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A Decision Model for the Planning and Management of Water on the Basin/Sub-Basin Scale Case Study: Western Algarve Water Sub-System (Portugal)

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ABSTRACT: Decision models can be a useful tool for water resources planning and management if an adequate and thorough examination of the problem's circumstances is carried out. For resource management and water allocation problems, relevant documents such as the Agenda 21 of the United Nations Conference on Environment and Development and more recently the European Water Framework Directive, recognize the water basin as the appropriate unit of analysis for integrated water resources management. The decision model used in this work helps the water authorities to decide about water allocation between different uses (*e.g.* agriculture and urban water supply) on the basin/sub-basin scale. The authors use the Western Algarve water sub-system as their case study. They employed data from a historic decade to evaluate the performance of the water system considering different planning time horizons and objectives for storage in the surface reservoirs at the limit of the planning time horizon. The results showed a high risk situation, at least while a new surface reservoir (the Odelouca dam) is not in operation.

INTRODUCTION

Mathematical decision models can be a useful tool for water resources planning and management. They can help with the selection of the best decision/set of decisions regarding the type, dimension or location of infra-structures to be constructed or support system's operations.

One of the critical steps in the development of decision models is a thorough examination of the problem's context. Adequate descriptive models should be used to properly reproduce the response of the water system to the interventions. For aquifer management purposes an appropriate descriptive model can range from a simple hydrologic balance up to the use of parameter distributed models, if a physical description of the groundwater flow is necessary and sufficient data is available. The temporal and the spatial scales can also differ widely depending on the characteristics of the problem. In terms of time scales, planners may be concerned just with an average answer or be interested in capturing a system's dynamic. In relation to space the analysis may deal with each component of the water system individually or be performed in an integrated framework at planning unit level.

For resource management and water allocation problems, relevant documents such as the Agenda 21 of the United Nations Conference on Environment and Development (UNCED, 1992) and more recently the European Water Framework Directive (Directive 2000/60/EC) recognize the water basin as the appropriate unit of analysis for integrated water resources management. It is at this level that water

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allocation decisions have wider hydrologic, economic, social and environmental implications. As a result, policy instruments designed to make more rational use of water resources are likely to be used (McKinney *et al.*, 1999).

In this work the authors present a decision model allowing the identification and evaluation of alternative resource management and water allocation decisions by the government on the basin/sub-basin scale. The decision model is described in the Chapter 0. Chapter 0 shows the application of the decision model to a simple case study, to assess its capabilities and indicate the kind of results that can be expected. The authors take the Western Algarve water sub-system as their case study, using hydrologic data from a historic dataset and considering different planning time horizons and objectives for storage in the surface reservoirs at the limit of the planning time horizon.

MODEL OVERVIEW

The decision model to be used in this work will help the water authorities to decide about water allocation between different uses (*e.g.* agriculture and urban water supply). Descriptive models are included in the formulation to describe the water storage in dams, the groundwater flow in the aquifers and the blending of different types of water in complex distribution systems. The . recommendations of the Water Framework Directive for the promotion of efficient and sustainable water use are taken into account, in particular the management of the resources on the basin/sub-basin scale, the use of the economic value of the water in resource allocation decisions and the adoption of an integrated framework for assessing water management policies.

The model minimizes intervention costs over the entire optimization period and the decisions are discretized in periods of one month (Figure 1). The objective function of the decision model has two distinct components, and is the sum of the variable operation costs (*e.g.* abstraction, pumping, treatment costs) plus a *Penalty*. The *Penalty* is determined for each water use (*e.g.* urban supply, irrigation) and represents an economic loss due to deliveries less than water demand.

In order to guarantee the feasibility of the solution and the sustainability of the system being managed some constraints are considered in the decision model. Surface water storage in dams is modelled with a mass balance equation. The groundwater flow in the aquifers is represented by means of distributed parameter models, employing the matrix response approach (*e.g.* Maddock, 1972; Peralta *et al.*, 1991). Water quality is specified in terms of the volumetric ratio of water from different sources. This approach was used by Yang *et al.* (2000) and later by Tu *et al.* (2005) to control the quality of the water delivered for public urban supply in a complex distribution system. Sustainability criteria, such as minimum piezometric heads, maximum abstraction from wells and minimum discharges from dams for ecosystem maintenance are included as constraints of the decision model.

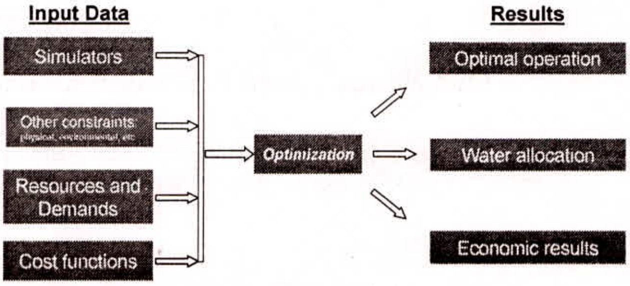

Fig. 1: Model input data and results

CASE STUDY

The Algarve region is the southernmost province of Portugal (Figure 2) and has a base population of 400 thousand inhabitants. The climate is characterized by an irregular precipitation regime (a short and sharp winter and a long dry summer) and the possibility of occurrence of periodic droughts. The main economic activities—tourism and irrigated agriculture—put the water resources under great pressure.

Fig. 2: Location of Portugal and its Algarve region in the Iberian Peninsula

For water management purposes, two sub-systems can be identified in the Algarve: the Western and the Eastern, although there is some connection between them. In the Algarve Western sub-system, as long the Odelouca dam is not in operation (this dam will be finished by 2010/2011), the water for the public water supply should come from four different sources: surface water from the Funcho and the Bravura dams, groundwater from the Querença-Silves aquifer system and water imported from the Eastern sector. Surface water from both dams has always an adequate treatment, before being used in the public water supply. Groundwater can be supplied for urban use without any treatment, but a maximum blend of 50% of groundwater is used to control water quality. The connection between the two sub-systems is assured by a main pipe allowing the transfer of up to a predetermined maximum amount of water, depending on the capacity of the established infrastructures. Through a complex pressurized system that includes main pipes, elevation pumps, intermediate reservoirs, water for urban use is delivered to 31 distribution reservoirs. Irrigation is associated with public investments made in both dams and to private interests in the Querença-Silves aquifer system. This set-up means that the authorities are able to interfere efficiently with the public water supply demand and the delivery of water for irrigation associated with both dams. Water demand for irrigation in the Querença-Silves aquifer system can not be regulated efficiently and thus is an input datum of the decision model.

Hydrologic Data

The analysis of the performance of the water system spanned 10 hydrologic years, starting in 1981/82 and ending in 1990/91).[*] That decade was characterized by a significant variation of the hydrologic variables (Table 1) and four of the first six years were classified as normal/dry, dry or very dry.

Table 1: Characteristics of the Hydrologic Years 1981/82–1990/91 (MAOT, 2000)

Hydrologic Year	*Characteristics*
1981/82	dry
1982/83	very dry
1983/84	normal
1984/85	normal/wet
1985/86	normal/dry
1986/87	normal/dry
1987/88	wet/very wet
1988/89	wet
1989/90	very wet
1990/91	normal

Figure 3 shows the monthly values of the inflows of the Funcho and the Bravura dams and the distributed recharge of the Querença-Silves aquifer system. The hydrologic year 1982/83 was the driest year of the decade: inflows to both dams are nearly zero; distributed recharge to Querença-Silves aquifer system reaches minimum values.

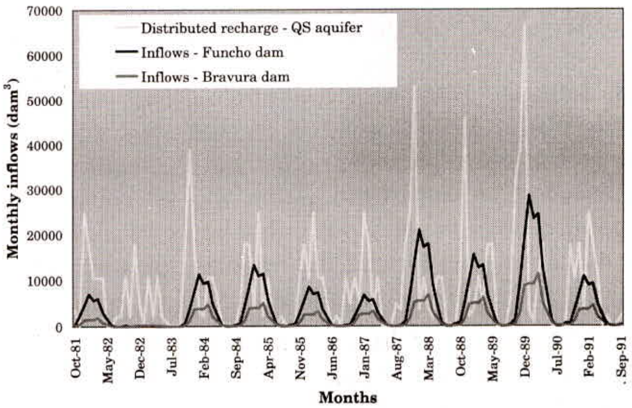

Fig. 3: Monthly inflows for the Funcho and the Bravura dams and distributed recharge of the Querença-Silves aquifer system (values in dam^3 = 1000 m^3)
Source: MAOT (2000)

Water Demand

Table 2 shows figures for the actual water demand of each use characterized by significant seasonal variations. Irrigation is necessary in spring and summer, and tourism also contributes crucially to increased public water supply demand in the same period.

Alternative Resource Management Scenarios

The first scenario considered, *Scenario B(Base)-PP(Perfect prediction of the hydrology for a period of ten years)*, assumed perfect prior knowledge of the hydrology in the decade. The model was solved with a single deterministic run in the period of analysis. However the presumption of perfect knowledge of the hydrology may result in unrealistic system operations with the anticipation of extreme events. Extra storage in the dams may be suggested before the occurrence of dry years to prevent greater shortfalls in water use over the critical period.

The evaluation of limited hydrology forecasting ability was considered with two scenarios that supposed a predictive capacity of one year—*Scenario B-M1 (Perfect prediction of the hydrology for a period of one year)*—and five years—*Scenario B-M5 (Perfect prediction of the hydrology for a period of five years)*. The problem was solved for a sequence of ten years

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[*] The hydrologic year in Portugal starts in October and ends the following September.

Table 2: Monthly Water Demand for the Different Uses (values in $dam^3 = 1000\ m^3$)

Water Use		*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Year*
Public water supply		4350	3224	3331	3331	3009	3331	5771	5963	6524	7630	7630	6524	60618
Irrigation	Funcho	0	0	0	0	0	549	876	1554	2137	2663	2394	1530	11702
	Bravura	0	0	0	0	0	123	214	306	542	737	701	420	3042
	Querença-Silves	1451	0	0	0	0	0	1693	3144	4353	5562	4836	3144	24182

for *Scenario B-M*1 (this means that ten runs were performed) and for two sequences of five years each for *Scenario B-M* (with two runs of five years each being performed). The initial state of the system (*e.g.* storage at dams, piezometric head in the aquifers) of a subsequent sequential model run was set equal to the ending state of the previous one. The series of *n*-linked consecutive runs formed the optimal operating policy for the entire period of analysis.

But in periods of drought these scenarios led to dead storage in dams at the end of the time horizon of each sequential run. Looking ahead to the discussion of results in the next chapter, this situation occurred very early in the first sequential run (*i.e.* hydrologic year 1981/82) when solving Scenario *B-M*1. The solution of the decision model revealed a scarcity situation, and the Funcho dam reached dead storage at the end of the time horizon. That volume corresponded to the minimum admissible storage in the Funcho dam, in agreement with one constraint of the decision model. This minimum storage in the end of the first sequential run had a tremendous impact on the operation of the water system in the next (and very dry) hydrologic year. Even with no abstractions and some discharges for ecosystem maintenance, the Funcho dam would enter dead storage during the hydrologic year 1982/83. That situation represented a violation of the model's constraints and the decision model had no feasible solution. For this reason the operation of the system in the hydrologic year 1982/83 was optimized to not consider the Funcho dam as a possible source for the water system.[**]

To prevent dead storage in the surface reservoirs at the limit of the time horizon, three hypothesis were tested. They result from the introduction of new constraints into the decision model and changes to the objective function.

The first hypothesis to be tested was simply to impose end storage higher than the dead storage. The sum of the end storage values in the Funcho and the Bravura dams would allow the satisfaction of approximately 75% of the public water supply demand in the first month of the next sequential run without entering the dam's dead storages. The remaining volume of water to meet the total satisfaction of the demand of the public water supply would come from the Querença-Silves aquifer system and the Eastern subsystem—*Scenarios MIN-PP*, *MIN-M*5 and *MIN-M*1.

The second hypothesis was related to the first one and supposed a stationary condition (*i.e.* the end storage is set equal to the initial storage) in the operation of the Funcho and the Bravura dams. But where there is significant variation in the hydrology, stationary conditions are valid only if the time horizon is sufficiently large. So the hypothesis of stationary condition in the operation of both dams was only admitted where there was perfect knowledge of the hydrology and of a five-year predictive capacity of the hydrology—*Scenarios EE-PP* and *EE-M*5.

The third hypothesis to be tested was the introduction into the objective function of a benefit associated with the dam's end storages. The refinement of the benefit function should involve a systematic search procedure, for many series of sequential runs over a long period of analysis (Draper, 2001). For this paper a linear function and two preliminary values of benefit associated with the end storage in the surface reservoirs were used. The end storage in the surface reservoirs had a value of 100 €/dam^3 in *Scenario PEN*1 and 200 €/dam^3 in *Scenario PEN*2.

All the *Scenarios* were programmed with GAMS (Brooke *et al.*, 2005) and solved with MINOS (Murtagh and Saunders, 1998), an optimization algorithm well-suited to continuous nonlinear models.

RESULTS AND DISCUSSION

Table 3 shows the values of the total deficit, the operation costs and the *Penalty* value obtained in each *Scenario*. In Table 4 it is possible to take a close look to the differences in the satisfaction of the demand by water use in each *Scenario*. In general, system performance is lower for shorter planning time horizons, owing to smaller satisfaction of the demands.

[**] The same situation occurred when solving Scenario MIN-M1 and Scenario PEN-M1.

Table 3: Total Deficit, Operating Costs and *Penalty* Value for Each *Scenario*

Scenario		*Total Deficit (hm³)*		*Operation Costs - OC (10³€)*		*Penalty – P (10³€)*		*OC + P (10³€)*	
		Monthly Aver.	*% Dif. Rel. Scenario B-PP*	*Monthly Aver.*	*% Dif. Rel. Scenario B-PP*	*Monthly Aver.*	*% Dif. Rel. Scenario B-PP*	*Monthly Aver.*	*% Dif. Rel. Scenario B-PP*
B-	*PP*	7,480	0%	563	0%	593	0%	1156	0%
	M5	8,228	10%	541	-4%	1133	91%	1674	45%
	M1	10,718	43%	–	–	+∞	–	–	–
MIN-	*PP*	7,480	0%	563	0%	593	0%	1156	0%
	M5	7,885	5%	548	–3%	663	12%	1210	5%
	M1	10,236	37%	–	–	+∞	–	–	–
EE-	*PP*	7,710	3%	563	0%	600	1%	1163	1%
	M5	7,816	4%	548	–3%	606	2%	1154	0%
PEN1-	*PP*	7,426	–1%	555	–1%	526	–11%	1081	–7%
	M5	8,556	14%	542	–4%	1128	90%	1670	55%
	M1	11,133	49%	–	–	+∞	–	–	–
PEN2-	*PP*	7,502	0%	558	–1%	527	–11%	1085	–6%
	M5	7,712	3%	555	–2%	640	8%	1195	3%
	M1	9,386	25%	528	–6%	20701	3392%	21230	1736%

Table 4: Satisfaction of Demand (monthly average) by Water Use for Each *Scenario*

Scenario		*Satisfaction of the Demand*					
		Public Water Supply		*Irrigation Funcho*		*Irrigation Bravura*	
		Monthly Aver.	*Minimum*	*Monthly Aver.*	*Minimum*	*Monthly Aver.*	*Minimum*
B-	*PP*	95%	66%	65%	0%	92%	57%
	M5	94%	27%	68%	0%	92%	56%
	M1	87%	0%	77%	0%	100%	100%
MIN-	*PP*	95%	66%	65%	0%	92%	57%
	M5	94%	66%	68%	0%	92%	56%
	M1	88%	8%	74%	0%	100%	100%
EE-	*PP*	95%	66%	63%	0%	92%	56%
	M5	95%	66%	63%	0%	92%	56%
PEN1-	*PP*	95%	70%	66%	0%	89%	43%
	M5	94%	27%	65%	0%	92%	56%
	M1	87%	0%	72%	0%	100%	100%
PEN2-	*PP*	95%	70%	65%	9%	89%	43%
	M5	95%	66%	67%	0%	92%	56%
	M1	91%	13%	68%	0%	100%	100%

Planning water management with a short time horizon and paying any attention to saving some water for the future in the surface reservoirs, *Scenario B-M*1, would lead to the total disruption of the public water supply in the hydrologic year 1982/83 (Figure 4). At the end of the first of ten sequential runs (*i.e.* end of the hydrologic year 1981/82), the Funcho dam reached dead storage (Figure 5). After a very dry hydrologic year, it would not be possible to use the Funcho dam without exploiting the dead storage, a situation that configured a violation of the model's constraints. The total disruption of the public water supply could be avoided with an inter-annual management of the resource (*Scenarios B-M*5 and *B-PP*). The differences in the total shortfall and in the satisfaction of the demands between the three scenarios are mainly due to alternative strategies of operating the Funcho dam. Anticipating the occurrence of dry periods, some water is saved to cope with droughts. Besides the emptying of the Funcho dam, total disruption in the hydrologic year 1982/83 and other significant shortages in the public water supply (*e.g.* October 1984, 1985 and 1986 in Scenario *B-M*1—see Figure 4) are also justified by the model's constraint demanding a maximum blend of 50% of groundwater in the water delivered for this use.

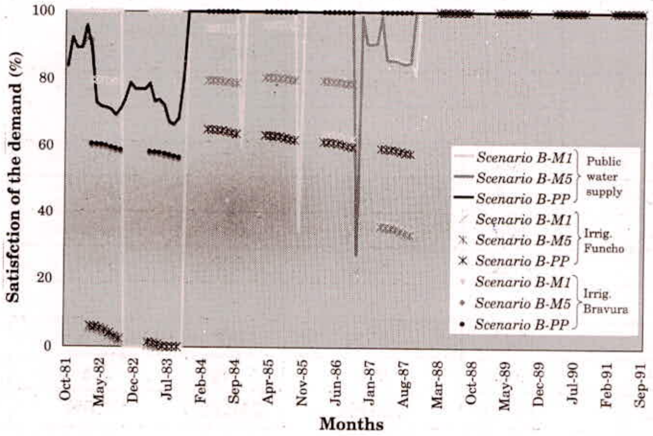

Fig. 4: Satisfaction of the demands in *Scenarios B-M*1, *B-M*5 and *B-PP*

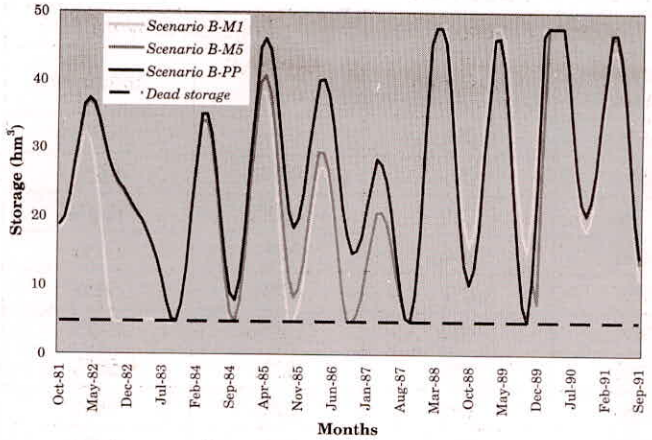

Fig. 5: Storage in the Funcho dam in *Scenarios B-M*1, *B-M*5 and *B-PP*

The greater satisfaction of the demand of the public water supply relative to the irrigation use in the Funcho dam (Table 4) depicts the higher economic value attributed to the first of the two uses. But irrigation use in the Bravura dam was not affected as much as might be supposed at first. Nevertheless, the total satisfaction of the irrigation demand in the Bravura dam in *Scenarios M*1 could not be justified by the economic value of this use. In *Scenarios M*1 the Bravura dam never reached dead storage, and so there was no real competition between the irrigation use and the public water supply. The contribution of the Bravura dam to the public water supply was not greater, because of either the drinking water production capacity of the water treatment plant associated with this dam, or the model's constraint that imposed equal relative satisfaction of the demand on all the distribution reservoirs. In the *Scenarios M*5 and *PP*, however, where dead storage was also reached in the Bravura dam, total satisfaction of the demand for irrigation was no longer attained (Table 4 and Figure 6) due to competition between the water uses.

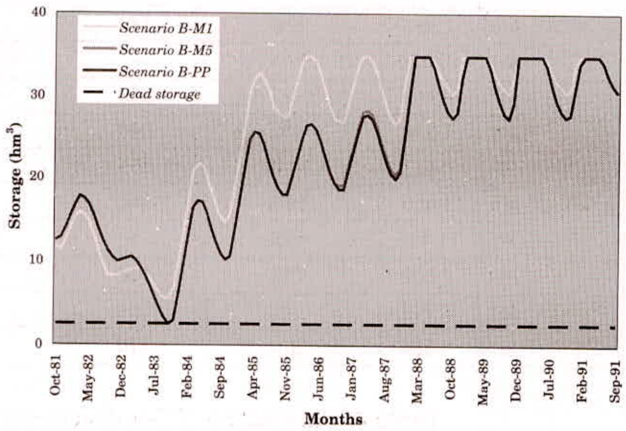

Fig. 6: Storage in the Bravura dam in *Scenarios B-M*1, *B-M*5 and *B-PP*

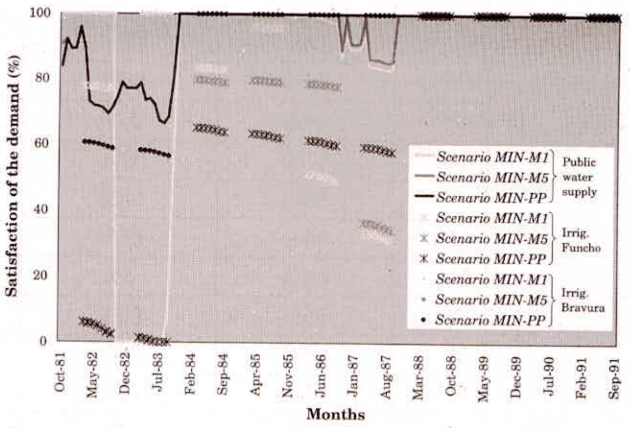

Fig. 7: Satisfaction of the demands in *Scenarios MIN-M*1, *MIN-M*5 and *MIN-PP*

When a final storage greater than the dead storage was enforced at the end of each sequential run some benefits on the system performance were observed (Figure 7). In the *Scenario MIN-M*5, saving some water at the end of the first sequential run (*i.e.* end of the hydrologic year 1985/86—September 1986) made it possible to avoid the serious shortage in the public water supply that occurred in *Scenario B-M*5 in October 1986. In *Scenario MIN-M*1 it was not possible to avoid the total disruption of the public water supply during the hydrologic year 1982/83, but the shortages happening in *Scenario B-M*1 at the beginning of the hydrologic years 1984/85, 1985/86 and 1986/87 were prevented.

When stationary conditions were enforced in a dam's operation, differences were clear when *Scenarios B-M*5 and *EE-M*5 were compared. Minimum satisfaction of the demand of the public water supply rose to 66% and the average monthly value of the economic losses due to deliveries of less than the water demand fell significantly (Table 3 and Table 4). The significant reduction in the average value of the *Penalty* is due to the prevention of the shortage in the public water supply that was happening in Scenario *B-M*5 in the hydrologic year 1986/87 (Figure 4).

In the *Scenarios* in which a benefit associated with the end storage in both dams was tested, the best overall results were obtained with the highest benefit factor tried (*Scenario PEN*2). Even in the scenario that presumed an annual management of the resource (*Scenario PEN*2-*M*1) it was possible to forestall the situation of total disruption of the public water supply during the hydrologic year 1982/83 (Table 3 and Table 4). Other situations of water scarcity were overcome with almost no restriction on the use of water for the public water supply (Figure 8).

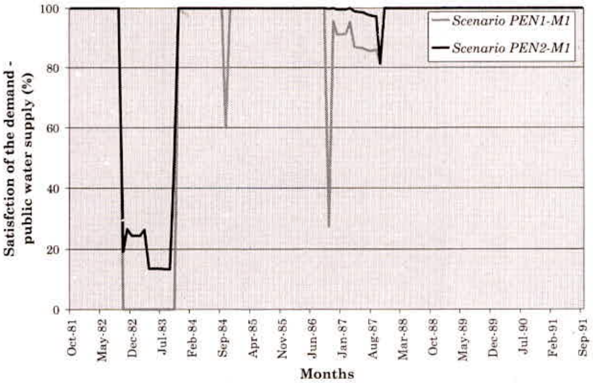

Fig. 8: Satisfaction of the demand of the public water supply in *Scenarios PEN*1-*M*1, and *PEN*2-*M*1

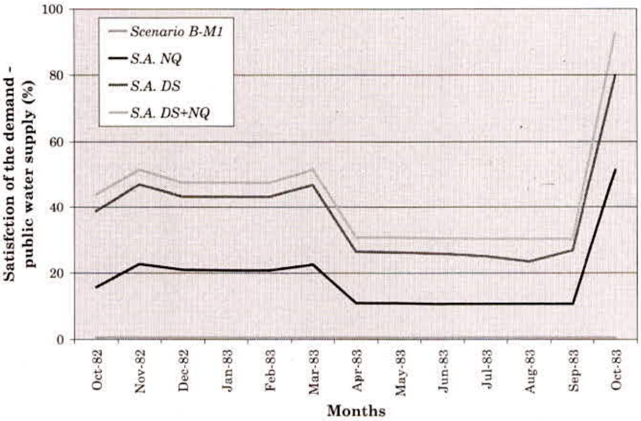

Fig. 9: Satisfaction of the public water supply demand in *Sensitivity Analysis NQ*, *DS* and *DS+NQ*

A *Sensitivity Analysis* (*S.A.*) was carried out on *Scenario B-M*1 between October 1982 and October 1983 to prevent the total disruption of the public water supply. To avoid this situation it was allowed to exploit up to half of the dead storage (*S.A. DS*) and the model's constraint demanding a maximum blend of 50% of groundwater in the water delivered for urban use was relaxed (*S.A. NQ*). Total disruption could be avoided, but significant shortages in the public water supply would persist, even if both measures were implemented by the authorities (Figure 9).

FINAL REMARKS

The application of a decision model to water use planning and management in the Western Algarve sub-system showed a high risk situation. As long the Odelouca dam is not in operation the system's performance could be seriously affected in periods of drought. But an integrated framework for deciding water management policies with inter-annual planning time horizons can help to cope with shortages during droughts. The carryover value of the storage in the surface reservoirs at the limit of the planning time horizon was also evaluated, and additional constraints were introduced into the decision model or changes were made to the objective function. Preliminary results indicate the best performance of the water system occurs with the introduction of a benefit function associated with the storage in the surface reservoirs at the limit of the planning time horizon.

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