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WATER AND URBAN LAND-USE PLANNING IN CALI, COLOMBIA

By Mark A. Ridgley[1]

ABSTRACT: A multiobjective urban land-use/water-resource model, appropriate for use at the strategic planning level in less-developed countries (LDCs), is described and applied to Cali, Colombia. Objectives are to minimize service costs and biochemical oxygen demand (BOD) loadings and maximize service levels while accommodating population growth. Vector optimization based on generating techniques allocates new residents to potential urban-expansion zones while simultaneously determining the optimal mix of various water-supply and sanitation systems. Potential flood impacts are then simulated and the results used to constrain development in critical areas. Further flood control and reduction of nonpoint-source pollution via detention basins are examined. Postoptimality analysis shows solutions to be quite sensitive to estimated water consumption and preset density limits. Deficiencies due to the optimization-simulation linkage and the runoff modeling assumptions are discussed and their significance for such modeling in LDC settings is appraised.

INTRODUCTION

Water-related issues should play an active, guiding role in land-use and urban-development planning in the Third World. At present, these issues are too often reactive in character, since they usually surface during implementation planning as design and engineering problems to be overcome so that urban expansion can proceed unhindered. However, since water issues and land use are inextricably related, goals concerning them should be considered simultaneously. Although the goals' interactions are complex, the models should not be. The foremost aim of such models should be to provide insight and understanding, not precise numerical output (Geoffrion 1976; Holling 1978); they should be used to learn about the interactions between water and land use and to explore options available. Second, their intended use as policy aids means they should be comprehensible, flexible, inexpensive, and easy to use (Goldberg 1983; Biswas 1976; Quade 1985). Not only are small, simple models more effective for these purposes than larger, complex ones, but the data-poor environment of the Third World city mitigates against the use of the latter. Furthermore, the multiplicity of criteria, decision makers, and stakeholders characterizing urban-development issues argues against a model's recommending a single, preferred solution, promoting instead an approach that retains options and displays their tradeoffs (Goeller and The PAWN Team 1985).

This paper describes a strategic planning model that links land use to water supply, sewage management, pollution abatement, and flooding. Its application to the case of Cali, Colombia (Ridgley 1986) has led to refinements of an approach presented earlier in a hypothetical context (Ridgley 1984). In brief, multiobjective optimization is used to allocate projected population growth among urban expansion zones while simultaneously determining the

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optimal spatial mix of different water-supply and sanitation (WSS) technologies capable of meeting service needs. The hydrological impacts of the resulting development pattern are then simulated, with the insights thus gained being used to revise development goals if so desired.

CASE STUDY OF CALI, COLOMBIA

Cali, with over 1,600,000 people, is the third largest city in Colombia and the principal economic center in the southwestern region of the country. In 1985, at the time this study was conducted, it was expected to gain close to 400,000 more residents within 10 years and planners from the Departamento de Planeacion Municipal and from Empresas Municipales de Cali (EMCALI), the public services agency, were busy developing strategies for urban expansion. Several potential expansion zones had been identified, some situated on the Andean slopes to the west, some on the relatively flat areas to the south, and one adjacent to the River Cauca to the east (Fig. 1). It was recognized that the characteristics of the different zones—topography and geophysical characteristics, distance from established service networks, existing service levels, and settlement density—would influence both the functional viability and the ultimate cost of water-related service systems. Moreover, although the attractiveness of each system would usually be evaluated on the basis of the development plan it was to support, it became clear that the service options could themselves be used to design the development plans. Consequently, the planning question became: Where should new residential development be encouraged, and which WSS systems should be selected to service it to minimize water pollution and cost of services and to mitigate flood hazard?

Multiobjective Model

In consultation with EMCALI, four criteria were selected by which to judge the desirability of potential future development patterns: economic cost of WSS services, service level, potential water pollution, and flood hazard. The first three were to be measured by the average total annual cost per capita (TACC), average per-capita water consumption, and aggregate yearly BOD_5 loading due to sewage disposal. Flood hazard was to be evaluated on the basis of both the magnitude of likely increased flooding as well as its spatial distribution.

The identification of technologically and culturally viable WSS systems and the determination of the TACC for each WSS system, in each zone, constituted a major task of the study and is described in depth elsewhere (Ridgley 1986, 1989). Table 1 indicates the 12 different WSS systems considered viable. The cost of service, varying almost thirtyfold from COL$394 (Colombian pesos) to COL$10,786, depended not only on differences in investment and operation and maintenance costs by technology, but also on variations in the economic cost of water from one zone to another, variations that are subsequently magnified by the technologies' differential usage of water. Table 1 also presents the potential sewage-derived BOD_5 loadings corresponding to each WSS system. These figures indicate the estimated organic pollutant not isolated underground or decomposed by biophysical processes (Kalbermatten et al. 1982; Feachem et al. 1980).

Any development plan should meet three basic requirements. First, total water consumption should not exceed the water treatment capacity. Second, densities in each expansion zone should be kept below the saturation levels already defined by the city planning department and EMCALI. Third, every-

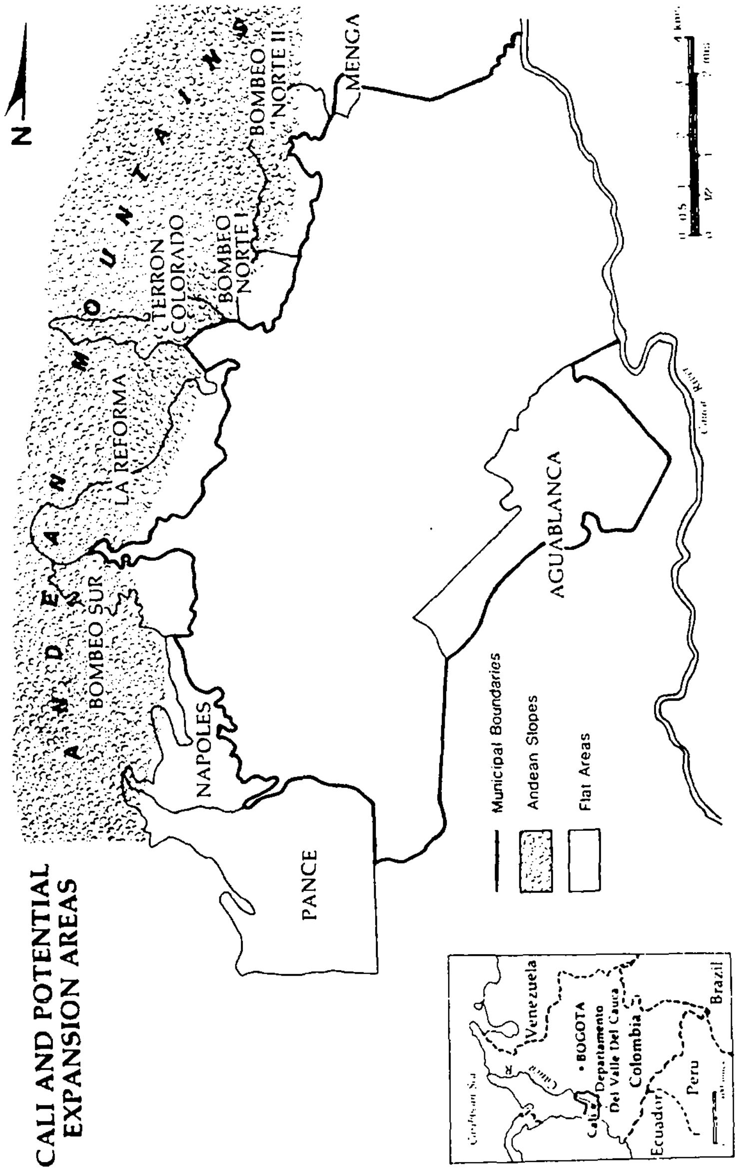

FIG. 1. Cali and Zones of Potential Expansion

TABLE 1. Potential 5-Day BOD Loadings (kg/yr) for Viable Water Supply/Sanitation Systems

Water supply type (1)	VIP latrine (2)	Pour-flush[a] latrine+ (3)	Vault and cartage[a] (4)	Septic[a] tank (5)	Sewered pour-flush and septic tank (6)	Sewerage (7)
Standpipe	0	0	11	N/V	N/V	N/V
Yard tap	N/V	0	13	0	7	N/V
Indoor plumbing: 180 Lcd	N/V	0	N/V	0	9	15
Indoor plumbing: 260 Lcd	N/V	N/V	N/V	N/V	N/V	17

[a] Includes soakaway.

Note: N/V = not viable.

one should be assigned to a service system.

Defining decision variables, coefficients, and right-hand sides (RHS) yields the following multiobjective mathematical programming model: let x_{ij} = number of new inhabitants to assign to growth area i and WSS system j.

$$\min z_1 = \sum_i \sum_j c_j x_{ij} \quad \text{(1)}$$

where c_j = TACC, in 1984 pesos (COL\$), for WSS system j.

$$\min z_2 = \sum_i \sum_j b_j x_{ij} \quad \text{(2)}$$

where b_j = BOD_5 (kg/yr) in the effluent of WSS system j.

$$\max z_3 = \sum_i \sum_j w_j x_{ij} \quad \text{(3)}$$

where w_j = water consumption in Liters/capita/day (Lcd) associated with WSS system j

subject to

$$\sum_i \sum_j w_j x_{ij} + w_r + w_c + w_g \leq w_{\max} \quad \text{(4)}$$

where w_r = existing residential water use; w_c = existing water use in other sectors; w_g = projected increase in w_c over the planning horizon; and w_{max} = treatment capacity expected by the end of the planning period.

$$\sum_i \sum_j x_{ij} = P \quad \text{(5)}$$

where P = projected population increase by the end of the planning period.

$$\sum_j x_{ij} + p_i \leq s_i \qquad \text{for } i = 1, 2, \ldots, 28 \quad \text{(6)}$$

where p_i = existing population in growth area i; and s_i = saturation population in growth area i.

$$x_{ij} \geq 0 \qquad \text{for all } i, j \quad \text{(7)}$$

Eqs. 1–7 represent what Ignizio (1982) calls the baseline model and consist of 165 variables and 30 constraints. Notice that Eqs. 1 and 3 represent total, rather than average, economic cost and water consumption. The same optimal program results either way, since dividing the RHSs of Eqs. 1 and 3 by 392,028, the projected population increase, will not affect values of x_{ij}. In reality, only one constraint, the nonnegativity condition of Eq. 7, was inviolable; all the others, not representing physical limits, could be violated with some sacrifice in the achievement of the objectives.

Given the inability of EMCALI's decision makers to state clearly their preferences regarding the three objectives, and the pluralism characterizing public-sector problems in general, it was decided to generate a set of nondominated solutions that would represent a range of possible plans. The generating technique used was the weighting method (Cohon 1978), where each objective was multiplied by a positive scalar, the objectives summed to form a single superobjective, and the resulting problem solved as a linear program (LP). Each weight set yielded a different LP, and the solution to each was nondominated with respect to the multiobjective model.

Letting $\mathbf{F}$ denote the feasible region defined by Eqs. 4–7 and $\mathbf{x}$ denote a solution vector for which Eqs. 4–7 are not violated, one can rewrite the weighted problem as

$$\min z = v_1 z_1 + v_2 z_2 - v_3 z_3 \quad \text{(8)}$$

subject to

$$\mathbf{x} \in \mathbf{F} \quad \text{(9)}$$

where v_1, v_2, and v_3 are the nonzero scalar weights.

Table 2 presents 10 nondominated solutions that are representative of the range of achievement for each objective. It also presents two other dimensions of interest: the number of people who would obtain their water from standpipes and the number who would be served by sanitation technologies that do not remove or kill pathogenic microorganisms. In general, solutions characterized by low water use are low cost and have low pollution potential; high water-use solutions tend to be costly, with heavy pollution potential.

Several of the first nine solutions were unrealistic or impracticable as long-range plans. Solutions 1 and 2, for example, were discarded because the number of people on standpipes was far too great; indeed, Solution 1 indicates that all the new residents in the next 10 years should be served by that system. Solutions 5, 7, and 8, with per-capita water consumption less than the current average, have the disadvantage that they actually cost more than the status-quo plan, Solution 9. However, despite the fact that Solution 6 yielded lower water-consumption levels at greater costs than would occur by continuing with current standards, it was not discarded. Since the city had yet to decide how to reduce its sewage effluent into the Cauca River, mandated by the Corporacion Autonoma del Valle del Cauca (CVC), it was felt that the 75% reduction in potential BOD_5 loading might well compensate for the 4% cost increase. The corresponding average water consumption of 177 Lcd, although a substantial reduction from the current level of 260 Lcd, was viewed as acceptable and serving 60,413 persons by public standpipes, while certain to cause some headaches, would not be unmanageable. So-

TABLE 2. Nondominated Planning Alternatives and Corresponding Flood-Related Impacts

		Water Supply, Sanitation, and Water Pollution					Flooding and Stormwater Management			
Solution number (1)	Plan number (2)	Average water use (Lcd) (3)	Average cost (TACC $COL) (4)	BOD (1,000s of kg/yr) (5)	Number of people on standpipe (6)	Number of people on WSS systems with public health risk (7)	Detention (acre-ft) (8)	BOD reduction (1,000s of kg/yr) (9)	Number of surcharge points (10)	Number of new surcharge points (11)
1[a]	—	30.0	459	0.0	392,028	0	—	—	—	—
2[a]	—	40.0	492	292.5	374,819	17,209	—	—	—	—
3	1	91.0	1,183	0.0	233,726	0	—[d]	—[d]	—[d]	—[d]
4	2	132.0	929	2,667.0	210,045	157,474	—[d]	—[d]	—[d]	—[d]
5[a]	—	138.0	2,125	0.0	0	0	—	—	—	—
6	3	177.0	1,906	1,666.1	60,413	98,007	0	0	16	6
7[a]	—	208.0	2,199	2,322.8	0	136,633	—	—	—	—
8[a]	—	237.0	1,842	4,754.1	0	279,654	—	—	—	—
9	4	260.0	1,833	6,664.0	0	392,028	—[d]	—[d]	—[d]	—[d]
10	5	162.0	1,183	3,332.0	151,489	196,014	0	0	7	2
—	3A[b]	174.0	1,906	1,666.0	66,791	98,007	0	0	14	7
—	5A[b]	160.5	1,183	3,332.0	155,579	196,014	0	0	1	0
—	3D[c]	177.0	1,906	1,666.0	60,413	98,007	5.28	11.3	15	6
—	5D[c]	162.0	1,183	3,332.0	151,489	196,014	4.31	11.3	6	2

[a] Screened out.

[b] A = Development relocation option.

[c] D = Detention option.

[d] Not analyzed.

lution 9, with conventional sewerage and water use of 260 Lcd, was also a viable alternative since it represented no change from existing sanitary engineering practice. Thus, Solutions 3, 4, 6, and 9 were retained for further discussion as Plans 1–4, respectively.

Despite the merits of the four options, dissatisfaction remained due to the apparent lack of an intermediate-cost solution with water-consumption levels in the neighborhood of 175 Lcd. It was felt that by allowing an increase in pollution potential, it should be possible to obtain moderate consumption levels at a cost significantly below that of the 260-Lcd option. To generate such a solution, the weighted model, Eqs. 8 and 9, was altered such that *the constraint method could be used*. An upper limit of COL$1,183 was set for average TACC (z_1), while total BOD_5 loading was restricted to below 3,332,238 kg/yr, or half the loading associated with Solution 9. Water use was then maximized subject to the augmented constraint set:

$$\max z_3 \tag{10}$$

subject to

$$\mathbf{x} \in \mathbf{F} \tag{11}$$

$$z_1 \le 1{,}183 \tag{12}$$

$$z_2 \le 3{,}332{,}238 \tag{13}$$

The optimum for Eqs. 10–13 was 162 Lcd, and this solution (number 10) led to Plan 5 (Table 3). As Plan 5 would require far fewer people on standpipes than Plans 1 and 2, these latter alternatives now looked less attractive and were not carried forward for flood evaluation.

Flood Dimension

The three candidate solutions correspond to different development patterns. Plan 3 (Fig. 2) calls for considerable development on the Andean slopes; Plan 4 (Fig. 3) would accommodate all future development within the existing built-up area; and Plan 5 describes a pattern somewhere between the two. Each of these would affect the hydrologic regime in different ways and these effects should be considered in selecting a preferred development plan. This was achieved by modeling stormwater runoff for a given rainfall event and comparing it to the runoff pattern likely to be produced under existing conditions. The net change under each development alternative then served as the basis for comparing the different plans.

The Penn State Runoff Model (PSRM), a single-event simulation program (Aron and Lakatos 1984), was chosen for the runoff analysis for several reasons. Relatively simple, small in size, and having minimal data requirements, it computes overland flow and permits drainage-element and reservoir routing with acceptable hydraulic accuracy. It also calculates runoff contributions from upstream subareas to peak rates at selected points of the catchment, facilitating the analysis of impacts due to the spatial distribution of land use. These attributes, together with the availability of microcomputer versions that would reduce the pressure on limited mainframe facilities, made the model particularly attractive to the public utilities engineer.

Modeling Existing Conditions

The area to be modeled was determined mainly by topography, availability of data, and the structure of the drainage network. The expansion areas on

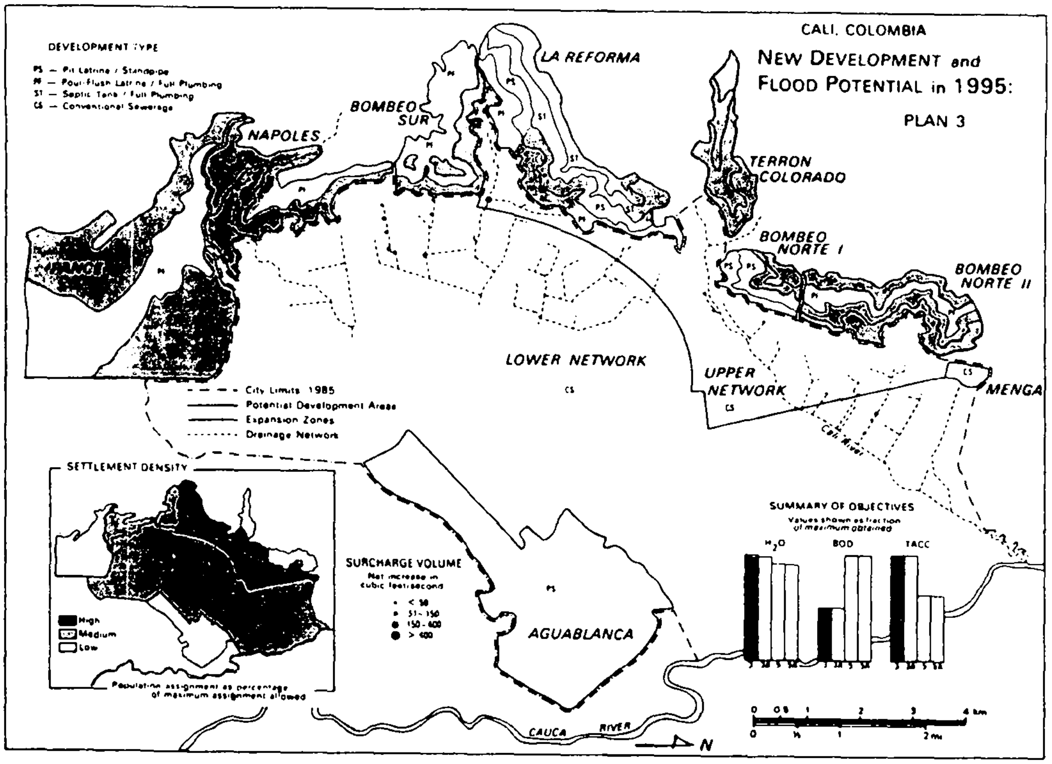

FIG. 2. Settlement Pattern (in White) and Flood Potential under Plan 3

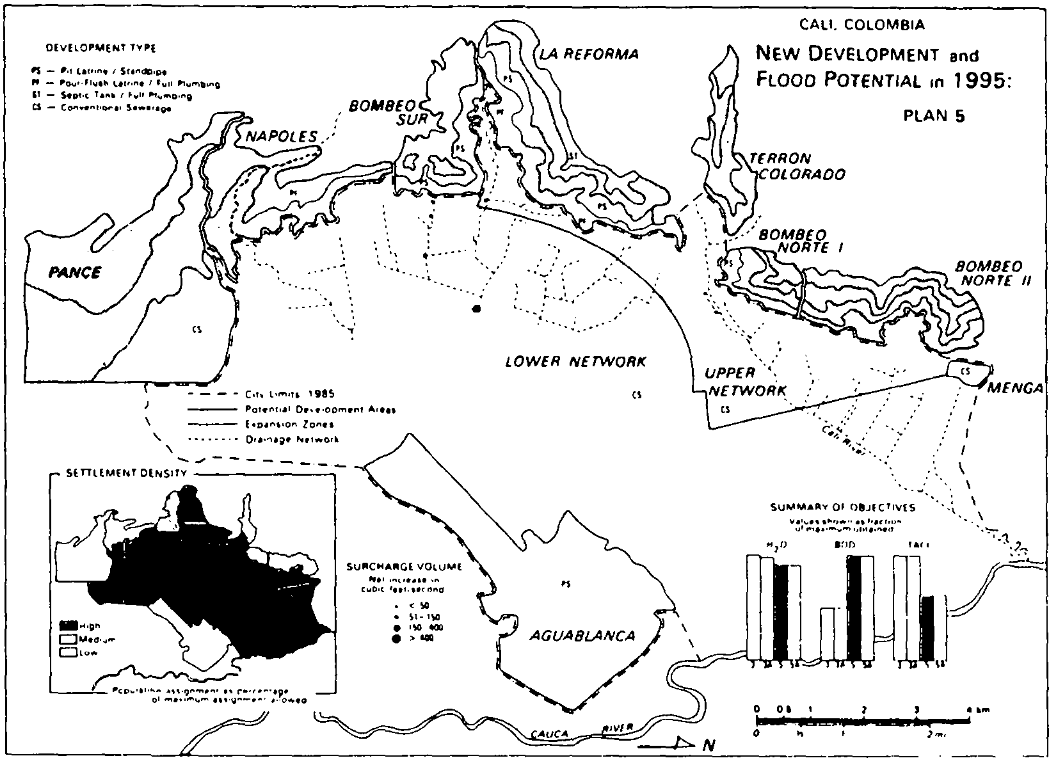

FIG. 3. Settlement Pattern (in White) and Flood Potential under Plan 5

the western slopes were of great interest since they were assumed to give rise to large quantities of runoff if developed. Most of the built-up areas were omitted since relatively little additional change to the land cover and drainage system would occur as a result of increasing population within them. Nonetheless, some of the areas adjacent to the foothills had to be included to see how runoff from the slopes would affect flooding in existing parts of the city. These factors resulted in the partitioning of the city and the surrounding expansion zones into six separate watersheds for the modeling exercise (Fig. 4).

Despite the merits of PSRM, it could not deal properly with Cali's looping sewers and diversion structures. Thus, several assumptions had to be made to allow its application. First, where diversion structures existed, a decision was made to eliminate one branch of the structure; the larger conduit was usually retained, since this most often corresponded to the storm sewer and

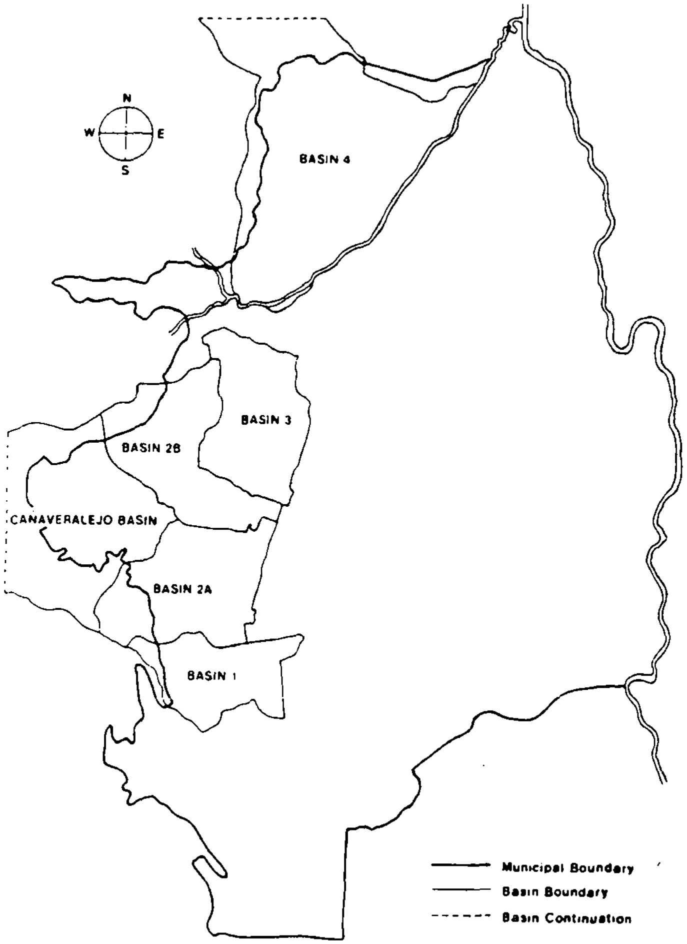

FIG. 4. Area Modeled and Catchment Boundaries for Flood Simulation Analysis

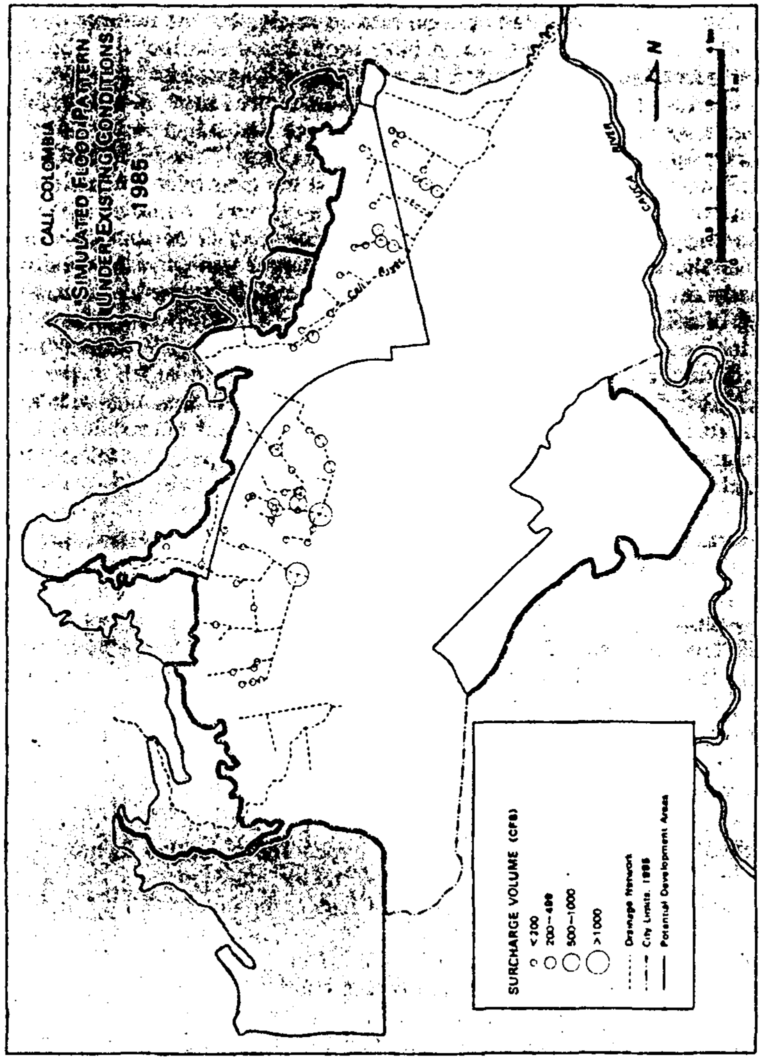

FIG. 5. Simulated Stormwater Flooding Pattern under Existing (1985) Land Use Conditions and 1-Hr, 5-Yr Rainfall

carried the wet-weather flows in any case. Another simplification was made in order to reduce the total size of the simulation. Since a single drainage element could consist of 10 or more sewers or open channels in sequence, each with different hydraulic characteristics, to model the stormwater conveyance completely would have required the inclusion of every such conduit. Since PSRM allows only one drainage element per subarea, each conduit would have had to correspond to its own, smaller subarea. Not only were the available watershed data not organized so finely, but the number of subareas and drainage elements would have proliferated enormously were this to have been done. The assumption made here was to use the hydraulic characteristics of the uppermost conduit for the entire length of the drainage element in question and to assign any surcharge that might occur an overland-flow velocity equal to the within-pipe velocity. Therefore, the runoff not entering the upstream inlet would arrive at the next inlet downstream at the same time as the flow within the drainage element. While equal velocities for overland and conduit flow are unrealistic, this compensates somewhat for the neglected storage capacities in larger downstream elements, especially for the cases where storage was reduced due to the elimination of one leg of a forking sewer or diversion structure. A fourth assumption was made in the computation of pipe-full flow velocities for the drainage elements. For circular or rectangular sewers, as well as for open trapezoidal channels, the Manning equation was applied directly. For conduits with more complicated cross sections, such as hanging-basket and horseshoe sewers, the Manning equation was used for flow in a circular pipe of the same cross-sectional area.

The model simulated the runoff produced by a one-hour, five-year design storm, totalling 1.89 in. (48 mm) of rainfall, taken from historical precipitation records for Cali itself (*Proyecto* 1985). Fig. 5 shows the distribution and magnitude of flooding simulated under existing (1985) conditions. To be consistent with the model's assumptions and the detail appropriate for strategic-level planning, the simulated surcharge flows are grouped into broad classes. This pattern is believed to accord well with that actually observed, reflecting the robustness frequently exhibited by simple models (IRLWR: "More sophisticated" 1985).

Modeling Future Conditions

Development of the expansion areas will undoubtedly increase total runoff and probably speed its movement downslope. The reduction in travel time is difficult to quantify, since it requires precise knowledge of the organization of the future built environment. Changes in runoff volume, derived largely from increases in imperviousness, are somewhat easier to predict and formed the kernel of the runoff modeling effort.

The runoff coefficient, a function of the basin's impervious fraction and the infiltration capacity of the soils, tends to rise markedly with urban development, and how well one can predict the hydrologic changes accompanying development depends in large measure on one's ability to estimate changes in this coefficient. In PSRM, the coefficient used is the U.S. Soil Conservation Service's runoff curve number. But while the curve number is defined by the hydrologic characteristics of the soil in question and the land use of the area (itself encompassing the degree of imperviousness), PSRM applies the curve number only to the pervious fraction of the watershed. Since the curve number as used in PSRM does not encompass the effect of impervious percentage, this parameter cannot be used by itself as a true runoff coefficient, and it becomes difficult to estimate new curve numbers for pervious areas alone. As a result, curve numbers for pervious areas were not altered to reflect new land use conditions; rather, the entire effect of future land development was assumed to be encapsulated by changes in the impervious fraction.

TABLE 3. Estimated Relation between Settlement Density and Imperviousness

Density (persons/ha) (1)	Paved streets (%) (2)	Unpaved streets (%) (3)
22.5	45	—
216.0	72	62
400.0	90	82

Exactly how imperviousness changes with development was not well defined, and establishing such a relationship was fraught with problems. First, there were no empirical studies available on the relationship between population density and degree of imperviousness for Colombian cities. Second, employing density-imperviousness relationships derived from empirical studies of U.S. cities would ignore such qualitative differences as the existence of shanties, mixed commercial-residential land use, and Colombians' preference for tiled patios over grassed lawns. Third, while it might be intuitively attractive to assume increases in imperviousness with rising population densities, situations not conforming to this expectation quickly surface: shanties and squatter settlements tend to have high densities but little paving, and commercial areas have comparatively few permanent residents but are almost entirely impervious. Moreover, imperviousness is commonly found to be asymptotic to some upper limit, since the value of land and the desire to preserve some open space in the heart of built-up areas give rise to multistoried structures on land already developed.

Notwithstanding these practical difficulties, the need to estimate changes in imperviousness under future development plans was unavoidable, and the following procedure was used. It was first assumed that developments employing public standpipes or single-yard taps would be unlikely to have paved streets, in contrast to those with in-house plumbing. Next, the three typical development types found in Cali—large-lot suburban, single-family detached or row house, and multifamily apartment blocks (*Areas de expansion* 1981)—corresponding to three distinct densities, were examined in an attempt to determine typical impervious percentages. These percentages were then related to street paving as indicated in Table 3. Although lacking voluminous empirical support, these figures were believed to reflect the general direction of the density-imperviousness relationship as it varied with development type.

Analysis of Future Flood Potential

Runoff was simulated under future conditions by applying the same design rainfall as employed earlier under the predevelopment situation. New development under Plan 4 is concentrated within the existing urban boundaries and in the Pance I expansion area situated on well-drained plains to the south of the city. The only settlement to take place on the western slopes would be further infilling of Terron Colorado I, and only 7,354 additional people would be assigned to that area. Runoff was not simulated under this option because 98% of the new inhabitants would be assigned to areas either already built up, resulting in minimal changes to land cover, or falling outside the study area. Although further development of the hillslopes in Terron Colorado 1 is likely to increase the runoff produced there, it is doubtful that additional flooding would result since the added runoff would drain directly into the Cali River.

Figs. 2 and 3, portraying the settlement patterns and likely flood implications under Plans 3 and 5, present a different picture. In both cases, major portions of Cali's future settlement would occur on the Andean slopes, giving rise to more runoff and resulting in increased flooding in the lower parts of the city. The two alternatives differ more in the spatial distribution of flood occurrence than in the magnitude of surcharge at any one location. In Plan 3, substantial development within the Bombeo Norte 1 and Bombeo Norte 2 expansion areas would exacerbate flooding at many points in the northern sectors of the city; in contrast, Plan 5 would give rise to increased flooding at only two points north of the Cali River. South of the river the situation is much the same, with Plan 3 showing many more points where flooding has been aggravated. The only indication that Plan 5 might present worse problems is given at the point where the sewer networks draining Basins 2A and 2B join to form a single channel. Here surcharging has increased by more than 400 cu ft/sec (11.3 m^3/s), hinting at the possibility that high runoff flows might continue to coincide in the lower portion of the network, causing ever more severe surcharging. Even were the modeling effort extended farther downstream, it would be risky with PSRM to attempt to ascertain the likelihood of such a cascade; errors due to the modeling assumptions and to simplifications of the drainage network would tend to grow and reduce the accuracy of the simulation even further.

Stormwater Management

Simulation was required because important aspects of the planning problem, the potential stormwater impacts, were unable to be incorporated in the optimization model. Since the information provided by the simulated flood patterns is used to judge the desirability of the candidate plans, the simulation results can be considered as refinements to the optimization model. These results act as exogenous constraints in that flood impacts deemed too severe will eliminate certain proposed development configurations. This is analogous to altering the feasible region of the multiobjective program. Such constraints can be made explicit by using them to amend the existing problem formulation, in this case by tightening population constraints corresponding to subareas causing runoff problems. In this fashion, the location of future residential development becomes a tool with which SWM goals might be achieved, rather than the usual case of presenting problems for which engineering solutions are sought.

In both Plan 3 and Plan 5, surcharge at inlet 10 in Basin 2B was identified as the most severe point of flooding (Fig. 6). Since flooding at that inlet already occurred under conditions of the five-year storm, one SWM goal became the maintenance of the 1995 surcharge flow at the 1985 level. Simulation analysis indicated subarea 4 to be the major contributor to flooding at inlet 10, with subareas 5 and 8 also registering significant amounts. Short of enlarging the drainage capacity at inlet 10, detention or elimination of the runoff flows produced by one or all of these subareas represented the principal SWM aim. As subareas 5 and 8 were already built-up, only subarea 4, falling within the La Reforma expansion zone, lent itself to the development-reassignment option. Consequently, subarea 4 became the focus of the SWM efforts.

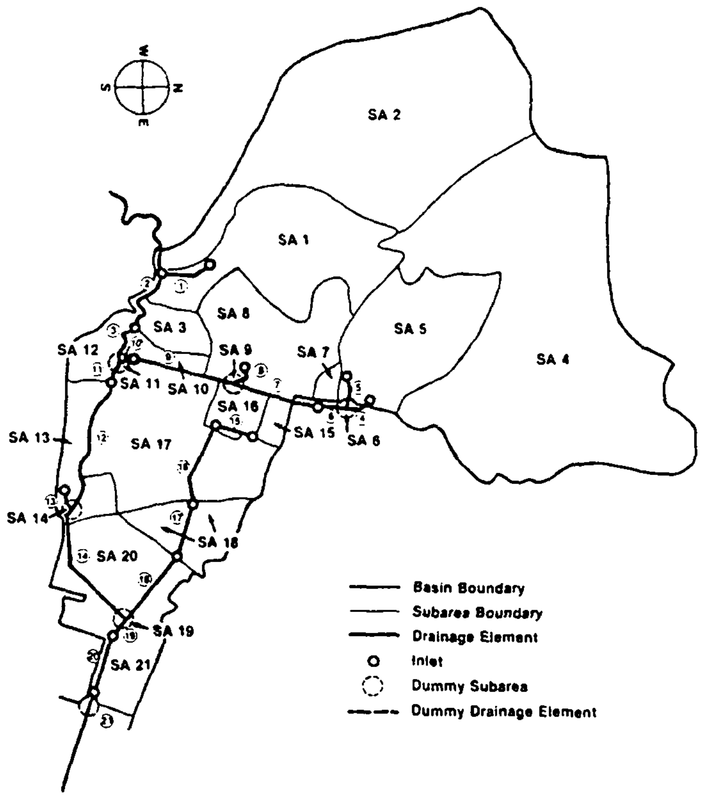

FIG. 6. Subareas and Drainage Elements of Basin 2B

All four subzones of the La Reforma expansion area were selected for development under Plan 3. To apply the development-reassignment option, it was therefore necessary to prevent development in the portion of each subzone corresponding to subarea 4. This amounted to reducing the maximum allowable population in each subzone, effecting changes in the RHSs of the appropriate constraints, as shown in Table 4. Fig. 7 shows the development pattern resulting from these changes and representing Plan 3A. Inlet 10 no longer shows aggravated flooding and the number of points with increased surcharge over the 1985 situation has decreased from 16 to 14. However, an additional new point has developed, raising to seven the number of new flood locations. The "cost" of improving upon the simulated flood pattern has been a fall of 3 Lcd in average water consumption, down to 174 Lcd. The only other significant change has been an increase in the number of inhabitants served by standpipes, from 60,413 to 66,791.

The same approach was followed in an attempt to alleviate flooding at

TABLE 4. Population Reassignment under Plan 3A

Expansion zone (1)	Original limit (2)	New limit (3)
La Reforma I	24,509	16,967
La Reforma II	22,291	12,109
La Reforma III	11,001	8,553
La Reforma IV	8,665	6,328

inlet 10 under Plan 5. In this case, no development had been assigned to La Reforma III, so only three constraints had to be altered, as shown in Table 5. The new development configuration, Plan 5A, would appear as in Fig. 8. No increase occurred at inlet 10, and the total number of inlets with worse flooding than in 1985 declined from seven to one. Moreover, no new surcharge points had developed. The sacrifice in average water consumption would be only 1.5 Lcd, while the number of people obtaining water from standpipes would rise slightly from 151,489 to 155,579. As in Plan 3A, total BOD_5 loading and average TACC would remain unchanged.

Not all stormwater problems can be solved by simply shifting proposed development to other locales and structural measures are the most common flood-control alternative. Detention facilities represent one class of engineering structure that can improve water quality while simultaneously reducing peak runoff. Based on SCS procedures ("Urban hydrology" 1975), detention basins at the outlet of subarea 4 would have to store approximately 5.3 acre-ft (6,538 m^3) under Plan 3 and 4.3 acre-ft (5,305 m^3) under Plan 5 in order to maintain peak runoff at inlet 10 at 1985 levels.

Assuming that the basins were designed properly, nonpoint-source BOD_5 could be reduced by about 50% by detaining the stormwater for 18 to 36 hours (Whipple and Hunter 1980). Yearly runoff in Cali is approximately 24 in. (610 mm). Since pollutant loading from a given storm is roughly proportional to the volume of runoff produced (Whipple 1979), multiplying the mean concentration of the pollutant of interest by the total yearly runoff will, for planning purposes, yield a reasonable estimate of total yearly pollutant loading. Although data on NPS pollutant loadings for Cali are very sparse, making predictions risky, figures from North America indicate mean BOD_5 concentrations to be around 20 mg/L. For subarea 4, this works out to approximately 122 kg BOD_5/ha/yr, comparing well with empirical data on loadings from various urban land uses in the United States (Whipple et al. 1983; Lazaro 1979). (The INGESAM-URS consortium, in its analysis of sewage treatment options for Cali, developed regression equations for pollutant loading by different land uses (*Proyecto* 1985). The equations relate loading in mg/s to discharge in L/s or m^3/s. The primary difficulty in using the formulas for planning purposes is estimating an average discharge for storms of varying intensity, duration, and frequency. For residential land use with paved streets, the relationship implies an average discharge of about 16 L/s to match the estimates provided here.) If 50% settled out in the detention basin, 11,315 kg BOD_5 would be removed every year. This reduction is less than 1% of the sewage-derived BOD_5 contributed by the new residents under either of the two plans being considered. However, this percentage will rise as greater portions of the urban area come under the influence of detention structures. Such improvement in water quality should be

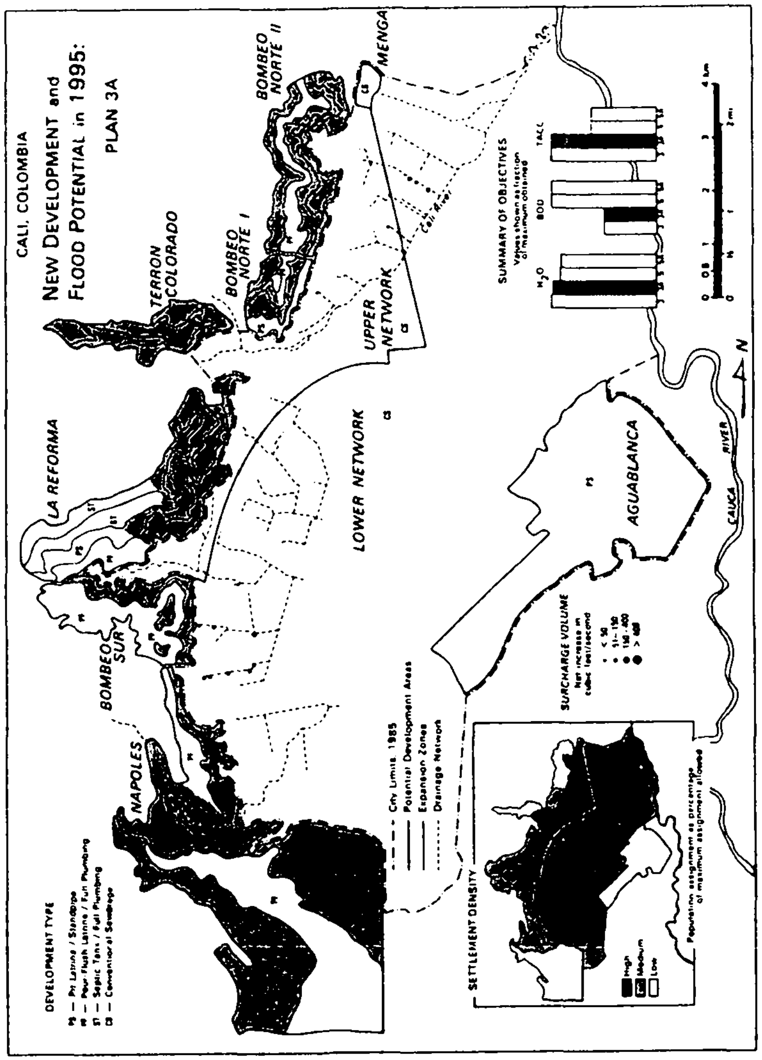

FIG. 7. Settlement Pattern (in White) and Flood Potential under Plan 3A

TABLE 5. Population Reassignment under Plan 5A

Expansion zone (1)	Original limit (2)	New limit (3)
La Reforma I	24,509	12,109
La Reforma II	22,291	16,967
La Reforma IV	8,665	6,328

taken into account when evaluating the costs and benefits of detention as an SWM alternative.

Sensitivity Analysis

One of the major points of uncertainty regards the water consumption levels expected to accompany the different water-supply systems. Since the values used were typical of consumption levels for the Third World as a whole, actual usage in Cali could vary substantially. The effect of such variance could be investigated by changing coefficients (w_j) in the objective function that maximizes average water consumption. If one considers these estimates to be within 25% of the corresponding consumption levels in Cali, then the optimal program should be stable when coefficients are changed by a similar amount. Postoptimality analysis indicated that the optimal program was indeed very sensitive to these estimates. In Plan 3, for example, 10 of the 14 decision variables for which assignments were made would cause changes in the optimal program if their objective function coefficients varied by less than 25%. Even in the highly unlikely case that Cali's consumption levels were within 5% of the estimates, the optimal development configuration could still change if some w_j were off by less than 1%. Therefore, full faith in the model requires empirical data on the relation between average water consumption and water-supply systems for Cali itself.

Projected population for 1995 is another parameter in which changes could occur. Although the population increase over the 10-year period was taken at 392,028, the true increment will assuredly be different. Sensitivity analysis indicates that this projection could underestimate the true increase by 99,569 or overestimate it by 7,668, without modifying the optimal development plan. Since the 392,028 figure was the lowest increase of the projections available, further refinement of the population projection is not necessary.

Unlike water consumption and population, saturation densities for the expansion zones have little to do with questions of data. These densities reflect planners' goals, and as with all goals, they are subject to possible change in the future. Several of these densities, if reduced by less than 10%, would cause changes in the recommended development program. A review of the criteria used to establish maximum permissible densities in those zones would therefore be advisable before adopting the plan.

Probably of greatest interest are the trade-offs among objectives. Recall from the earlier discussion of generating methods that these trade-offs are merely the relative weights when the weighted technique is used, or the dual prices associated with each objective-cum-constraint in the case of the constraint method. Equally important, however, is how changes in desired upper bounds for average TACC ($z_2 \leq \text{COL\$1,906}$) and total BOD loading ($z_3 \leq 1{,}666{,}119$ kg/yr) affect the preferred plan. The plan would be particularly sensitive to z_2, since allowing it to rise only 1% or drop by 7% would change

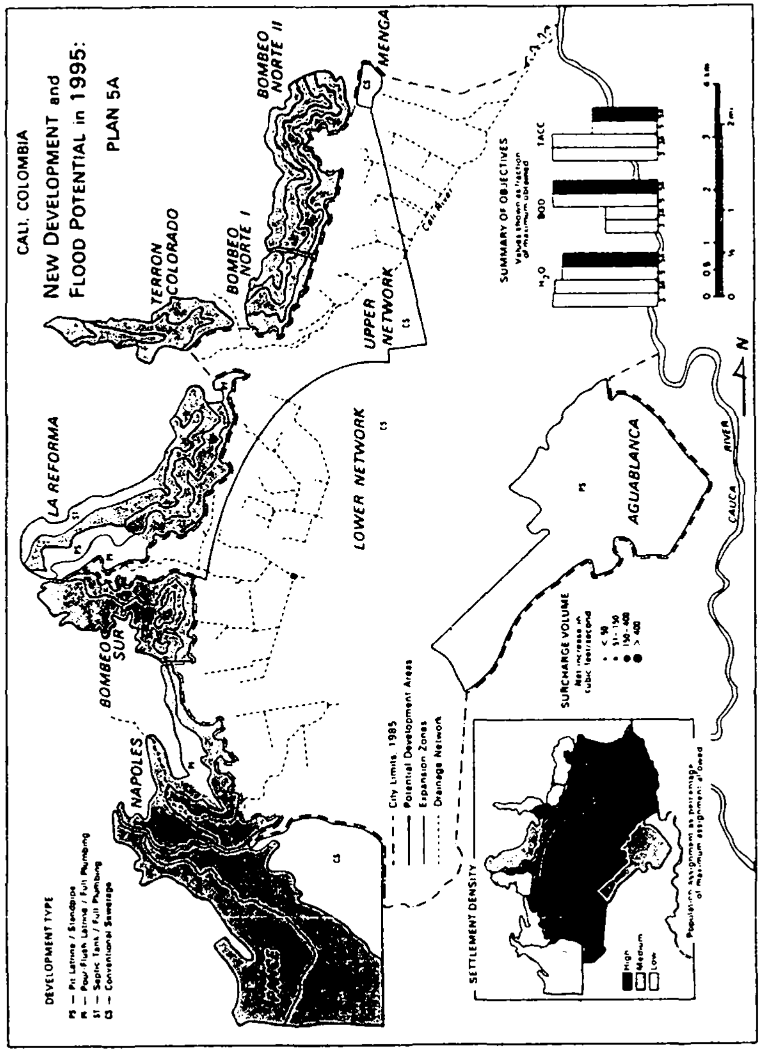

FIG. 8. Settlement Pattern (in White) and Flood Potential under Plan 5A

the structure of the plan, that is, the combinations of zones and systems to which people are assigned. On the other hand, upper bounds on BOD can increase by 25% or decline by 9% without affecting the plan's structure. In both cases, however, the number of people assigned to each zone and system, as well as the optimal value for average water consumption, may well change (Schrage 1984).

CONCLUDING REMARKS

The model presented here can be evaluated from two vantage points: (1) Its internal structure and functioning and how well these represent the relevant aspects of the situation at hand; and (2) its utility vis-à-vis policy analysis. Regarding the first, more sophisticated versions of the model's components could certainly be developed. Adding zero-one variables to the all-linear optimization model would allow it to consider off-site sewage-disposal options, while a multiperiod model could easily generate expansion scenarios through several planning horizons. The objectives themselves could also vary. For example, one might wish to consider the minimization of the sum of WSS costs and land costs, since many on-site systems require well-drained locations and these tend to be more expensive than poorly drained sites.

Doubtless, a more sophisticated simulation model could represent the runoff and routing processes more accurately than PSRM. Any attempt to improve upon the simulation in such a way must, however, deal with the very severe data limitations facing stormwater modeling in the developing world. In this study, for example, the following data were either unavailable, imprecise, or laborious to collect and verify: plans of the sewerage and drainage works; land use and land cover; soils and runoff coefficients; historical rainfall-runoff records; nonpoint-source pollutant loadings; relations between population density and imperviousness. And Cali is far better off in this regard than most Third World cities.

The linkage between the optimization and the simulation components is probably the weakest point in the procedure. As the number of surcharge points requiring abatement increases, so does the number of development-relocation constraints that must be appended to the multiobjective model. Not only can this become onerous, but with more than one new constraint it makes more complex the elucidation of trade-offs between land-use control and structural methods of runoff management. Related to this is the question of how to decide on the best mix of stormwater detention and land-use controls. Finally, since appending new constraints alters the optimal development pattern, in turn leading to a new pattern of flooding, the procedure has the potential to continue indefinitely. Although various rules can be applied to decide when to terminate the search (Ridgley 1986), none is without problems.

Considered as a tool for the analysis of urban development policy, the model has proven useful on a number of fronts. The procedure offers an integrated framework for treating four water-related problems—water supply, sewage disposal, flooding, and water pollution—that are commonly dealt with separately. It has demonstrated that these diverse water-related problems are not only affected by spatial patterns of land use, but to the extent that mitigation of these problems represents goals of urban development they can be employed to design alternative land-use patterns as well. The evaluation of such patterns then can play an important role in developing an urban growth strategy. Further, it has been shown that the selection of technologies for water supply and sewage disposal is not merely a technical problem, since the mix of systems chosen can enhance or stymie the achievement of larger social goals, such as that of effecting more equitable urban spatial development.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

b = BOD_5 (kg/yr);
c = total annual cost per capita (COL$);
$\mathbf{F}$ = feasible set of values for $\mathbf{x}$;
P = projected population increase;
p_i = existing population in growth area i;
s_i = saturation population of growth area i;
v = nonzero scalar weights of the objective functions;
w_c = water use by nonresidential sectors;
w_g = projected increase in water use by nonresidential sector;
w_j = water consumption (liters/capita/day) for system j;
w_{max} = projected sewage-treatment capacity;
w_r = water use by residential sector;
$\mathbf{x}$ = vector of decision variables x_{ij}; and
z_k = value of objective function k.

Subscripts

i = growth area; and
j = water and sanitation system.

DECISION SUPPORT FOR ESTUARINE WATER QUALITY MANAGEMENT

By Uwe Arnold[1] and Gerald T. Orlob,[2] Fellow, ASCE

ABSTRACT: Management of water quality in estuarine systems is a multistepped process, ranging from characterization of the hydrological and hydromechanical properties that govern water quality changes through identification of waste loads, regulatory constraints, and water quality attributes to identification of alternative candidate plans and selection by so-called decision makers of the best plan to be implemented. The ultimate step in this complex process is to operate the physical system within the stipulated performance goals. Recently, with the advent of ever-increasing computer power, geographic information systems (GIS) and interactive graphics, supporting integrated user-friendly data management and processing, have been added to the body of tools intended to support the decision process through its many steps. This paper focuses on implementation of a new generation microcomputer as the sole host of the decision support system, and seeks to demonstrate how it may be used at each step of the decision process. Special attention is given to features like: (1) Object-oriented data and control handling; (2) the integration of simulation models into the decision support system; and (3) the water quality management process. The case of a small estuary in Southern California is presented as a demonstration of the approach.

INTRODUCTION

Water quality management of an estuarine environment is a multistep process that seeks to find, implement, and operate the most economical and politically acceptable alternative for the control of waste emissions, for the regulation of upstream hydrology, and for the protection of the indigenous ecosystem, within regulatory water quality constraints defined for all beneficial uses of the estuary. The major steps in the process are the following:

1. Characterization of the hydrological and hydrodynamic regimen of the estuary and its tributary basin.
2. Identification and quantification of waste loads, domestic and industrial, that are presently discharged to the estuary or that may be discharged in the future.
3. Identification of regulatory constraints, standards of water quality, emission controls, and institutional restrictions that do presently, or could ultimately, govern the acceptability of alternative management systems.
4. Identification of key decision makers, managers, public- and private-interest groups, and institutional entities concerned with, or obligated to be involved in the choice of the preferred management alternative.
5. Characterization of the water quality of the estuarine system under present and projected future loadings.
6. Quantification of costs and economic trade-offs between management al-

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