WATER RESOURCES MANAGEMENT OF ALGARVE - INTERFACING SYSTEM DYNAMICS AND MULTIOBJECTIVE PROGRAMMING

António S. Câmara[1], José G.A. de Meneses[2], João P.A. Fernandes[2],
Ana P.N. Amaro[3] and M. Graça Viegas[4]

[1] New University of Lisbon, Lisbon, Portugal
[2] University of Evora, Evora, Portugal
[3] Direcção-Geral da Qualidade do Ambiente, Lisbon, Portugal
[4] Gabinete de Estudos e Planeamento, Ministério da Qualidade de Vida, Lisbon, Portugal

ABSTRACT

The Algarve province in Southern Portugal has been undergoing a rapid growth due to a large increase in tourist demand. The mismanagement of the region's limited water resources is leading those growth trends to a halt.

This paper introduces a model developed to provide a needed rational framework for Algarve water resources management, interfacing a system dynamics model with multiobjective programming formulations. The definition of water supply and demand sectors, on a spatially disaggregated basis, is an essential component of the model, with attempts to provide a tool to evaluate the effects of different strategies controlling water supply and demand upon a set of impact variables.

To select an optimal strategy one has to solve a multiobjective programming problem, where the components of the objective function are the impact variables referred above. Solution methods include the analytic hierarchy process and the value display approach.

The model written in Z-BASIC was run using a simulation period of 10 years.

INTRODUCTION

The Algarve province in Southern Portugal is a prime example of the consequences of a rapid, largely unplanned growth upon the water resources of a region.

The typically dry weather and the distinct geomorphological features of Algarve, mountainous in the North and flat in the coastal zone, contribute for scarce surface water (a few, low flow streams) and limited groundwater resources.

Algarve has had, in the past, a low-yield agriculture based economy. In recent years, the large increase in tourist demand has changed the picture. Today, the fast-growing tourism and affiliated industries are the main economic activities of the region. The resulting mismanaged construction boom is well documented by the new chaotic landscape, the degradation of the environmental quality, in the coastal areas and the severe reduction of water resources. The latter has occurred mainly due to the continuous application of unreasonable groundwater draft rates, and to the insufficient number of dams storing surface water. Although several authorities are trying to improve the situation, there is the need for a global framework for the rational management of Algarve water resources.

The goal of this paper is to introduce a mathematical model developed to provide such a framework. The model, interfacing system dynamics with multiobjective programmming formulations, assesses the impacts of different sets of control strategies upon the water supply and demand sectors, and selects the optimal one.

MODEL DEVELOPMENT

The water resources management of Algarve presented in this paper includes a system dynamics model and multiobjective programming formulations. The system dynamics model considers three components: sub-model I, representing the water supply sector; sub-model II, modelling the demand sector; and sub-model III, including management variables. These sub-models are operated as a chain, sub-model I preceding sub-model II, which precedes sub--model III which feeds back into sub-model I and II for each step of the simulation period.

The development of the model was based on causal diagrammatic idealizations of the sub-systems involved. These diagrammes were then translated into system dynamics type equations, which have the important feature of allowing for spatial disaggregation: the water supply sub-model considers four hydrogeologically homogeneous sub-areas (Figure 1); and the water demand sub-model comprises nine demand-wise similar sub-areas (Figure 1). The nine units were also used in the management sub-model. The global model was implemented and run in a microcomputer using Z-BASIC.

Multiobjective programming formulations were then applied to evaluate different strategies controlling water supply and demand and, ultimately, select the optimal one. They included methods such as the analytic hierarchy process and the value display approach.

SYSTEM DYNAMICS MODEL

Sub-model I - Water Supply Sector

The main objective of the water supply sub-model is to evaluate

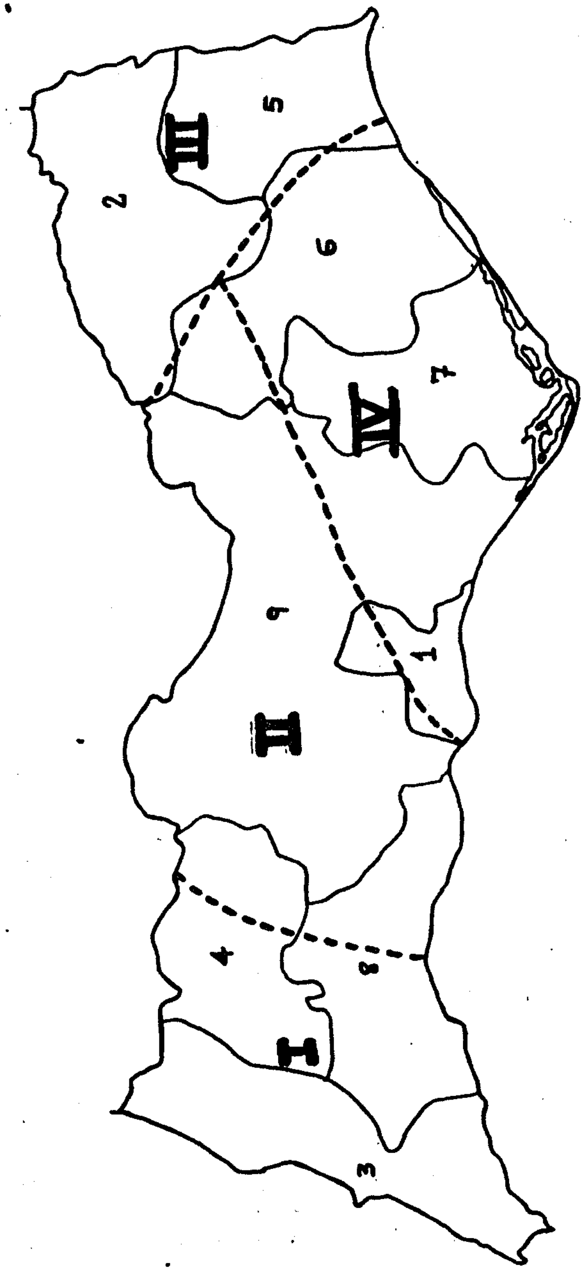

Figure 1 - SPATIAL DISAGGREGATION OF ALGARVE FOR MODELLING PURPOSES

Spatial Units

Water Supply
I. Canadian watershed
II. Praia da Oura - Tavira
III. Lagoa - Lagos
IV. Atlantic - Odeceixe

Water Demand and Management
1. Albufeira
2. Alcoutim
3. Vila do Bispo, Aljezur
4. Monchique
5. Castro Marim, Vila Real de Sto. António
6. Tavira
7. Faro, Olhão and S. Brás de Alportel
8. Portimão, Lagos, Lagoa
9. Silves, Loulé

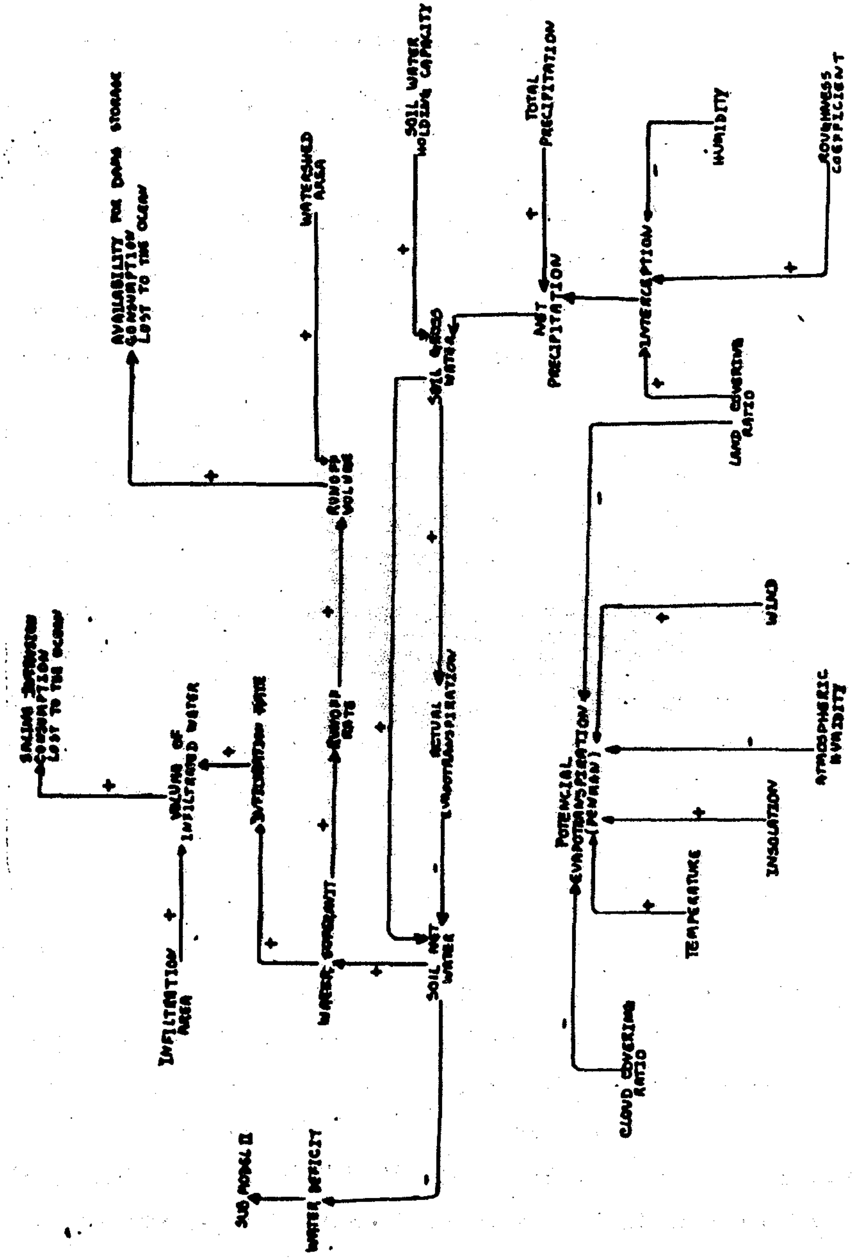

FIGURE 2 - CAUSAL DIAGRAMME OF WATER SUPPLY SUB MODEL

fore, indirectly determine the water demand of these facilities.

4. Population comsuption - with moderate growth rates.

These growth and decay rates are influenced by the water deficit or superavit, the former generating significant feedback loops such as the decrease of the tourism growth rate and the area of irrigated agricultre. A simplified version of the causal diagramme this sub-model and its links to the other sub-models are shown in Figure 3. Initial values and constants were taken from references [3, 4, 5, 6, 7 and 8].

SUB-MODEL III - MANAGEMENT

Sub-model III consists of a series of processes related to the water deficit conditions occurring at a given moment. These decisions involve mainly suspensions in the supply of water to the different demand sectors following a pre-defined priority ordering; the water supply should be first suspended to swimming pools then to construction. The suspensions should be avoided whenever possible for the industry and a minimum level of supply should be assigned to the population, tourism and green areas sectors. Decisions concerning the cut of water to the irrigation of uncontrolle agriculture are not taken. However, if the comsumption levels attain certain values, losses due to the salinization and/or dry of wells may occur.

Each suspension results in a certain damage that was taken into account either through feedback processes influencing growth of decay rates or just recorded in counters. Superavits of water

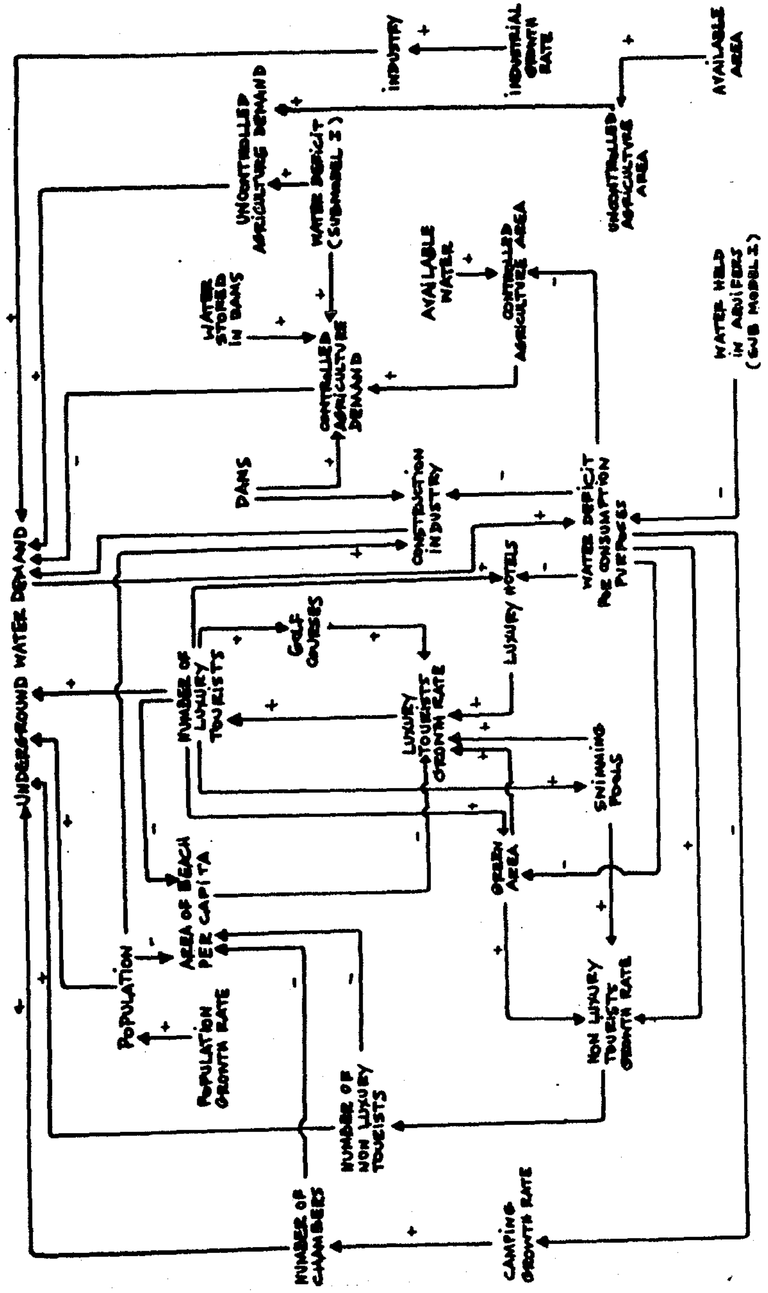

FIGURE 3 - CAUSAL DIAGRAMME OF WATER DEMAND SUBMODEL

representing mismanagement situations are also registered in appropriate counters.

MULTIOBJECTIVE PROGRAMMMING FORMULATIONS

The ultimate goal of the model is to evaluate the effects of different strategies controlling water supply and demand upon a set of impact variables. Each strategy is defined by a set of three items: (1) the value of a certain control variable CV will take at (2) a certain moment and (3) its spatial location. Control variables CV considered in the model include growth rates of industry, support facilities, hotels, the land covering ratio and the construction of dams. The number of "luxury tourists", the irrigated/non-irrigated agricultural areas ratio and counters of water deficit of superavit conditions are typical impact variables IV included in the model.

To select an optimal management strategy one has to solve a multiobjective programming problem, where the components of the objective function are the impact variables referred above, that may be represented for a simulation period T as vectors $[IV_T^k]$. The solution process consists of three steps:

1. For each alternative j, translate vectors $[IV_T^k]$, into a vector $[IV^k]_j$ by aggregating each vector $[IV_T^k]$ into a scalar IV^k. This is done by dividing simulation period T into sub-periods t_1, t_2, t_3 ... t_n, synthesizing sub-vectors $[IV_{t_i}{}^k]$ into a scalar by computing the summation, mean, median, mode, maximum or minimum for the values of $[IV_{ti}{}^k]$, depending on the nature of IV^k, assigning weights W_{ti} to the sub-periods to assess their relative importance applying

Saaty's analytic hierarchy process [9] and finally calculating $[IV^k]_j = \sum_{ti} w_{ti} \cdot [IV_{ti}^k]_j \cdot \forall k$.

2. Using a value display method and the calculated $[IV^k]_j$, define the non-inferior alternatives j. If there is a superior strategy the optimization stops, otherwise one advances to step 3.

The value display method adopted by Schilling [10], consists of displaying value paths which are lines drawn for each alternative to indicate the level of achievement of each objective: a line high upon the scale for an objective indicates a high value for that objective. An example of the application of this concept is included in the next section.

3. Normalize the $[IV^k]_j$ and define weights W_{iv} for each IV^k, using again Saaty's methodology. Compute then the summations $\sum_k w_{IV^k} \cdot IV^k$ for each j. The highest value of those corresponding to the optimal strategy.

MODEL APPLICATION

The logical structure of a water resources management model developed for Algarve was introduced above. The model has been implemented and tested extensively on a microcomputer using a Z-BASIC translation of DYNAMO III. At the moment, there are still some flaws resulting primarily from unrealiable data on the industrial base, "non-luxury tourism" and camping, and from the incipient knowledge one has of Algarve groundwater hydrology. The management options internal to the model should also be improved to reflect more realistically the policies that local authorities

usually assume. Thus, the example provided in this section should be interpreted solely as an illustration of the model's potential applications.

To apply the model one has to start by identifying the strategies to be evaluated. From a mathematical standpoint, the number of those, according to the definition of strategy given above, is almost unlimited. Applying a screening process using feasibility considerations one can, however, eliminate numerous alternative strategies from further analysis and define a relatively small number to be assessed with the model.

In the example presented below, the alternative strategies were generated on the basis of an exercise in scenario writing. For feasible scenarios for Algarve's evolution in the next ten years were considered: (1) the present socio-economic trends will continue; (2) a period of economic prosperity will arise; (3) development policies will privilege tourism and maintain the current growth rates for other economic sector; and (4) an international recession will lead to a crises in the tourism sector and the development of agriculture and industry will be thought. Four corresponding strategies were then defined by assigning appropriate values to the set of control variables integrating each strategy. In this case, four control variables were considered: industrial growth rate, growth rate of "luxury hotels", the parameter controlling the growth rate of green areas and the growth rate of irrigated agriculture areas. To assess these strategies four impact variables were chosen as most representative: the number of "luxury tourists", the area of irrigated agriculture, importation of drinking water and the counter of water superavit conditions.

Table 1 includes the strategies, control variables and their values and impact variables considered in this sample application. The model was run including all the four supply units but only three demand units (1, 7 and 8) to facilitate the illustration of the subsequent multiobjective programming formulations. The simulation period was ten years and a DT of one month was used.

For each alternative j, the vectors $[IV_T^k]_j$ were then translated into a vector $[IV^k]_j$ applying the methodology described in the previous section. An example of the calculations involved is shown in Table 2. Table 3 presents the $[IV^k]$ obtained for each strategy for each unit. For Algarve, the summation of the IV^k determined for units 1, 7 and 8 is considered in this application to be representative of the values of IV^k of the province.

A value display method and the calculated $[IV^{k}]_j$ were then used to define the non-inferior alternatives as shown in Figure 4. One may observe that there is no superior alternative. Normalizing the values of the impact variables and assigning them weights w_{iv}^k using Saaty's approach one can then compute $\sum_k w_{iv}^k \cdot IV^k$ for each j the highest value of those corresponding to the optimal strategy. In this example, as shown in Table 4, strategy 2 - growth of tourism, industry and agriculture was found to be the best option.

CONCLUSIONS

This paper introduces a model developed to provide a needed

Table 1

STRATEGIES, CONTROL AND IMPACT VARIABLES CONSIDERED IN THE SAMPLE APPLICATION

. Strategies and Control Variables

Control Variables	Strategies			
	1	2	3	4
Industrial growth rate ($month^{-1}$)	.01	.03	.01	.02
Growth rate of "luxury hotels" ($year^{-1}$)	1	2	2	0
Parameter controlling the growth rate of green areas ($month^{-1}$)	1.2	1.5	1.5	1.0
Growth rate of irrigated areas ($month^{-1}$)	.1	.15	.1	.13

. Impact Variables

- "luxury tourists"
- Areas of irrigated agriculture
- Importation of drinking water
- Counter of water superavit conditions

Table 2 - COMPUTATION OF THE IV^k_j VECTOR - AN EXAMPLE (DEMAND UNIT 1, STRATEGY 2)

	Time Periods										
	1		2		3		4		5		
IV^k	$IV^k_{t_i}$	W_{t_i}	$IV^k_{t_i}$	W_{t_i}	IV^k_{ti}	W_{t_i}	$IV^k_{t_i}$	W_{t_i}	$IV^k_{t_i}$	W_{t_i}	$IV^k{}_j$
LT	45655	1.22	45589	1.22	45203	1	45012	1	44899	8	45315
UA	213	1.22	225	1.22	234	1	245	1	258	8	233
WS	13.8E6	1	13.5E6	1	12.9E6	1	12.3E6	1	11.9E6	1	12.9E6
IDW	0	.8	40449	1	50259	1	59200	1.22	68521	1.22	47047

$IV^k{}_j = \sum IV^k_{t_i} \cdot W_{t_i} \;/\; \sum W_{t_i}$; $t_i - t_{i-1} = 2$ years

$IV^k_{t_i}$ — LT "luxury tourists" - average of the annual maximum values

— UA uncontrolled agriculture - avegerage of the annual maximum values

— WS water superavit - average

— IDW importation of drinking water - average of the annual maximum values

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Table 2

IV^k OBTAINED FOR EACH STRATEGY FOR EACH UNIT

Demand units	Strategies	Impact Variables			
		"luxury tourists" (month^{-1})	area of irrigated agriculture (ha/year)	importation of drinking water (l/year)	water superavit (l/year)
1	1	45360	218	46971	13360000
	2	45315	233	47047	12880000
	3	45315	218	47047	12000000
	4	45355	230	46971	11900000
7	1	2207	1830	39852	10100000
	2	1865	1913	39782	4340000
	3	2194	1860	39760	8580000
	4	2207	1902	37856	10440000
8	1	21647	1062	54800	3880000
	2	22081	1135	47020	10460000
	3	22080	1062	50693	2500000
	4	22080	1099	50719	3400000
Algarve	1	69214	3110	141623	27340000
	2	69261	3281	133849	27690000
	3	69589	3140	137500	23080000
	4	69642	3231	135546	25740000

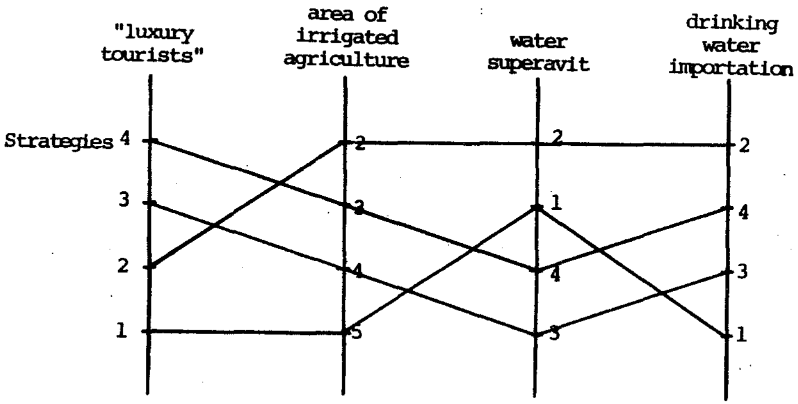

Figure 4 - Application of a value display approach

Table 4 - DEFINITION OF THE OPTIMAL STRATEGY

IV^k	Strategies				W_{iv}^k
	1	2	3	4	
	Normalized Values				
LT	1	1.001	1.005	1.006	.37
UA	1	1.055	1.010	1.039	.39
WS	1.185	1.199	1	1.115	.08
IDW	1	0.945	0.971	0.957	.16
Final Score	1.015	1.028	1.001	1.019	

rational framework for Algarve water resources management, interfacing a systems dynamics model with multiobjective programming formulations. Sub-models of water supply and demand sectors and of internal management decisions, defined on a spatialy disaggregated basis, are essential components of the model which provides a tool to evaluated the effects of different strategies controlling water supply and demand upon a set of impact variables.

To select an optimal strategy one has to solve a multiobjective programming problem where the components of the objective function are the impact variables referred above. Solution methods include Saaty's analytic hierarchy process and the value display approach.

This methodology was applied in a simple example were the demand sub-model only considered three spatial units. The objective was solely to provide an illustration of the approach and point out the potential interest of the model in a management process.

It was noticed that there are still flaws in the model resulting primarily from unrealiable information on socio-economic variables and on Algarve's groundwater hydrology. At this stage, one may nevertheless assert that despite these limitations, the proposed model is a sound basis for the development of a rational framework for the management of the scarce water resources of Algarve.

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