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The Dynamics of Water Allocation in Semi-Arid Regions

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ABSTRACT

The critical role of water for sustainable development and limitations of supply management have increased the importance of demand management in meeting water needs. As an integral part of demand management in water-stressed regions water allocation policies address the competition between different user groups for scarce water resources. This paper presents a dynamic simulation model of a water system in semi-arid regions for the purpose of analyzing the effectiveness of allocation policies in meeting two objectives: 1) fill current demand and 2) provide adequate supply for future use. The model was calibrated and tested with data and policies from the Mediterranean island of Cyprus. Analysis of water allocation policies reveal that locally rational but overly risk adverse policies degrade performance and that counterintuitive water allocation policies can be more effective in satisfying both current demands with future water supply needs than current policies.

INTRODUCTION

One-fifth of the world's population lack access to adequate, clean water supplies. This threatens national security as well as prosperity, prompting Wally N'Dow, Secretary-General of the United Nations Conference on Human Settlements to predict "…a shift from oil to water as the cause of great conflicts between nations and peoples." (U.S. Water News Online 1996). Increases in supplies of water are limited because easily accessible sources are invariably exploited first (Brooks, 1997), causing underutilized water sources to grow increasingly difficult and expensive to exploit. While supply management approaches to insufficient water can help in some areas of the globe it cannot indefinitely relieve the pressure on the world's water supply in the future (Postel, 1992). This is particularly true in areas of water scarcity (Al-Ibrahim, 1990). For example Hamdy et al. (1995) classified Mediterranean countries into three groups according to future water problems: 1) countries where water supplies are currently sufficient, 2) semi-arid countries with currently sufficient but declining resources and 3) arid countries already facing water shortage crises. Semi-arid regions are characterized by long, hot, dry summers and short, mild, wet winters. Tourism is also highest in the summer, in some

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cases increasing the population by 50 to 100%. Although these countries can currently meet their overall water needs they face periods of shortages due to high demand and inconsistent supply. Total demand can only be met by means such as over pumping aquifers, which allows salt water intrusion and pollution of the aquifer (Brooks, 19xx). These countries cannot sustain any significant increase in per capita withdrawals or economic growth with their current water management and can only partially meet their current water needs.

We focus on semi-arid regions due to their combined critical need for improved water resource management and opportunities to avoid crisis conditions. Having done what they can to increase available supply through water development projects, water managers in these regions must manage demand in addition to supply. Three forms of demand management are used to match demand and supply: total demand management, load management and allocation. Total demand management reduces water needs. Semi-arid regions are often dominated by water uses (e.g. agriculture) and economic forces (e.g. growth) that severely limit the reduction of total demand. Load management changes the pattern of supply, use, or both over time to match periods of high demand with periods of high supply. Allocation of available supply occurs when water managers cannot or choose not to meet all demands and distribute available supply among users. Allocation decisions divide scarce resources among competing uses to meet various social, economic or political goals (Stiles, 1997). Allocation is often the primary tool of water managers in semi-arid regions (Haten-Moussallen, Gaffney, Cox, and Batho, 1999). Due to its critical role we focus here on the impacts of allocation policies on filling water needs. In contrast to water resource management models that focus on supply characteristics such as variability (e.g. Wilchfort and Lund, 1997) we focus our investigation on management policies as they are used by practitioners. Understanding these policies is critical to understanding system performance. By modeling the actual policies of practitioners we investigate their impacts on performance and changes which can improve system performance.

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ALLOCATION POLICIES

Water managers in semi-arid regions face the difficult task of developing and implementing allocation policies that will simultaneously fulfill current demand and save adequate supplies to provide continuity of supply during droughts. The underlying objective of this second allocation objective is to translate an inherently uncertain supply into a predictable and dependable series of releases that users need for prosperous and sustainable lifestyles and work. To meet these goals allocation policies must strike a balance between how much water should be released in years of plentiful supply and how much should be saved for drier years. Understanding how the allocation policies used by managers impact current demand satisfaction and continuity of supply requires understanding of how managers use the information available to them to develop expectations of future supply and set allocations and an understanding of how those decisions impact current and future fulfillment of demand. Access to managers of the water system studied provided us rich data concerning the information, parameters and processes used to allocate limited water resources. This allowed us to model and analyze an important aspect of water resource management with a depth and richness rarely possible.

The Mediterranean island of Cyprus is an example of a semi-arid country where water allocation policies have important impacts. Cyprus experience water shortages but is expected to meet their water demand in the near future through water supply management (Hamdy et al., 1995). In years of above-average rainfall existing and new supplies are expected to provide enough water to meet demand from all sources. However droughts every two to four years are common on Cyprus (Haten-Moussallen et al. 1999). Being aware of this behavior pattern, Cypriot water managers plan for droughts when allocating water. They acknowledge that they cannot sustain any significant increase in demand and one or two years of lower-than-average rainfall will force stricter demand management and allocation polices (Grimble and Archimandritou 1982c). Therefore effective allocation policies for Cyprus must use water storage to de-couple the highly variable and relatively unpredictable supply from the desired reliable and consistent outflows without sacrificing fulfilling user needs.

Means of improving water allocation policies in semi-arid regions are not obvious. The interactions of water manager decisions, political and social objectives and priorities, the water supply system and demand centers are dynamic, delayed, nonlinear and closed in that system conditions and information are fed back to managers to control the system. These factors create a very complex decision environment for water managers. They have a central, unknown variable (water supply) upon which they must base allocation decisions which will in turn create a multitude of economic, political and social effects. For example allocation decisions for some crops must be made before most of the rain has fallen. Water managers are forced to build expectations of water supplies across future months for annual allocations and years to meet long term supply needs. Therefore farmers must plant some crops under allocation decisions that were made based on projected, not actual, rainfall amounts. In addition, the year following a drought year is often a time of restricted water supply as managers replenish storage. Therefore from the users perspective drought conditions persist after the rainfall has returned to normal. This complexity has caused purely economic approaches to the design of water allocation policies at the same location studied here to generate results that are inconsistent with actual behavior and confounding to researchers (Haten-Moussallen et al. 1999). An approach is needed that explicitly addresses the dynamic complexity of water allocation decision-making and its impacts on water resource system performance.

Water managers in semi-arid regions need an improved understanding of how allocation policies impact multiple objectives. Explicit descriptions of policies as used in practice with the information used, expectations developed, use options considered and priorities of uses are needed to understand current practice. This can form a basis for improvement. In addition to improved policy descriptions a means of predicting the impacts of current policies and policy alternatives on water resource system performance from both user and managerial perspectives is needed to evaluate policies. Finally, a means of analyzing the structure through which allocation policies influence performance is needed to design improved policies and transfer lessons from analysis cases to other systems. We address these needs by developing a dynamic simulation model of the interactions of water allocation policies and a water resource system including managerial agents and decision making, information flows and physical system responses to allocation policies. We describe the model structure in the next section. Then the model's calibration and testing with a specific water resource system in Cyprus and the allocation policies used to manage it are described. We illustrate our model analysis approach and explain how analysis results are used to identify weaknesses in current policies and direct the design of improved policies. Finally, we draw conclusions concerning our work and make recommendations for future research.

THE MODEL

Our model is a system of nonlinear differential equations. Model components and their interactions are based on existing water resource theories and our field studies. For example the structure of the water storage sector is based on the conservation of mass, decision-making structures on the theory of bounded rationality (e.g. Simon 1995), allocation policies on resource management theories (e.g. Jacobs and Vogel 1998), and existing water resource models (e.g. Belaineh, Peralta, Hughes 1999) as well as previous dynamic water resource models. Consistent with previous research, realistic storage conditions are modeled, including the preservation of dead storage volume and flood conditions (Jacobs and Vogel 1998, Haten-Moussallen et al. 1999, Sheer, Ulrich, and Houck 1992). We focus here on the model structures, behavior and policies that reflect the inadequate supply conditions that dominate water-stressed regions and water allocation policies. Andersen (1998) provides complete model description and documentation. Because no closed-form solutions are known we simulate the system's behavior.

Our model includes water uses that differ in their volume, efficiency and timing of use and contributions to economic performance. These differences can have significant impacts on performance and managerial decision-making and are therefore important in describing and analyzing allocation policies. Figure 1 shows the interactions among the three demand sectors (agricultural use, residential use and tourism use), the water storage sector and the water allocation sector. The Agricultural Use, Residential Use and Tourism Use sectors accept water from the Water Storage sector and provide information on their respective demand levels to the Water Allocation sector. Within the Water Allocation sector, information concerning the supply from the Water Storage sector and demand from the three use sectors are used to predict available supply. Allocation policies are then applied to determine releases for specific uses, which reduces supplies in the Water Storage sector.

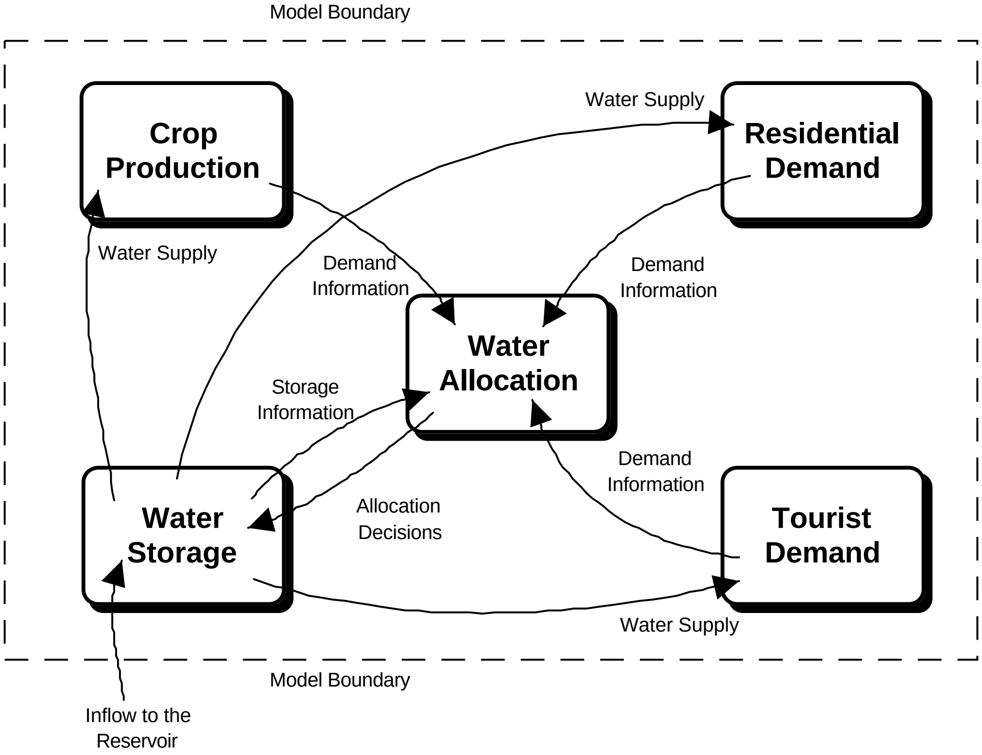

Figure 1: Water System Model Sectors

The Water Use Sectors

Each of the three water use sectors models the demand for water and the performance of the sector. Total Demand (D) is the sum of the agricultural (D_a), residential (D_r), and tourism (D_t) demands for water:

$$D = D_a + D_r + D_t \tag{1}$$

where: D – Total demand for water (m^3 per month)
D_a – Agricultural demand for water (m^3 per month)
D_r – Residential demand for water (m^3 per month)
D_t – Tourism demand for water (m^3 per month)

Agricultural Use

The Agricultural Use sector models crop irrigation requirements and crop production. A generic structure simulates each crop type, which is calibrated with parameter values to represent a specific crop (e.g. citrus trees, potatoes, greenhouse crops). The generic structure is based on documentation provided by the water development department at the calibration site and interviews with the chief water manager. Differences in growing seasons among crop types are an important driver of water demand. Therefore the annual demands for each crop are spread across the year to reflect different growing seasons for each crop type. We used the same fractional portions for each month which are used by the water managers in the system we investigated to make allocation decisions. Unit irrigation requirements are modeled as the product of the annual demand for water per hectare of the specific crop i (d_i) and the fraction of annual demand required in specific months (s_i). Consistent with Belaineh, Peralta, and Hughes (1998) water use efficiencies (e_i) are included and the result multiplied by the land area the crop covers (a_i) to estimate total irrigation demand. The water demands of individual crop types are aggregated to estimate the total agricultural demand. Therefore the monthly agricultural water demand for any number of crop types n is:

$$D_a = \sum a_i * ((d_i * s_i) / e_i) \quad i \in \{1, 2, 3...n\} \qquad (2)$$

Where: a_i – cultivated land area of crop i (hectacres)
d_i – annual water demand of crop i (m^3 per hectacre per month)
s_i – monthly fraction of annual demand for crop i (%)
e_i – efficiency of water use by crop i (%)
n - number of crop types

Separately modeling different crop types allows us to analyze the potential use of different crops and land use plans. To measure the performance of the system from the users perspective this sector compares the amount of water that each crop needs to the amount it receives. This ratio drives a nonlinear relationship that was previously developed for each crop type by water managers and used to estimate the fraction of maximum crop yield produced. The product of this fraction and the yield possible with optimal water is the crop produced (Grimble and Archimandritou 1982a).

Residential Use

Residential water demand is water needed for basic household needs such as drinking water, water for cooking, cleaning, laundry, lawn care and so on. Demand is modeled as the product of population (p), water required per capita per year (d_r) and a multiplier that adjusts demand for seasonal differences in demand (s_d).

$$D_r = p * d_r * s_d \qquad (3)$$

where: p – population (residents)
d_r – unit annual residential water demand (m^3/resident/month)
s_d – monthly fraction of annual residential demand (%)

Residential water management performance is measured by comparing the water demand and water actually supplied to determine the average number of days per month that supply falls short of demand.

Tourism Use

Water demand for tourism is modeled as the product of the number of tourist arrivals each month (t), the average monthly water demand per tourist (d_t)and the average length of stay (v).

$$D_t = t * d_t * v \tag{4}$$

where: t – tourist arrival rate (tourist per month)
d_t – unit tourism water demand (m^3 per tourist per month)
v – average length of tourist visit (months)

Performance in the tourism sector is measured with the number of months in which rationing or other measures are required due to releases not completely filling tourism demand.

The Water Storage Sector

Our storage sector is relatively simple but driven by the inflow data set for our calibration system (Kypris and Panayiotis 1994). Water stored in the one reservoir is modeled as the accumulation of actual inflows (I) and losses as measured at the water system (L) and managed outflows. This is consistent with previous approaches to simulating the impacts of different allocation policies (Wurbs 1997). In our case the managed outflow are releases to users (R) as determined by our model of manager's allocation policies (described next). Therefore:

$$\partial S / \partial t = I - L - R \tag{5}$$

Where: S - Stored supply of water (m^3)
I - net inflows to water storage (m^3 per month)
L - Water losses from storage (m^3 per month)
R – Total water releases from water storage (m^3 per month)

The performance of the storage sector reflects the continuity of supply provided by a given policy. Due to the long delays in some water resource system feedback loops supply can change gradually over several years. Therefore we compare the water available for future use at the end of the simulation period using different policies to assess water storage management performance.

The Water Allocation Sector

Based on our studies of practicing water managers two critical decisions are made in distributing available water to users that impact both fulfillment of current needs and long term supply. First managers decide how much water to release from supply. This form of supply-side load management allocates water supply between filling demand in the current year and saving water for future use. Second, managers decide how to allocate the released volume among users. Our model explicitly separates the policies that describe these two decision processes, allowing the investigation of their separate and combined impacts on water resource management performance.

The Release Volume Policy

One simple but naive management policy releases water in a pattern that closely mimics the currently available supply of water, releasing up to demand when the reservoir is full and less as the reservoir level drops. While this approach fills current demand during adequate supply it leaves managers vulnerable to exhausting supplies during droughts and open to criticism for not including droughts in their allocation policies. Worse, one year of drought can easily cause two or three years of drought-like conditions for users as managers withhold water from users to allow the storage system to recover before releases that match demand can be resumed. Since water managers in regions of highly variable supply are aware of tradeoffs between using water for current needs and saving water for future needs they attempt to anticipate available supplies and incorporate those expected supplies into allocation policies. The requirement to make release decisions prior to the rainfall that provides some of the water to be distributed, the uncertainty of that rain, and the complexity of the impacts of release decisions preclude defining an optimal release policy. As one manager we interviewed admitted, “We do not have an algorithm in helping us to decide on the best possible levels of restrictions per use.” (Andersen, 1998).

Therefore manager's expectations about supply are paramount to understanding their release volume policies.

Consistent with the literature on decision-making (e.g. Simon, 1995) we assume that water managers' expectations about water storage do not change as abruptly as changes in the water level of the reservoir. Instead managers are strongly influenced by historical supplies in formulating their expectations of future water supplies. For example managers may expect supplies to be inadequate even though current supply is plentiful if the region has experienced a drought in the previous few years. Therefore expectations lag behind current conditions. Since recent experiences are given more importance than older conditions (ref here) we model expected storage (E) as an exponential adjustment toward the current storage (S)over a period of time (τ_E) estimated to be 18 months:

$$\partial E / \partial t = (S - E) / \tau_E \qquad (6)$$

where: E – Expected water supply (m^3)
S - Water supply (m^3)
τ_E - Time to adjust expected water supply (months)

In regions prone to drought, water managers often adopt risk adverse policies for allocating water between present and future needs. In a model of water stressed regions the adjustment time of expectations about water supply (τ_E) is one descriptor of the level of risk aversion or conservativeness incorporated into policies. Longer adjustment times reflect more conservative policies as managers "remember" times of inadequate supply longer even as current supplies increase and therefore expect and plan for inadequate supplies more. Conservative policies for regions that also regularly experience periods of abundant supply (not addressed here) would be modeled with short adjustment times when supplies decrease to reflect manager's quick "forgetting" of plentiful supplies. Such asymmetric adjustment times have been used to model changes in expectations (Oliva 1999) and can easily be incorporated into our model.

A second descriptor of the managerial level of risk aversion is how managers respond to the available supply when making decisions about how much water to release. When anticipating drought managers hold water in storage until they feel an acceptable level of confidence that adequate supply is available that water can be released more freely. We use the concept of “coverage” to describe how much supply managers want to have available. We define coverage as the ratio of the expected storage (E) to how much water is needed to meet the unfilled demand for that particular year or in the next year as the current year nears it’s end (D_u). The water coverage ratio compares the coverage and desired coverage, a third measure of risk aversion to determine if, and by what margin, supply will last for the remainder of the dry season or, as current demand approaches zero, the beginning of the next year. For example a water coverage ratio of 1.2 indicates a 20% surplus over what is believed to be needed to meet unfilled demand. Values less than 1 indicate a shortage in supply, which would be a warning if occurring in the dry season since additional supply would not be available until the next rainy season. Releases (R) are reduced from the levels indicated by purely by demand (D)in response to supply through a nonlinear relationship between the water coverage ratio and releases (f_C). Including the preservation of dead storage:

$$R = \mathrm{Min}(S - S_d, D * f_C(E / D_u) \tag{7}$$

$$D_u = D - \int(R)\partial t \tag{8}$$

Where: S_d - "Dead" (unavailable) storage (m^3)
f_C – Effect of expected coverage on releases (dimensionless)
D_u – Unfilled demand for water (m^3)

Our field studies and other management policy research (Ford and Sterman 1998, Meadows 1970) have found the nonlinear nature of managerial assessments and responses to system conditions are critical drivers of behavior and essential to understanding how policies used in practice can be improved. By explicitly modeling these nonlinearities we capture important system components and relationships missed or inadequately modeled with purely linear approaches. The shape of this curve is reflective of the conservative nature of water management on Cyprus. Figure 2 shows an example of the effect of coverage on releases based on our fieldwork.

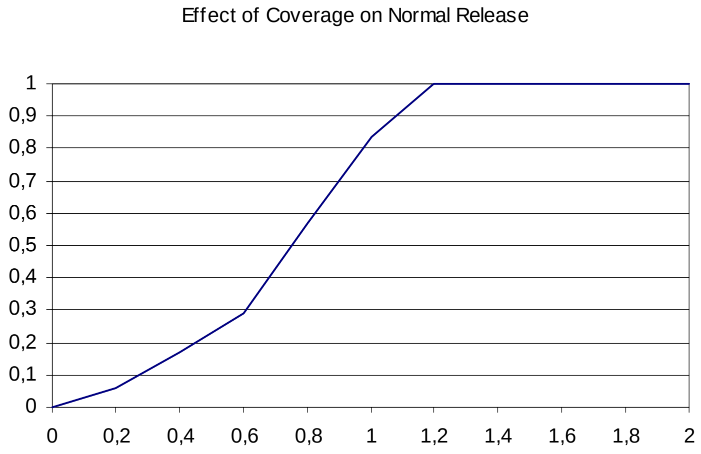

Figure 2: Effect of Coverage on Releases

The Allocation Policy

Water managers often prioritize use objectives to facilitate allocation decisions (Sheer Ulrich and Houck 1992, Haten-Moussallen et al. 1999). Policies incorporated into the model reflect the priorities among competing potential uses of available water. In our fieldwork we observed the following priorities during times of adequate or nearly adequate supply:

1. Preservation of "dead" (unavailable for use) storage in the reservoir
2. Dictated uses determined by legally binding covenants (e.g. riparian rights of land owners), recharging aquifers and transfers of water to other reservoirs
3. Residential and tourist uses
4. Agricultural uses (primarily irrigation), with a higher priority given to keeping long lived production plants such as fruit trees alive
5. Retention of water supply for future use

In times of adequate water supply releases fill user demands (priorities 2, 3, and 4 above). However this is often not possible because total releases are less than total demand (equation 7). In those years total releases must be distributed among users. To do this managers first preserve dead storage and fill all dictated uses (priorities 1 and 2). The remaining water released is distributed proportionately among agricultural, residential and tourism uses based on their contribution to total demand. Agricultural releases are used first to fill minimum long-lived production plant needs as suggested by Keshari (2000).

The remainder of the agricultural releases is distributed among the different crop types proportionately according to each crop type's contribution to agricultural demand.

The policy above captures the fundamental drivers of water release and allocation but remains a generalization of the actual policies used by water managers at our calibration site. For example, actual policies varied from the model description during the first few years of operation as managers initially filled the reservoir. Managers have also applied a trial-and-error approach in search of an optimal policy. For example during one period after dead storage and dictated demands were met 80% of domestic demand was provided first, then a percentage of the demand for long-lived production crops, then the remaining 20% of domestic demand, then other crops' demand, etc. However these managers consistently used the rank order of priorities above and a policy of allocation proportionate to contribution to total demand throughout the simulation period. Therefore the model is considered useful for policy analysis.

Model Testing and Calibration

To test our model and provide a real-world basis for policy analysis we calibrated it to the Kouris Dam water district on the island of Cyprus. The Kouris Dam is the largest reservoir on Cyprus with a 92 MCM reservoir and is part of Cyprus's Southern Conveyor Project (Cyprus—Southern Conveyor Project Case Study, 1986; Water Development in Cyprus, 1996). Parameter estimates are based on research literature, data from the Southern Conveyor Project and our field studies of water management in the region. Actual records of losses and uses due to non-agricultural, residential or tourism causes were used to model dictated uses. Over the eight-year records available for the case study these flows averaged approximately 10% of total releases with relatively low variability. They therefore are assumed to not influence our release policy conclusions. Through extensive field work we gathered reliable data for calibrating the majority of the model's exogenous variables that describe a particular water resource system, including time series data on rainfall, population, tourist arrivals as well as the nonlinear crop water to yield relationships, maximum yields for different crops throughout the year and average length of tourist visits. Eight years of monthly historical data (1988 – 1996) for total releases from the reservoir were collected and reservoir storage volumes were calculated from actual inflow, losses and releases to test our model's ability to replicate actual system behavior. Figure 3 shows the actual and simulated reservoir storage. Simulations used the Euler integration method and weekly time step.

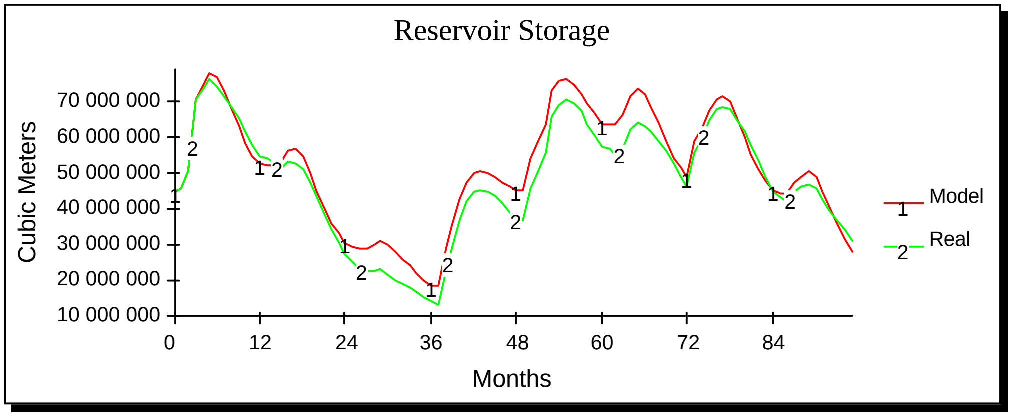

Figure 3: Actual and Simulated Reservoir Storage

The simulated behavior closely matches the behavior pattern (shapes, timing and amplitudes) of the actual system behavior with acceptable error (R^2=96%). Disaggregation of the error using Theil statistics (Sterman, 1984) reveal the majority (92%) of the error is due to covariation and not variation or bias. This indicates that differences between simulated and actual behaviors are due primarily to mismatches between individual simulated and data points and not due to a systemic bias (vertical translation)or exaggeration of amplitudes. Comparison of model and actual behavior for total releases shows more but still acceptable error (R^2=53%) and high (89%) covariation. Andersen (1998) describes additional tests of model structure and behavior used to develop confidence in the model's ability to simulate water system behavior from the underlying structural drivers and for analyzing water allocation policies.

MODEL ANALYSIS

Sensitivity Analysis

Sensitivity analyses were performed to identify system components which most influence system behavior. Tests were limited to components which managers can reasonably influence. For example managerial expectations were tested but population was not. Water storage was simulated for a base case and pessimistic and optimistic values of 19 parameters, reflecting the modelers's estimate of the 90% confidence band. Performance ranges relative to the base case performance when test values were individually set to the pessimistic and optimistic values were used to identify influential parameters. See Ford (1995) Mahieu (1998) and Andersen (1998) for detailed examples of our approach to sensitivity analysis. water storage was found to be most sensitive to the total demand expected by managers, managerial response to coverage in determining releases, crop efficiency of water use and manager's desired supply coverage. The high sensitivity of performance to managerial expectations and beliefs supports our hypothesis that these policies are important in improving water resource system management. In particular, two of the sensitive parameters (response to coverage and desired coverage) describe the degree of risk aversion in managerial decision-making.

The same analysis procedure was used to analyze the sensitivity of crop production to those parameters most directly related to them. All three crop types are most numerically sensitive to maximum yield, cultivated area of the specific crop type, and the crop's efficiency of water use. This is consistent with the findings of authors who have promoted the use of more efficient conveyance and distribution systems in combating water shortages (Makin, 1982; Mill, 1995; Mishalani, 1988; Postel, 1992, 1989; Roodman, 1996; Van Tuijl, 1993; Xie, 1993). These factors are all impossible or very difficult for water managers to influence.

Base Case Analysis

A base run was generated using the calibration conditions of the model except that dictated releases were held constant to focus on policies for residential, tourist and agricultural use described above. Therefore the policy in the base case reflects the policies used in Cyprus during the simulation period. The behavior of the storage of the base case is close to the calibration and testing case (Figure 3) in both shape and numerical values.

The optimum yield for any crop requires the proper mix of soil conditions, sunlight, evapotranspiration, etc. as well as adequate water. Similarly, families, businesses and tourist areas respond to water availability in ways not included in the model such as the common Cypriot practice of filling rooftop water tanks with rain or tap water during wet times to provide short-term relief in times of severe water shortages. Because these factors impact actual optimal performance and are beyond the scope of our model simulated performance values are not predictions of performance in real systems. To evaluate different policies we compare the performance of the system when managed using specific policies to the optimal performance possible in the model. By simulating and measuring performance over an eight year period that includes both times of adequate and inadequate supply we capture both the ability of policies to fill current demands in different naturally occurring supply conditions. We measure the ability of policies to reserve adequate supply for future use with the stored supply at the end of the eight year simulated period using the policy.

The performance of the system using the base case policy is shown in Table 1. Of the three crop types modeled citrus performed best in the base run policy. Citrus farmers lost 25.6% of maximum yield because of water shortages, compared to 67.0% and 65.6% for greenhouses and potatoes, respectively. Residential users suffered an average monthly deficit of 2.64 cubic meters per month per capita over the 8 years, while tourism was particularly hard-hit with 90.6% of the months (87 of 96) experiencing a water shortage.

Performance Measure	**Units**	**Base Case Performanc**	**Optimum Performanc**	**Variance**
Agricultural Water Use				
Citrus yield (8-year average)	tons/ha	37.2	50	-25.6%
Citrus yield range	tons/ha	31.0	0	31.0 tons/ha
Seasons with zero citrus yield	each	0	0	0
Greenhouse yield (8-year average)	tons/ha	12.2	37	-67.0%
Greenhouse crop yield range	tons/ha	18.1	0	18.1 tons/ha
Seasons with zero greenhouse crop yield		0	0	0
Potato yield (8-year average)	tons/ha	12.1	35	-65.6%
Potato yield range	tons/ha	20.9	0	20.9 tons/ha
Seasons with zero potato yield	each	0	0	0
Residential Water Use				
Average residential supply shortfall	m3/month/capit	2.64	0	2.64 m3/mont
Tourism Water Use				
Months tourist supply shortfall	each	87	0	90.6%

Table 1: Performance using Base Case Policy

Reservoir Storage began to recover after 1983 but neither domestic or irrigation supply matched or exceeded demand thereafter. We hypothesize that a primary cause of these consistent shortages over the eight years is the risk averse nature of the manager's policy. Cypriot water managers showed a tenacious adherence to risk averse policies. During interviews in 1997 they repeatedly mentioned the 1990-1991 drought when inflows to the

Kouris Dam and to all the dams on Cyprus were unusually low and stressed the need to "assume the worst" about inflows and to consider the next few years even in "good" years, in case such a severe shortage happens again.

We tested our hypothesis and the effects of the risk adverse policy used by managers by simulating performance using a less risk averse policy. We modeled a less risk averse policy by decreasing the expected total demand and the desired water coverage and a steeper slope of the effect of coverage on releases. The performance of this less conservative policy is better than performance using the current, risk averse policy (table 1). This shows that less risk adverse water allocation policies than are currently used in semi-arid regions can perform better. Performance using other parameter values to describe more or less risk averse policies provides consistent results. These results support our hypothesis. The seemingly reasonable practice of larger releases in times of plentiful supply and restricted releases in times of inadequate supply contributes to the inconsistency in releases that Cypriot water managers want to avoid. Overly conservative policies can fill current demands fairly well but increase vulnerability to future droughts. A policy that reflects the variability of natural supply (and therefore vulnerability to drought) is needed.

Conclusions

Our findings are counterintuitive because they reverse what appears to be a logical approach to managing water in areas of shortage. Indeed, the ultimate purpose of building supply-related infrastructure such as reservoirs, pipeline networks, desalination plants, etc. is to allow people to control their own water supply. When drought sets in, restrictions on releases are thought of as temporary coping mechanisms that will be withdrawn when "normal" conditions return. water managers in areas of inadequate and variable supply institute release policies that supply to demand conditions in wet years and fall back on restrictions in dry years. The infrastructure gives the impression that supplying to meet demand will be the normal operating procedure, while droughts will sometimes interfere and cause releases to be lower that normal.

This research indicates that in areas of severe water shortage, the chances of providing consistent releases increase if policies are centered around what can actually be supplied, rather than how and when can we finally release enough water to satisfy all demand. Any policy that moves away from "rewarding" a population who suffered through drought by giving them more water when possible will probably have to be combined with information campaigns to inform and gain the support of the public. It will definitely need the support of the command centers in government so they do not interfere.

Our results should be considered within the context of the limitations of our model, which reflect a single-reservoir system without water supplied by sources other than rainfall. This research also ignored allocation policy that is concerned with distributing water fairly between competing users. Water was always distributed to a particular demand center according to its percentage of the total demand. Thus, policies that favor one type of demand over another, for example domestic demand over irrigation demand, were not investigated. These policies have great impact on society, particularly the income distribution of a region. They are arguably more politically charged than the policies investigated in this research. Providing cheap irrigation water via subsidies, for instance, is a policy often strongly discouraged in academic literature and in reports from such organizations as the World Bank and the Food and Agriculture Organization of the United Nations. Subsidies are still in widespread use, however, and not only for water. This research can be expanded to investigate the long-term impacts of such prioritization of sectors on the ability of water managers to provide consistent and reliable supply to all users

Future variations of the model can also investigate the impact of increasing the efficiency of supply as well as the situation in which water managers work closely with demand centers to improve efficiency, timing of demand, and other things not directly under water managers' control. Similarly, the model could be expanded to include water conservation measures. The actions of using water more efficiently through better infrastructure and water-saving devices could be an extra source of supply in water scarce areas. Along the lines of Amory Lovins' "nega-dam" revolution, the water saved could help the quest for consistent supply by providing relief from situations of overstressed water supply. By improving our understanding of how managerial policies impact water resource system performance we can improve that performance and provide the water needed for sustainable development and prosperity.

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