater costs consist of different cost components; depreciation of the well and the pump and power unit, the annual fuel costs and the annual operation and maintenance costs.

Data on yield, static water level and total depth for 96 wells were used for the calculations. These data were collected during the well inventory which was done in the area from June 1986 until May 1987 (WRAY report 15.2, 1990).

Calculation of fuel costs

To calculate the fuel cost per m^3 for each well the hydraulic head was calculated by adding the depth from the surface to the static waterlevel and an assumed average drawdown of 3 m and an assumed average head above land surface of 2 m. The net and gross capacities of the power unit required to lift the measured yield were calculated according to the following equations:

$$\text{Net capacity} = \frac{9.81 * Q * H}{1000} \text{ (kW)}$$

Q = yield of the well (l/s)
H = hydraulic head of the well

$$\text{Gross capacity} = \frac{9.81 * Q * H}{1000 * nu_p * nu_a} \text{ (kW)}$$

nu_p = efficiency of the pump (75%)
nu_a = efficiency of the power unit (75%)

The following equation was used to calculate the fuel consumption per m^3 of water for each well:

$$\text{Diesel (l/m}^3\text{)} = \frac{\text{Gross capacity} * 0.35}{\text{yield (m}^3\text{/h)}}$$

0.35 = conversion factor: 0.35 litre of diesel is equivalent to 1 kWh

From the annual abstraction the annual fuel costs were calculated for each well.

Investment costs for well and pump and power unit

For the construction costs of the wells an average price of 2000 YR per metre depth was assumed. The construction costs for each well were determined from total depth of the well as measured during the well inventory. For determination of the costs of the pumps and power units the gross capacities were transferred to HP, and a brief market survey was done to obtain the prices for the different capacities. During the well inventory it was found that the power units are usually overdimensioned; to take this into account the calculated capacities were doubled.

Depreciation for well and pump and power unit

The lifetimes of the well and the pump and power unit were taken to be respectively 30 years and 15 years for the calculation of the depreciation.

Costs of operation and maintenance

The annual costs of operation and maintenance were assumed to be 20% of the annual fuel costs.

Total annual cost of groundwater

The total annual cost of groundwater abstracted, in YR, was calculated for each well by summing the annual fuel costs, the depreciation of the well and pump and power unit and the annual cost of operation and maintenance.

Relationship between cost per m^3 of groundwater and depth to groundwater

For each well the total costs per m^3 were calculated. A regression analysis was done to arrive at a generalized relation for the Marib area between these costs and the depth to groundwater. The following linear relation was found:

$$\text{Cost (YR per } m^3) = 0.11 + 0.018 * D$$

where D = depth to groundwater, measured from land surface to static water level (in m).

LOSSES IN THE WADI

1. Discharge measurements on 9 and 10 July 1991

Introduction

Discharge was measured in the wadi between the Marib dam and diversion structure A on 9 and 10 July 1991. The objective of the measurements was to determine the distribution of the losses over the wadi.

Six cross sections were selected, about 1.5 km apart. The first section is located about 1.5 km downstream of the Marib dam. The dam was opened on 8 July, at 17.00 hrs, with a release of 10 m^3/s. The release on 9 July was also 10 m^3/s; on 10 July 5 m^3/s was released.

Table A3.1 presents the results for a release of 10 m^3/s. The results suggest that only 7% of losses occur between the dam and section 4. 28% of losses occur between sections 5 and 6. The total losses are 43%. With a release of 5 m^3/s, however, the losses between the dam and the first section are much higher, 21%, and the total losses reach 69% (see table A3.2). The losses between sections 1 and 5 are similar for both releases.

Discharge measurement and groundwater modelling study by WRAY-3

Table A3.3 gives results of discharge measurements done by the WRAY-3 team in 1988 are given. The average conveyance efficiency of the wadi between the dam and diversion A derived from the 36 measurements is 61%. The conveyance efficiency of the wadi between diversions A and B as derived from 26 measurements is 13.5%. From the measurements the following relations were found (Verbeek and te Stroet, 1990):

- Losses between dam and diversion A:

$$Q(d\text{-}A) = 0.1620 + 0.3608 * Q(d) \quad (m^3/s)$$

for $Q(d) > 2\ m^3/s$

- Losses between diversions A and B:

$$Q(A\text{-}B) = 0.5854 + 0.6431 * Q(A) \quad (m^3/s)$$

for $Q(A) > 2\ m^3/s$

Verbeek and te Stroet determined the distribution during a groundwater modelling study (op.cit.). They found that 25% of the losses occur in the first 4 km downstream of the dam, 37.5% in the next 4 km and 37.5% in the remaining 2 km upstream of diversion A.

Discussion

The most remarkable difference between both releases in July 1991 occurred between the dam and the first section. No satisfactory explanation could be found for this, however, on the second day of the measurements water must

have left the wadi in the stretch between the dam and the first section. Indeed, ERADA experts observed this. This results must therefore be disregarded.
The conveyance efficiency found with a discharge of 10 m^3/s is 57%. According to the equation the conveyance efficiency would be 62%. These values are in reasonable agreement.

Conclusion

The losses are relatively small in the upper part of the wadi, upto section 5. Considerable losses occur in the last 2 to 3 km upstream of diversion A, where the stream channel is very wide and shallow. If the losses between the dam and the first section as measured during the second day are disregarded, the distribution of losses is comparable to what Verbeek and te Stroet found.

The average conveyance efficiency of the wadi between the dam and diversion A as derived from 36 measurements conducted during August and September 1988 is 61%. The conveyance efficiency derived from the measurements on 9 July 1991 is 57%. The conveyance efficiency for the wadi between diversions A and B as derived from the 26 measurements conducted during the same period is 13.5%.

2. Discharge measurements after construction of an earthen canal

After the discharge measurements discussed above an earthen canal was constructed in the wadi between the dam and section 6. During November discharge measurements took place at the same locations as the previous measurements with a release of 2.5 m^3/s on 17 days and of 3.5 m^3/s on 2 days. The results are given in table A3.4. The losses between the sections are comparable to those found during the measurements on 9 and 10 July 1991 and those found during the groundwater modelling study. The average conveyance efficiency was 62%. According to the equation derived for this stretch of the wadi the conveyance efficiency for a release of 2.5 m^3/s would be 57%. The conveyance efficiency is improved by 5%, which is within the error margin of the measurements. This can be explained by the fact that in the part of the wadi between the dam and section 5 the original stream bed was relatively narrow. The wetted perimeter in this stretch is therefore not significantly reduced by the earthen canal. In the stretch between section 6 and diversion A the stream bed is very wide and shallow; the larger part of the losses occurs there.

Table A3.1 Results of discharge measurements for a release of 10 m^3/s on 9 July 1991.

Section	Q (m^3/s)[1]	efficiency (%)	losses between sections (%)
1	9.5	95	5
2	9.5	95	
3	-[2]	-	-
4	9.3	93	2
5	8.5	85	8
6	7.1	71	14
div. A	5.7	57	14
		57	43

[1] Discharges were measured three times during the day except in section 1 and 2, where only one measurement could be done.
[2] No measurement

Table A3.2 Results of discharge measurements for a release of 5 m^3/s on 10 July 1991.

Section	Q (m^3/s)	efficiency (%)	Losses between sections (%)
1	3.97	(79)	(21)
2	3.89	78	1
3	3.82	76	2
4	3.81	76	0
5	3.2	64	12
6	3.14	63	1
div. A	1.52	31	32
		(31)	(69)

Table A3.3. Losses between Dam, Diversion A and Diversion B as measured in 1988.

Date	Q (dam) (m^3/s)	Losses D-A (%)	Losses A-B (%)
15/8/88	7.7	46.8	
16/8/88	7.7	46.8	
17/8/88	7.7	46.8	
18/8/88	7.7	46.8	
21/8/88	7.7	46.8	
22/8/88	12.0	42.5	
23/8/88	8.0	38.8	
27/8/88	15.0	54.0	
28/8/88	15.0	63.0	
30/8/88	8.0	26.3	
31/8/88	8.0	32.5	73.8
1/9/88	7.8	37.2	73.0
3/9/88	7.8	37.2	74.4
4/9/88	7.8	30.8	75.6
5/9/88	7.8	37.2	75.6
6/9/88	7.8	37.2	85.9
7/9/88	7.8	37.2	85.9
8/9/88	7.7	36.4	85.7
11/9/88	7.8	37.2	89.7
12/9/88	7.8	17.9	89.7
13/9/88	7.8	37.2	89.7
14/9/88	7.8	37.2	89.7
15/9/88	7.8	37.2	89.7
17/9/88	6.0	36.7	86.7
18/9/88	6.0	43.3	85.0
19/9/88	6.0	36.7	85.0
20/9/88	5.9	35.6	84.7
21/9/88	5.9	35.6	84.7
22/9/88	5.9	35.6	84.7
24/9/88	5.8	34.5	94.8
25/9/88	5.8	34.5	94.8
27/9/88	5.7	33.3	94.7
28/9/88	5.7	33.3	94.7
29/9/88	5.0	46.0	94.0
1/10/88	5.0	46.0	94.0
2/10/88	5.0	46.0	94.0
average		39.1	86.5

Table A3.4. Results of discharge measurements after the construction of the earthen canal in 1991.

Date	Q(1)	%(D-1)	Q(3)	%(1-3)	Q(4)	%(3-4)	Q(5)	%(4-5)	Q(6)	%(4-6)	Q(7)	%(6-7)	%tot loss	eff %
10/29	2.34	6.4	2.31	1.5										
10/30	2.36	5.6	2.36	0										
10/31	2.48	0.8	2.41											
11/3	(2.5)		2.3	(8.8)	2.05	10.8	1.91							
11/4	2.44	2.4	2.16	11.6	1.98	8.1	(2.07)		(2.04)		1.56	23.3	38	62
11/5	2.44	2.4	2.33	4.6	1.96	15.6	(2.01)		1.89	3.7	1.56	17.5	38	62
11/6	2.38	4.8	2.23	(42)	1.97	11.5	(1.98)		1.90	3.7	1.54	18.7	38	62
11/7	2.42	3.2	2.3	5	1.97	14.6	(2.0)		1.90	3.5	1.55	18.4	38	62
11/9	2.4	4.0							1.96		1.5	23.3	40	60
11/10	2.4	4.0	2.27	5.4	2.02	10.1	(2.05)		1.99	1.8	1.41	29.2	44	56
11/11	2.37	5.2	2.27	4.2	1.99	12.3	(2.01)		1.98	0.5	1.52	23.2	39	61
11/12	2.41	3.6	2.34	2.9	2.09	10.9	2.04		2.0	4.0	1.55	22.8	38	62
11/13	(2.5)				2.13		1.97		1.78	16.4	1.52	14.4	39	61
11/14	2.33	6.8					2.03		2.02		1.53	24.5	39	61
11/16	2.39	4.4			1.98		1.84		1.85	6.5	1.56	15.6	38	62
11/17	2.44	2.4			1.91		(1.97)		1.91	0	1.52	20.4	39	62
11/18	2.34	6.4			2.02		1.81		1.89	6.8	1.49	21.3	41	59
11/20	3.08	(10)			2.92		2.62		2.60	11.1	2.44	(6.0)	29	71
11/21	2.75	(20)							2.73		2.33	14.7	32	68
avg.		4.2		5.0		11.8				5.3		20.5	38	62

( ) value not correct
Q (1) discharge at section 1
%(D-1) percentage of discharge lost between the dam and section 1

WELL INVENTORY MARIB AREA 1991

Introduction

In the period of 12 May to 13 June and 29 June to 11 July a well inventory was done in the Marib area. As the well inventory was considered as an update of the former well inventory done by the WRAY-3 project from June 1986 to May 1987, and mainly aimed at obtaining data required for the Water Resources Management study, a shortened questionnaire was used. The well inventory was carried out by four teams, each consisting of a member of the General Department of Hydrogeology and of a member of ERADA.

Results

In total, 1869 wells were visited. In 814 wells (44%) the yield could be measured. Complete data on duration of pumping (pumping hours per day, days per week, weeks per season) was obtained for 657 wells (35%) for the summer season and for 606 wells (32%) for the winter season. 193 wells (10%) were disregarded during the analysis as the questionnaire indicated they were either found dry (46 wells - 2.5%), closed (13 wells - 0.7%) or had no pump (134 wells - 7%).

The data on the remaining 1676 wells were entered in a spreadsheet (Lotus). To obtain the missing data the area was divided in vertical strips 5 kilometres wide, coinciding with the grid of the groundwater model. For the wells occurring in these strips average pumping hours and yields were determined. These averages were entered for the wells with missing data. Averaging per strip was considered to be more accurate than averaging for the whole area as it was assumed that yields and pumping hours might differ going in downstream direction.

It was also assumed that during the winter season (the wheat season) the farmers use their pumps for a maximum of 3.5 months. The maximum duration of the remaining season was assumed to be 7.5 months.

The average yield is 11 l/s. It appeared that during the winter season the farmers use their pumps more hours per day and more days per week than during the rest of the year. See table A4.1.

Table A4.1. Average yield, pumping duration and abstraction 1991.

	Winter season	Rest of the year
yield (l/s)	11	11
hrs/day	11	9
days/week	6.5	5.5
total abstraction (Mm^3)	70	104

The total abstraction for 1991 is 174 Mm^3. In 1987 the total abstraction was 136 Mm^3, implying that groundwater abstraction increased by approximately 10 Mm^3 per year. The number of wells visited in 1987 was 1513, so that the increase in the number of wells was approximately 90 per year. This increase took place all over the Marib area, but is very evident in the Al-Shabwan area, in the area at the end of the South Canal (Al-Tuhayl), around Al-Hunish and Al-Hany, around Al-Jithwa, around Al Al-Erada and in the area around the road to the Dam.

Discussion of possible errors

In several areas the teams were refused access to the wells. An estimated number of 80 wells therefore could not be visited. During the well inventory of 1987 an average yield of 16 l/s was found. A possible explanation for the lower yield could be that because of the increased fuel costs (a major complaint of the farmers, as revealed by the socio-economic survey) the farmers now operate their pumps with lower yields.

EXAMPLES OF INPUT AND OUTPUT FILES

ALL INPUT AND OUTPUT FILES CONCERN STRATEGY NUMBER 5

INPUT FILE: IRRUNIT.DAT

NR	TP1	TP2	NAME	TOTAL AREA1 (HA)	TOTAL AREA2 (HA)	PRIO-RITY-LEVEL	IRR LSS INF1	IRR LSS INF2	IRR LSS EVAP	ABSTR MAX1 10E06	ABSTR MAX2 10E06	INIT DEPTH (m)	START ACTIV PERIO	YEAR MAX DEV	YEAR KIND SWAP
1	5	4	Sector 1	95	100	1	0.44	0.49	0	3.5	1.3	22	1991	1996	1994
2	5	4	Sector 2	304	346	1	0.44	0.58	0	12	5	20	1991	1996	1994
3	5	4	Sector 3	166	180	1	0.44	0.58	0	7.5	3	20	1991	1996	1994
4	5	4	Sector 4	249	272	1	0.44	0.58	0	11.5	4.5	21	1991	1996	1994
5	5	4	Sector 5	277	371	1	0.44	0.58	0	12.5	5	28	1991	1998	1996
6	5	4	Sector 6	248	248	1	0.44	0.49	0	12.5	4.9	30	1991	1998	1996
7	5	4	Sector 7	268	273	1	0.44	0.49	0	14	5.3	39	1991	1998	1996
8	5	4	Sector 8	280	368	1	0.44	0.49	0	12.5	4.9	40	1991	1998	1996
9	5	4	Sector 9	87	234	1	0.44	0.61	0	4	1.5	53	1991	1999	1995
10	5	4	Sector 10	102	229	1	0.44	0.58	0	4.5	1.7	55	1991	1999	1995
11	5	4	Sector 11	94	326	1	0.44	0.58	0	4.5	1.5	60	1991	2001	1995
12	5	4	Sector 12	107	234	1	0.44	0.58	0	3	1	65	1991	2001	1995
13	5	4	Sector 13	180	271	1	0.44	0.61	0	7	3.1	23	1991	1996	1994
14	5	4	Sector 14	148	326	1	0.44	0.61	0	5.5	2.3	32	1991	1998	1994
15	5	4	Sector 15	91	306	1	0.44	0.61	0	3	1.1	53	1991	2003	1997
16	5	4	sector 16	88	368	1	0.44	0.48	0	2.5	1.1	70	1991	2003	1997
17	5	4	Sector 17	101	208	1	0.44	0.42	0	3	1.3	75	1991	2001	1997
18	5	4	Sector 18	15	246	1	0.44	0.48	0	1	0.2	75	1991	2007	1997
19	5	4	Sector 19	68	203	1	0.44	0.58	0	2	0.7	75	1991	2002	1998
20	5	4	Sector 20	35	101	1	0.44	0.45	0	1	0.1	95	1991	2004	1998
21	5	4	Sector 21	44	153	1	0.44	0.61	0	1	0.2	80	1991	2004	1998

22	5	4	Sector 22	14	103	1	0.44	0.58	0	1	0.3	70	1991	2008	1998
23	5	5	Groundw.unit 1	1546	1546	1	0.44	0.44	0	50	17.7	35	1991	1996	2017
24	5	5	Groundw.unit 2	1170	1170	1	0.44	0.44	0	52	19.6	30	1991	1996	2017
25	5	5	Groundw.unit 3	821	821	1	0.44	0.44	0	33	12.5	28	1991	1996	2017
26	5	5	Groundw.unit 4	727	727	1	0.44	0.44	0	27.5	10.2	26	1991	1996	2017
27	5	5	Groundw.unit 5	263	263	1	0.44	0.44	0	10	3.7	40	1991	1996	2017
28	5	5	Groundw.unit 6	136	136	1	0.44	0.44	0	4	1.4	99	1991	1996	2017
29	5	5	Groundw.unit 8	90	90	1	0.44	0.44	0	6.5	1.2	41	1991	1996	2017
30	5	5	Groundw.unit 9	217	217	1	0.44	0.44	0	11.5	2.4	21	1991	1996	2017
32	2	4	Al Maneen	128	128	1	0.55	0.45	0	4.5	0.6	30	1991	1996	1994
31	4	4	Sector A	274	344	1	0.46	0.45	0	8	3.2	28	1991	1996	1994

Note:
The IRRUNIT.DAT file contains the main data for the irrigation units

NR	nr. of irrigation unit
TP1	present type of irrigation (2=SW, 4=conjunctive use, 5=GW)
TP2	type of irrigation in the year of completion
AREA1	present cultivable area
AREA2	cultivable area in year of maximum development
PRIORITY LEVEL	priority for surface water allocation
IRR LSS INF1	present irrigation losses due to infiltration
IRR LSS INF2	irrigation losses due to infiltration in the year of maximum development
IRR LSS EVAP	irrigation losses due to evaporation
ABSTR MAX1	present groundwater abstraction capacities
ABSTR MAX2	groundwater abstraction capacities in the year of maximum development
INIT DEPTH	present depth to groundwater
START ACTIV PER	start active period of an irrigation unit (base year)
YEAR MAX DEV	year of maximum development
YEAR KIND SWAP	year in which the type of irrigation changes (year of completion)

OUTPUT FILE: AGRIAREA.TAB

Average per unit for total simulation period (these data are also given per agricultural year)

Unit	Name	Plev		Areas:				Season1:			Season2:	
			Max.	Cult.	%S1	%S2	SW1	GW1	GW0	SW2	GW2	GW0
32	AL Maneen	1	128	228	66	12	67	14	0	0	13	0
31	Sector A	1	336	596	77	27	170	75	0	0	65	0
1	Sector 1	1	99	177	82	33	43	34	0	0	26	0
2	Sector 2	1	341	616	80	31	148	116	0	0	83	0
3	Sector 3	1	178	324	83	34	77	67	0	0	50	0
4	Sector 4	1	269	490	83	34	116	100	0	0	77	0
5	Sector 5	1	356	646	78	32	130	135	0	0	92	0
6	Sector 6	1	248	451	92	48	88	131	0	0	102	0
7	Sector 7	1	272	497	91	47	97	144	0	0	112	0
8	Sector 8	1	354	641	82	36	129	148	0	0	104	0
9	Sector 9	1	208	378	67	21	85	40	0	0	29	0
10	Sector 10	1	206	374	70	24	84	47	0	0	34	0
11	Sector 11	1	275	496	66	21	110	45	0	0	34	0
12	Sector 12	1	206	349	65	21	78	30	0	0	22	0
13	Sector 13	1	260	476	74	25	115	72	0	0	48	0
14	Sector 14	1	298	542	68	21	131	58	0	0	41	0
15	Sector 15	1	250	437	60	21	90	38	0	0	25	0
16	Sector 16	1	295	525	57	19	108	43	0	0	27	0
17	Sector 17	1	184	326	69	28	65	51	0	0	33	0
18	Sector 18	1	167	294	55	19	62	13	0	0	9	0
19	Sector 19	1	171	294	57	21	58	25	0	0	16	0
20	Sector 20	1	83	129	60	26	27	8	0	0	5	0
21	Sector 21	1	122	199	54	19	41	10	0	0	6	0
22	Sector 22	1	71	107	70	37	22	9	0	0	6	0
23	Groundw. unit 1	1	1546	2709	45	32	0	605	0	0	382	0
24	Groundw. unit 2	1	1170	2110	59	43	0	661	0	0	408	0
25	Groundw. unit 3	1	821	1476	55	40	0	427	0	0	265	0
26	Groundw. unit 4	1	727	1299	52	37	0	350	0	0	218	0
27	Groundw. unit 5	1	263	475	52	38	0	129	0	0	81	0
28	Groundw. unit 6	1	136	239	42	30	0	49	0	0	31	0
29	Groundw. unit 8	1	90	160	51	39	0	42	0	0	29	0
30	Groundw. unit 9	1	217	383	45	35	0	89	0	0	56	0

Note:
The AGRIAREA.TAB file contains data on the net area of the irrigation units, the percentage of the net area that is actually cultivated per season and the area that is cultivated from groundwater and from surface water.

Plev	priority level for surface water allocation
Max. (Area)	maximum area that can be cultivated (net area of the irrigation unit)
Cult. (Area)	area actually cultivated, winter and summer season are added
%S1	percentage of net area that is actually cultivated during season 1 (winter season)
%S2	percentage of net area that is actually cultivated during season 2 (summer season)
SW1	area irrigated with surface water during season 1
GW1	area irrigated with groundwater during season 1
GW0	area irrigated with groundwater during an intermediate period between season 1 and 2
SW2	area irrigated with surface water during season 2
GW2	area irrigated with groundwater during season 2
GW0	area irrigated with groundwater during an intermediate period between season 2 and 1

OUTPUT FILE: AGRIRES.TAB

Reservoir balance in 10E6 m^3
Summary for the period 2015/27 - 2016/26
Sedimentation up to this period: .004 m
Spilling volume in this period: .000 10E6 m^3.

Year	Ts	Release	Inflow	Rain	Evap	Inftr	Rechar	Volume	Area 10E6 m^2	Level m
2015	27	1.241	0.62	0	0.839	0.023	0.558	41.437	7.505	1203.37
2015	28	1.132	-1.417	0	0.738	0.023	0.558	37.569	7.029	1202.87
2015	29	1.132	-1.088	0	0.691	0.021	0.558	34.079	6.587	1202.39
2015	30	1.747	-1.035	0	0.712	0.022	0.558	30.006	6.053	1201.8
2015	31	1.821	-0.899	0	0.451	0.018	0.558	26.259	5.542	1201.22
2015	32	1.821	-0.837	0	0.413	0.017	0.558	22.614	5.023	1200.6
2015	33	2.431	-0.561	0	0.374	0.015	0.558	18.675	4.433	1199.86
2015	34	2.046	-0.836	0	0.274	0.013	0.558	14.948	3.838	1199.07
2015	35	2.046	-0.888	0	0.238	0.012	0.558	11.208	3.192	1198.16
2015	36	2.249	-1.054	0	0.217	0.011	0.558	7.118	2.401	1196.92
2016	1	1.983	0.243	0	0.152	0.007	0.558	4.661	1.854	1195.96
2016	2	0	0.003	0	0.118	0.006	0.558	4	1.692	1195.65
2016	3	0	0.271	0	0.118	0.006	0.558	4	1.692	1195.65
2016	4	0.323	12.197	0	0.087	0.005	0.558	15.223	3.883	1199.13
2016	5	0.804	8.313	0	0.2	0.012	0.558	21.963	4.928	1200.48
2016	6	0	4.986	0	0.203	0.012	0	26.734	5.608	1201.29
2016	7	0	1.999	0	0.497	0.017	0	28.219	5.812	1201.53
2016	8	0	-0.009	0	0.515	0.017	0	27.677	5.738	1201.44
2016	9	0	1.572	0	0.559	0.019	0	28.67	5.873	1201.6
2016	10	0	24.84	0	0.459	0.018	0	53.034	8.86	1204.71
2016	11	0	1.185	0	0.693	0.027	0	53.5	8.912	1204.76
2016	12	0	4.999	0	0.697	0.027	0	57.775	9.387	1205.21
2016	13	0	2.325	0	1.039	0.028	0	59.033	9.525	1205.34
2016	14	0	2.595	0	1.054	0.029	0	60.545	9.69	1205.49
2016	15	0	2.068	0	1.18	0.032	0	61.401	9.782	1205.58
2016	16	0	1.437	0	1.097	0.029	0	61.712	9.816	1205.61
2016	17	0	1.324	0	1.1	0.029	0	61.906	9.837	1205.63
2016	18	0	1.808	0	1.103	0.03	0	62.582	9.91	1205.69
2016	19	0	2.065	0	1.09	0.03	0	63.528	10.011	1205.79
2016	20	0	2.072	0	1.101	0.03	0	64.469	10.111	1205.88
2016	21	0	1.511	0	1.223	0.033	0	64.723	10.138	1205.9
2016	22	0	0	0	0.988	0.03	0	63.704	10.03	1205.8
2016	23	0	0	0	0.978	0.03	0	62.696	9.922	1205.7
2016	24	0	0	0	1.064	0.033	0	61.6	9.804	1205.6
2016	25	0	0	0	1.061	0.029	0	60.509	9.686	1205.49
2016	26	0	0	0	1.048	0.029	0	59.432	9.569	1205.38
Total/mean:		20.8	69.8	0	24.4	0.8	8.4	39.922	7.046	1202.57

Note: The AGRIRES.TAB file contains data on the reservoir balance and the volume, the area and the level of the water in the reservoir.
Ts = time step of 10 days, time step 27 is the period from 21 to 31 October

OUTPUT FILE: AGRIFLW.TAB

Waterflows in the Wadi in m3/s and 10E6 m^3
Summary for the period 2015/27 - 2016/26

Year	Ts	Q-Wadi 1	Loss-W1	Q-Wadi 2	Loss-W2
2015	27	2.082	0.272	1.577	0.15
2015	28	1.956	0.253	1.469	0.14
2015	29	1.956	0.253	1.469	0.14
2015	30	2.425	0.325	1.888	0.18
2015	31	2.753	0.37	2.149	0.205
2015	32	2.753	0.37	2.149	0.205
2015	33	3.459	0.473	2.752	0.262
2015	34	3.013	0.408	2.372	0.226
2015	35	3.013	0.408	2.372	0.226
2015	36	2.954	0.402	2.339	0.223
2016	1	2.941	0.397	2.31	0.22
2016	2	2.941	0.397	2.31	0.22
2016	3	1.758	0.227	1.318	0.126
2016	4	1.02	0.116	0.67	0.064
2016	5	1.576	0.198	1.145	0.109
2016	6	0	0	0	0
2016	7	0	0	0	0
2016	8	0	0	0	0
2016	9	0	0	0	0
2016	10	0	0	0	0
2016	11	0	0	0	0
2016	12	0	0	0	0
2016	13	0	0	0	0
2016	14	0	0	0	0
2016	15	0	0	0	0
2016	16	0	0	0	0
2016	17	0	0	0	0
2016	18	0	0	0	0
2016	19	0	0	0	0
2016	20	0	0	0	0
2016	21	0	0	0	0
2016	22	0	0	0	0
2016	23	0	0	0	0
2016	24	0	0	0	0
2016	25	0	0	0	0
2016	26	0	0	0	0
Totals:		32.239	4.289	24.92	2.373

Note:
The AGRIFLW.TAB file contains data on the flow and the losses in the wadi stretch between the dam and diversion A and between diversion A and B.

OUTPUT FILE: ECOMARIB.TAB

Calculation for the period 1991/27 - 2016/26
Discount rate for this calculation = 10.00%

ECONOMIC ANALYSIS
Amounts per ha in 1000 YR

Unit	Name	Input area (ha)	Crop reve-nues	Non water costs	Grw. water costs	Surf. water costs	Total bene-fits	Disc. bene-fits
1	Sector 1	99.4	1089.4	344.7	152.2	0	592.5	201.6
2	Sector 2	341	1071.6	345.5	158.1	0	568	199.6
3	Sector 3	178.3	1155.3	367.6	179.1	0	608.5	214.2
4	Sector 4	269.2	1134.1	361.2	185.1	0	587.9	200
5	Sector 5	356	1041.3	333.2	216.9	0	491.1	158.2
6	Sector 6	248	1418.8	440.2	305	0	673.6	220.3
7	Sector 7	272.2	1393.8	435.2	378.1	0	580.5	173.2
8	Sector 8	353.9	1130.6	356.5	286	0	488.1	144.7
9	Sector 9	207.5	721.3	238.9	200.3	0	282.1	73.6
10	Sector 10	206.1	784.3	257	233.8	0	293.5	75.2
11	Sector 11	275	662.8	217.7	182	0	263.1	62.8
12	Sector 12	206.1	610.1	198.8	174.4	0	236.9	52.9
13	Sector 13	260.1	825.8	300.1	144.8	0	380.9	123.5
14	Sector 14	297.5	662.5	246.5	130	0	286	80.9
15	Sector 15	250.1	519.3	192.1	141.1	0	186.1	31
16	Sector 16	295.2	568	190.2	144.8	0	233	38.4
17	Sector 17	184.5	779.8	254.1	278.8	0	246.8	32.1
18	Sector 18	167.5	469.7	161	81.9	0	226.8	39.2
19	Sector 19	170.6	550.1	181.8	178.1	0	190.2	23.9
20	Sector 20	82.5	470.6	155	128	0	187.7	27
21	Sector 21	122.5	401.7	147.1	105.5	0	149.1	17.1
22	Sector 22	71	570.5	177	165	0	228.6	43.8
23	Groundw.unit 1	1546	858.6	218.3	212.4	0	427.9	150.9
24	Groundw.unit 2	1170	1256.5	318.9	268.3	0	669.3	243.5
25	Groundw.unit 3	821	933.5	284	230.8	0	418.7	136.1
26	Groundw.unit 4	727	865.8	261.7	201.1	0	403	135.2
27	Groundw.unit 5	263	765.4	259.8	290.9	0	214.8	45.8
28	Groundw.unit 6	136	628.8	192	494	0	-57.2	-67.3
29	Groundw.unit 8	90	859.9	256	298.6	0	305.2	97.3
30	Groundw.unit 9	217	705.1	219	143.5	0	342.6	115.9
31	Sector A	335.6	1121.5	303.9	124.1	0	693.5	237.6
32	Al Maneen	128.0	843.1	245.7	68.4	0	529.1	194.9
	Totals:	10347.7	914.7	273.5	212.7	0	428.5	137.1

Note: The ECOMARIB.TAB file contains the economic data for the 25 years simulation period.
Input area = average net area

LAND USE STUDY

Introduction

The study aimed to prepare a land use map from SPOT satellite images covering Marib area and to supply a technical report showing the methods of analysis and interpretation and the land use statistics deduced from it.

Five satellite images were acquired; three panchromatic images (SPOT P) of 23 and 29 January 1989 and of 2 may 1991, and two multispectral images (SPOT XS) of 2 May and 18 June 1991.

The panchromatic images were used for the creation of a digital elevation model (D.E.M). The multispectral images were used for geographic correction and to prepare the landuse map. A field check was necessary to interpret of the multispectral images and classify different land uses. The field survey had to cover 15 fields for each crop, phenological stage and plant density recorded, and was carried out from 15 to 18 June 1991.

Results

The following land use themes were distinguished:
- Citrus, big trees
- Citrus, small trees
- Wheat
- Sesame
- Sorghum
- Maize
- Tomato
- Potato
- Alfalfa
- Watermelon
- Natural vegetation
- Housing
- Water
- Fallow
- Base map (Sand dune, Pediments, Alluvial gravels, ...)

Two tables of classification were prepared; non-generalized classification and generalized classification. In the generalized classification isolated pixels were eliminated in order to smooth the information and to give a workable cartographic result. Table A6.1 presents the generalized classification.

The cropping intensities were calculated from the generalized classification table. As only an image of the summer season was obtained, certain assumptions were necessary. Although tomato, potato and water melon had already been harvested at the time of the field check, their previous location could be indicated, and classification could take place from the XS-image of 2nd of May, as they were still on the field on that date. The winter crops of wheat and barley were harvested during February.

It appeared that areas found fallow during the field check that had been cultivated with wheat during the winter season could be distinguished from other fallow lands. The values under 'wheat' in table A6.1 refer to these areas. To arrive at the total area of wheat cultivated during the winter season it was assumed that in addition to area of wheat thus found, the entire area occupied by sesame and sorghum during the summer season had previously been under wheat. To correct for a possible overestimation, it was assumed that maize was not preceded by wheat. It was also assumed that the area under barley is negligible (Neefjes, 1991).

To calculate the cropping intensities for each crop and each irrigation unit the area (in ha) of each crop was divided by the total cultivated and fallow area (in ha) for each unit. The intensities calculated for each crop per unit are given in table A6.2, as well as the total cropping intensity per unit.

Accuracy

Accuracy levels were determined by comparing the classification derived from the satellite image with the ground data, according to the following formula:

$$\frac{\text{well-classified pixels}}{\text{well-classified pixels, mis-classified pixels and non-agricultural pixels}}$$

Most of the land uses had levels of accuracy close to or higher than 50%. The crops covering big areas (Citrus big trees, Wheat and Sesame) were correctly classified. Relatively poor accuracy was found for Citrus small trees, Alfalfa and Watermelon. For Citrus small trees and Alfalfa this can be attributed to the fact that they are often grown together on the same plot, so that it would be more correct to group them under the same land use. For Watermelon the spectral content appeared to be very heterogeneous, including the spectral classification for bare land. May be some of the watermelons had already been harvested at the time of the first XS image.

Additional remarks

The ground plots indicating the land use Fallow showed a spectrally heterogenous result. According to GEOIMAGE, the field check indicated that the photo-interpretation also classified bare grounds, such as sands, alluvial deposits and lower parts of mountains as Fallow. In the final classification only spectrally and structurally homogeneous areas were considered as Fallow. However, if the area classified by GEOIMAGE as uncultivable (called 'Basemap') is compared with the total net area per unit it appears that for several irrigation sectors (sectors 9, 10, 11, 12, 14 to 22) more than 50% would be uncultivable. It is assumed that this is an overestimation of 'uncultivable' land, as cultivable land that has not yet been levelled is probably included in the theme Basemap.

The areas given by GEOIMAGE for the irrigation sectors differ from those given by Electrowatt. As the cropping intensities were calculated relative to the total area as given by GEOIMAGE it is assumed that this error was levelled out.

Table A6.1. Areas per crop and per irrigation unit in ha. (The second column gives the areas as digitized by GeoImage)

I.U	area	citrus big	citrus small	citrus tot.	wheat	sesame	sorg-hum	maize	tomato	potato	alfalfa	water melon	natural veg.	hou-sing	water	fallow	cult. area	base map
GW1	3956.0	110.4	19.5	129.8	283.5	218.5	125.7	122.0	203.2	133.1	32.1	27.2	18.8	120.7	0.0	442.4	1275.2	2099.0
GW2	3958.0	241.0	25.0	266.0	276.1	176.5	103.4	93.4	123.6	78.9	55.4	8.7	40.0	3.2	1.2	118.0	1182.2	2613.4
GW3	2315.6	112.0	8.9	120.9	151.0	216.2	96.5	44.8	63.9	21.7	23.2	4.4	1.4	9.9	0.0	169.2	742.6	1392.4
GW4	3838.5	72.7	5.2	77.9	152.3	176.7	70.5	21.8	113.0	16.7	15.0	5.3	78.6	33.1	0.0	158.5	649.2	2919.1
GW5	2773.1	9.7	1.5	11.2	52.8	137.0	5.4	10.6	26.4	3.4	4.1	6.1	132.5	30.3	0.0	16.6	275.0	2336.7
GW6	3324.9	2.1	0.4	2.6	10.1	56.4	2.0	3.5	16.6	0.6	1.4	1.9	113.7	7.6	0.0	56.5	94.9	3052.1
GW8	2118.5	3.4	0.4	3.7	17.0	25.0	4.4	2.3	24.8	2.0	2.5	2.4	83.4	22.4	0.0	16.2	84.1	1912.4
GW9	1942.8	9.1	1.6	10.7	59.2	52.5	14.1	16.9	11.6	7.2	3.5	3.7	9.9	20.5	0.0	59.9	181.4	1671.1
S.1	279.5	7.4	2.0	9.4	38.5	13.7	6.5	8.8	14.7	15.0	1.6	1.1	51.2	0.1	0.0	4.8	109.3	114.1
SA	445.1	9.9	1.4	11.4	98.2	37.5	27.4	11.5	30.7	14.6	5.4	1.0	14.6	2.4	0.3	66.1	237.6	124.1
S1	133.0	8.8	1.2	10.0	17.8	18.8	7.7	3.9	20.4	4.0	2.4	1.6	0.0	1.3	0.0	20.7	86.5	24.5
S2	427.6	55.1	5.6	60.7	66.8	58.0	28.1	18.1	44.8	24.0	11.0	2.5	0.3	24.1	0.0	23.6	314.0	65.6
S3	222.1	33.4	2.2	35.7	31.3	33.7	20.4	13.4	27.2	7.7	7.2	1.9	0.6	2.3	0.0	5.3	178.4	35.5
S4	341.9	35.1	1.5	36.6	35.4	68.6	36.4	22.7	43.3	10.5	10.2	3.2	2.7	1.1	0.0	10.5	266.8	60.8
S5	472.8	46.2	3.6	49.8	57.6	71.6	32.6	17.7	45.1	9.2	11.3	7.4	2.1	0.8	0.0	5.9	302.1	161.9
S6	323.5	61.9	3.0	64.9	33.7	68.2	37.3	23.8	42.5	8.8	15.6	2.7	0.0	0.8	0.0	3.2	297.7	21.8
S7	310.9	53.4	2.1	55.4	31.0	84.3	41.9	26.0	35.7	8.4	12.0	2.3	0.0	0.7	0.0	1.1	297.0	12.0
S8	454.9	41.5	3.4	44.9	52.0	84.8	25.8	15.0	53.7	8.7	13.7	7.0	0.4	2.1	0.0	5.2	305.7	141.5
S9	258.9	7.8	0.7	8.6	14.7	36.8	4.6	4.1	18.5	2.3	3.1	1.5	6.6	0.9	0.0	3.0	94.1	154.4
S10	291.6	8.7	1.0	9.7	19.1	37.2	10.1	2.0	19.7	1.4	2.7	2.8	2.1	0.1	0.0	8.4	104.6	176.4
S11	416.5	5.6	0.5	6.1	13.2	38.2	4.5	2.4	24.7	0.5	3.6	4.5	18.5	0.0	0.0	6.1	97.7	294.2
S12	470.1	1.3	0.1	1.4	6.8	23.2	2.9	2.8	13.1	0.6	6.3	3.6	7.9	0.0	0.0	58.0	60.5	343.7
S13	342.1	29.7	4.0	33.6	59.7	55.4	17.5	4.8	8.6	2.7	8.4	3.3	0.2	0.8	0.0	6.1	194.0	141.0
S14	398.5	9.7	2.2	11.9	38.2	66.1	12.0	2.4	6.5	2.4	5.6	8.3	0.7	0.0	0.0	10.5	153.3	234.1
S15	308.8	3.7	1.0	4.6	17.1	32.8	4.9	1.2	3.6	1.2	2.8	2.8	0.6	1.6	0.0	29.8	70.8	206.0
S16	426.0	1.7	0.8	2.5	18.6	43.3	4.1	1.2	2.3	1.6	1.6	2.5	2.5	0.0	0.0	20.7	77.6	325.2
S17	262.5	3.6	1.0	4.5	17.6	44.2	5.0	1.7	4.1	0.9	2.9	2.5	0.2	0.0	0.0	28.2	83.5	150.7
S18	302.2	0.7	0.3	1.0	2.5	6.8	0.7	0.1	0.2	1.2	0.2	0.3	0.5	0.1	0.0	4.5	13.0	284.2
S19	250.1	0.9	0.4	1.3	7.0	23.1	3.3	0.6	2.3	0.3	2.1	1.4	0.4	7.1	0.0	33.4	41.4	167.9
S20	184.4	0.2	0.0	0.2	0.5	4.3	0.6	0.0	0.1	0.1	0.1	0.4	1.3	0.2	0.0	32.8	6.2	144.0
S21	314.1	0.3	0.1	0.4	2.4	7.8	0.9	0.1	0.8	0.6	1.0	1.2	0.7	0.3	0.0	34.2	15.3	263.6
S22	317.6	0.0	0.1	0.1	0.0	0.7	0.3	0.0	0.3	0.1	0.0	0.1	2.1	0.0	0.0	14.0	2.0	299.6
sum	32182	987	101	1087	1682	2018	757	500	1046	390	268	125	594	295	1	1473	7894	21943

Table A6.2. Cropping intensities per crop and per unit (crop.int.) in percentage.
Cultivated area and fallow land in ha.

I.U.	cult. area	cult.+ fallow	crop. int.	citrus	wheat	sesame	sorghum	maize	tomato	potato	alfalfa	water melon	fallow
G.U.1	1275	1718	104	7.6	36.5	12.7	7.3	7.1	11.8	7.8	1.9	1.6	25.8
G.U.2	1182	1300	137	20.5	42.8	13.6	8.0	7.2	9.5	6.1	4.3	0.7	9.1
G.U.3	743	912	132	13.3	50.9	23.7	10.6	4.9	7.0	2.4	2.5	0.5	18.6
G.U.4	649	808	122	9.6	49.5	21.9	8.7	2.7	14.0	2.1	1.9	0.7	19.6
G.U.5	275	292	142	3.8	67.0	47.0	1.9	3.6	9.1	1.2	1.4	2.1	5.7
G.U.6	95	151	104	1.7	45.2	37.2	1.3	2.3	10.9	0.4	0.9	1.2	37.3
G.U.8	84	100	119	3.7	46.3	25.0	4.4	2.3	24.7	2.0	2.4	2.4	16.1
G.U.9	181	241	108	4.4	52.1	21.8	5.8	7.0	4.8	3.0	1.4	1.5	24.8
S.I.	109	114	123	8.3	51.4	12.0	5.7	7.7	12.9	13.2	1.4	1.0	4.2
S A	238	304	105	3.7	53.7	12.3	9.0	3.8	10.1	4.8	1.8	0.3	21.8
S 1	87	107	117	9.3	41.3	17.5	7.2	3.6	19.0	3.8	2.2	1.5	19.3
S 2	314	338	140	18.0	45.3	17.2	8.3	5.4	13.3	7.1	3.3	0.7	7.0
S 3	178	184	150	19.4	46.5	18.4	11.1	7.3	14.8	4.2	3.9	1.0	2.9
S 4	267	277	151	13.2	50.6	24.7	13.1	8.2	15.6	3.8	3.7	1.2	3.8
S 5	302	308	152	16.2	52.5	23.2	10.6	5.7	14.6	3.0	3.7	2.4	1.9
S 6	298	301	161	21.6	46.3	22.7	12.4	7.9	14.1	2.9	5.2	0.9	1.0
S 7	297	298	165	18.6	52.7	28.3	14.1	8.7	12.0	2.8	4.0	0.8	0.4
S 8	306	311	153	14.4	52.3	27.3	8.3	4.8	17.3	2.8	4.4	2.3	1.7
S 9	94	97	152	8.8	57.8	37.9	4.7	4.2	19.1	2.4	3.1	1.5	3.0
S 10	105	113	145	8.5	58.7	32.9	8.9	1.7	17.5	1.3	2.4	2.5	7.4
S 11	98	104	145	5.9	53.9	36.9	4.3	2.3	23.8	0.4	3.4	4.4	5.8
S 12	61	119	80	1.2	27.7	19.6	2.4	2.4	11.0	0.5	5.3	3.0	48.9
S 13	194	200	154	16.8	66.2	27.7	8.7	2.4	4.3	1.3	4.2	1.7	3.0
S 14	153	164	152	7.3	71.0	40.4	7.3	1.5	4.0	1.5	3.4	5.0	6.4
S 15	71	101	115	4.6	54.4	32.6	4.8	1.2	3.5	1.2	2.7	2.7	29.6
S 16	78	98	131	2.5	67.1	44.0	4.2	1.2	2.3	1.6	1.7	2.6	21.0
S 17	83	112	126	4.1	59.9	39.6	4.5	1.6	3.6	0.8	2.6	2.2	25.2
S 18	13	17	124	5.6	57.5	38.9	4.1	0.8	1.0	6.6	0.9	1.9	25.6
S 19	41	75	95	1.8	44.6	30.9	4.4	0.8	3.1	0.4	2.8	1.8	44.7
S 20	6	39	29	0.4	13.7	11.0	1.4	0.1	0.4	0.1	0.2	0.9	84.1
S 21	15	49	51	0.9	22.5	15.8	1.7	0.2	1.7	1.3	2.0	2.3	69.1
S 22	2	16	17	0.6	6.7	4.6	1.8	0.0	1.8	0.3	0.1	0.4	87.6
out of units	578	9366	99	2.8	39.9	22.3	4.1	3.4	4.3	15.3	1.1	2.2	31.0
avg	257	568	121	8.45	48.0	25.50	6.52	3.76	10.21	3.28	2.61	1.76	21.62

SUMMARY OF RESULTS OF CALCULATIONS FOR CASES AND STRATEGIES

Table A7.1. Discounted economic benefits, irrigated areas and water balace terms for the cases

CASE no.	Discounted economic benefits period 1991-2016		Area[1]								Waterbalance[2]						
	Total	Per/ha of input area	Input area	Total irrigated	SW1	GW1	SW2	GW2	%S1	%S2	ET_{crop}	E_{lake}	SW	GW	RF	Net abstr	R
	10^6YR	10^3YR	ha	ha	ha	ha	ha	ha	%	%	Mm^3/yr						
BASE	826	98	8433	10639	222	5217	--	5200	100	96	101	33	3	172	77	94	20
CASE 0	1834	217	8433	10639	222	5217	--	5200	100	96	101	33	3	172	77	94	20
CASE 1	1867	212	8786	10853	957	4766	--	5130	99	92	102	29	15	172	88	84	19
CASE 2	1990	192	10340	11821	2976	3591	--	5254	99	79	108	29	45	165	105	60	13
CASE 3	2880	180	15963	18222	2975	7058	--	8189	99	77	167	29	45	267	151	116	13
CASE 4	3487	337	10340	15107	2961	6779	--	5367	91	54	152	25	49	243	144	99	7
CASE 5	2008	194	10340	11795	2956	3585	--	3254	99	79	109	29	45	165	105	60	14
CASE 6	2010	194	10340	11823	2950	3619	--	5254	99	79	109	29	45	165	105	60	11
CASE 7	1775	172	10340	15850	----	10288	--	5562	87	85	109	15	--	209	105	104	78
CASE 8	1536	149	10340	9705	2976	3441	--	3288	97	52	83	29	45	116	81	36	13
CASE 9	1802	174	10340	11438	2338	4107	93	4900	97	75	105	26	48	178	125	53	8
CASE 10	2171	210	10340	12138	3286	3290	--	5562	99	85	113	34	41	157	90	68	12
CASE 11	2474	200	12356	15627	----	7985	--	7642	100	100	148	24	--	255	113	142	49
CASE 12	948	92	10340	6432	2976	1842	--	1614	81	26	52	29	45	60	54	6	7
CASE 13	935	90	10340	11821	2976	3591	--	5254	99	79	109	29	45	165	105	60	13

1) SW1 - area irrigated with surface water in season 1 (the winter season)
GW1 - area irrigated with groundwater in season 1 (the summer season)
SW2 - area irrigated with surface water in season 2
GW2 - area irrigated with groundwater in season 2
%S1 - percentage of total area of irrigation units irrigated in season 1
%S2 - percentage of total area of irrigation units irrigated in season 2

2) SW - surface water used for irrigation
GW - groundwater used for irrigation
RF - percolation water from the fields
R - recharge from wadi and recharge basins

Table A7.2. Discounted financial benefits per hectare per irrigation unit (*1000 YR)

	base	case0	case1	case2	case3	case4	case5	case6
sector 1	291	461	475	481	475	837	488	480
sector 2	451	693	611	622	616	737	632	621
sector 3	513	774	691	703	696	811	713	702
sector 4	421	651	575	590	582	812	577	589
sector 5	410	651	656	536	531	693	545	536
sector 6	511	799	804	847	839	977	832	846
sector 7	422	696	699	760	752	934	741	773
sector 8	282	499	502	515	509	755	497	527
sector 9	100	272	274	196	194	424	166	214
sector 10	147	329	332	241	239	469	254	258
sector 11	38	186	187	139	139	403	151	155
sector 12	-34	29	30	41	42	387	48	51
sector 13	317	519	376	400	397	505	409	398
sector 14	95	228	147	174	172	395	185	174
sector 15	-7	93	96	95	94	296	108	110
sector 16	-84	14	16	23	7	519	24	24
sector 17	-72	36	38	49	36	513	50	50
sector 18	-41	83	84	91	86	740	91	92
sector 19	-66	8	9	51	51	342	64	66
sector 20	-24	-2	-1	22	22	521	25	25
sector 21	-60	-23	-23	7	15	248	15	16
sector 22	12	34	35	36	29	317	38	39
gw unit 1	332	515	512	499	461	969	499	497
gw unit 2	649	958	957	940	882	1228	940	938
gw unit 3	348	548	550	544	534	884	544	543
gw unit 4	296	473	475	475	466	868	475	475
gw unit 5	-30	67	69	78	70	657	77	79
gw unit 6	-156	-81	-81	-77	-79	409	-77	-76
gw unit 8	104	231	234	240	233	920	240	241
gw unit 9	147	256	257	253	248	1035	254	253
sector A	318	472	459	467	463	904	478	451
Al-Maneen	47	76	253	582	580	1111	596	561
c.o.v	1.21	0.87	0.86	0.84	0.84	0.39	0.82	0.82

Table A7.2 (continued)

	case7	case8	case9	case10	case11	case12	case13
sector 1	454	348	471	500	457	252	314
sector 2	643	447	516	737	687	356	411
sector 3	725	496	578	801	771	383	471
sector 4	604	407	474	682	652	309	388
sector 5	550	394	437	641	647	318	349
sector 6	792	616	829	880	808	463	564
sector 7	685	558	737	796	709	416	491
sector 8	487	373	480	532	505	296	322
sector 9	77	180	130	257	268	175	102
sector 10	150	202	177	303	320	186	133
sector 11	41	132	97	179	190	127	67
sector 12	-19	46	10	68	39	47	3
sector 13	331	313	304	496	503	271	254
sector 14	94	153	121	223	222	145	92
sector 15	13	96	59	129	103	95	41
sector 16	43	26	26	21	34	13	-75
sector 17	59	35	53	45	55	18	-57
sector 18	88	94	93	89	96	31	-32
sector 19	-29	61	21	79	24	63	9
sector 20	-2	23	18	27	4	23	-0.1
sector 21	-42	19	-15	26	-11	23	-15
sector 22	22	27	21	46	34	19	15
gw unit 1	507	387	499	498	480	167	316
gw unit 2	949	732	940	939	861	343	631
gw unit 3	550	413	545	543	491	204	343
gw unit 4	478	362	476	474	429	162	298
gw unit 5	74	65	80	75	78	28	-20
gw unit 6	-79	-59	-76	-78	-54	-30	-151
gw unit 8	240	246	242	238	221	115	113
gw unit 9	259	257	254	252	230	261	144
sector A	430	341	460	477	418	247	314
Al-Maneen	535	509	572	595	529	355	380
c.o.v.	0.95	0.78	0.89	0.80	0.81	0.75	1.05

Table A7.3. Area with drawdown more than 50 m after 50 and 100 years for the cases

CASE nr.	aquifer lost after 50 year ha	%	aquifer lost after 100 year ha	%
BASE	1902	3	19857	27
CASE 1	1925	3	20121	28
CASE 2	2008	3	25980	36
CASE 3	9289	13	n.a[1]	n.a
CASE 4	14403	20	n.a	n.a
CASE 5	2000	3	25981	36
CASE 6	2965	4	26537	36
CASE 7	13779	19	35966	49
CASE 8	1952	3	6032	8
CASE 9	2820	4	31574	43
CASE 10	2012	3	28760	40
CASE 11	21440	2	n.a	n.a
CASE 12	1876	3	1979	3
CASE 13	2008	3	25980	36

[1] not applicable

Table A7.4. Discounted economic benefits, irrigated areas and water balance terms for the strategies

STRAT. NO	Discounted economic benefits period 1991-2016		Area[1]								Waterbalance[2] in mm^3/yr								
	total	per ha of input area	input area irr. units	total irrigated	SW1	GW1	SW2	GW2	S1	S2	ET_{crop}	E_{lake}	SW	GW	RF	Net abst	R	Wadi losses	Net Tot
	10^6YR	10^3YR	ha	ha	ha	ha	ha	ha	%	%									
STRAT1	843	81	10348	7062	2278	2672	--	2112	76	35	59.7	26.9	32.7	81.8	56.7	25.8	15.5	11.9	-1.6
STRAT2	1876	181	10348	11213	2518	5090	--	3605	81	41	107.7	26.3	33.5	150.0	79.6	70.4	12.4	15.2	42.8
STRAT3	1374	133	10348	10908	2583	4349	--	3976	95	62	97.2	27.6	31.6	34.5	72.0	62.5	16.0	11.6	34.9
STRAT4	1127	109	10348	9473	1514	4602	--	3357	84	52	83.6	24.8	22.3	131.6	73.0	58.6	28.5	10.5	19.6
STRAT5	1384	134	10348	8497	2142	3806	--	2531	66	30	78.9	26.1	33.7	116.9	74.0	42.9	15.2	12.2	15.5
STRAT6	1500	145	10348	8555	1440	2369	--	4786	50	44	90.1	17.3	40.3	132.6	85.1	47.5	15.9	14.1	17.5

1) SW1 = area irrigated with surface water in season 1
GW1 = area irrigated with groundwater in season 1
SW2 = area irrigated with surface water in season 2
GW2 = area irrigated with groundwater in season 2
%S1 = percentage of total area of irrigation units irrigated in season 1
%S2 = percentage of total area of irrigation units irrigated in season 2

2) SW = surface water used for irrigation
GW = groundwater used for irrigation
RF = percolation water from the fields
R = recharge from the wadi and the recharge basins

Table A7.5. Discounted financial benefits in 1000 YR per hectare per irrigation unit for the strategies.

	strat1	strat2	strat3	strat4	strat5	strat6
sector 1	283	531	372	302	425	445
sector 2	295	584	424	312	437	452
sector 3	320	595	435	346	468	492
sector 4	292	560	400	308	438	459
sector 5	267	486	354	262	379	384
sector 6	368	634	462	405	527	565
sector 7	320	569	405	341	470	500
sector 8	256	439	311	257	376	386
sector 9	167	292	195	100	219	206
sector 10	173	304	204	113	234	223
sector 11	144	243	202	177	188	178
sector 12	121	215	176	152	167	155
sector 13	209	408	284	193	304	305
sector 14	155	286	189	107	215	206
sector 15	94	169	144	121	126	116
sector 16	100	172	152	131	142	128
sector 17	110	220	170	143	181	175
sector 18	98	164	154	134	120	103
sector 19	89	167	142	119	125	113
sector 20	89	184	144	132	117	105
sector 21	63	137	114	89	87	76
sector 22	97	209	161	138	138	132
gw unit 1	203	454	379	342	337	370
gw unit 2	357	715	575	552	537	582
gw unit 3	211	457	365	339	336	367
gw unit 4	188	429	349	310	314	343
gw unit 5	85	277	206	181	190	210
gw unit 6	9	116	63	49	63	72
gw unit 8	177	356	272	237	263	281
gw unit 9	206	353	277	251	264	285
sector A	313	573	397	323	475	491
Al-Maneen	342	580	407	365	394	373
c.o.v.	0.50	0.46	0.45	0.50	0.49	0.53

Table A7.6. Area with drawdown more than 50 m after 100 years for the strategies

Strategies	Aquifer lost after 100 years ha	%
Strategy 1	11347	16
Strategy 2	38022	52
Strategy 3	37260	51
Strategy 4	17269	24
Strategy 5	12505	17
Strategy 6	20218	28