Risk-Averse Water Allocation Policies in Semi-Arid Regions

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Abstract

The critical role of water in development and the 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 among user groups for scarce water resources. Managers use these policies to meet two objectives when faced with naturally oscillating patterns of supply: 1) satisfy current demands and 2) preserve adequate supply for future use. This paper sets the challenges of balancing these short-term and long-term performance objectives in the context of a central system dynamics concept. A dynamic simulation model of a water system in a semi-arid region is described and used to test hypotheses on the effectiveness of water allocation policies in meeting short and long-term performance goals. The model was calibrated and tested with data from the Mediterranean island of Cyprus. Sensitivity analyses revealed the importance of managerial expectations and risk aversion to system performance. Analysis of water allocation policies revealed that changing the level of risk in policies shifts performance between satisfying short-term and long-term objectives. Potential changes by managers to improve performance and system dynamics research needs are discussed.

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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 develop and use. While supply management approaches such as building reservoirs to store water can help in some areas, they cannot indefinitely relieve the pressure on the world's water supply (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 relative to demand, and 3) arid countries already facing water shortage crises. These semi-arid regions are characterized by long, hot, dry summers and short, mild, wet winters. Tourism is also highest in the summer, in some 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 aquifers (Brooks, 1997). These semi-arid countries cannot sustain significant increases in per capita withdrawals or economic growth with their current water management. This study focuses on water policies in semi-arid regions due to their critical need for improved water resource management and opportunities to avoid crisis conditions.

Water system planners, designers, and managers in semi-arid regions must use demand management in addition to supply management to meet water needs. In a simplified dynamic description of water management in a water-stressed region (Figure 1) managers initially increase water supply through supply-side management methods to control water deficits (loop B2). Storage reservoirs and desalination plants are examples of water supply management tools. Faced with increasing demand due to population growth, economic development, and lifestyle improvements, water deficits persist or grow. Over time supply management depletes unexploited supplies, making the remaining unexploited supplies increasingly difficult or expensive to develop. This reduces the effectiveness of supply management (loop R1). Therefore managers are forced to also manage demand to control water deficits with tools and methods that restrain or change water uses (Loop B1). Pricing policies, conservation, and allocation among users are examples of demand management tools. In contrast to water resource management models that focus on supply characteristics such as variability (e.g. Wilchfort and Lund 1997), the current work focuses on the effects of managerial decision-making practices on demand management and thereby on water system performance.

Insert Figure 1 here

As used here, managers can apply three forms of demand management to control water deficits: total demand management, load management, and allocation. Total demand management reduces water needs. The economies of semi-arid regions are often dominated by high water uses (e.g. agriculture) and economic forces such as growth that prevent or severely limit reductions in 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. When applied to supplies, load management allocates water between current and future demand. Allocation of available supplies occurs when water managers cannot or choose to not meet all current demands and, instead, distribute the available supply among users. Both supply-side load management and demand-side distribution decisions allocate scarce resources among competing uses to meet various social, economic, or political goals (Stiles, 1997). Allocation is often the primary tool available to water managers in semi-arid regions (Haten-Moussallen, Gaffney, Cox, and Batho, 1999). Therefore, understanding water allocation policies and their impacts is critical to improving system performance.

To improve the understanding of water allocation policies in semi-arid regions the current work proposes and tests hypotheses of how policies impact performance in one semi-arid water system. The results are the basis for initial attempts to design policies that can improve total performance. The challenges of water allocation policies are described in the next section. The research site is described and four hypotheses of the relationship between policies and performance are proposed. Then the model developed for policy investigations is described. Hypothesis testing and its results are presented as the basis for new policy designs. Conclusions discuss the impacts of the work on water management research and practice and suggest future research topics.

The Challenges of Water Allocation Policy Development

Water managers in semi-arid regions face the difficult task of developing and implementing allocation policies that will simultaneously fulfill current demand as best possible and save adequate supplies to provide continuity of supply during droughts. The first objective seeks to optimize short-term system performance. The second objective seeks good long-term performance by translating an inherently uncertain supply into predictable and dependable releases over many years. These objectives appear mutually exclusive because the water in the system studied is only used to meet one goal or the other. Pursuing good short-term performance by drawing down water reserves to meet current demand can cause disastrous long-term performance in case of drought. This vividly illustrates the system dynamics tenet that policy resistance can destroy long-term performance through the unintended side effects of shortsighted policies. More important, the challenges of water allocation will be used to illustrate that practicing managers are very cognizant of this tenet and incorporate it into policies, but face major barriers to using it to improve total system performance. To do this the current work seeks to answer several questions. How do water managers in semi-arid regions seek to fulfill short-term and long-term performance? How do they allocate limited supplies across time and different uses? What level of system performance do these policies produce? How can those policies be improved?

Understanding and improving water allocation policies in semi-arid regions is difficult. The interactions of the water supply system, water management decisions, political and social objectives and priorities, and demand centers are linked in a dynamic, nonlinear and closed system in which information is delayed, consolidated, and interpreted by managers to control the system. These factors create a complex decision environment where system conditions and performance can evolve over many years in response to past, present, and expected conditions and decisions. For example, at the research site allocation decisions for some crops must be made before most of the rain in a given season has fallen. Water managers are therefore forced to predict water supplies during the rest of the season to allocate water during the current season and possibly withhold supplies to meet long-term needs. In addition, the year following a drought year is often a time of restricted water supply to users as managers replenish storage. These forecasts and delays distort information queues that are used in decision-making and cause behavior to vary from purely rational behavior. This has caused 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). A system dynamics approach can explicitly address the dynamic complexity of water allocation decision-making and its impacts on water resource system performance and therefore can provide insight.

The Research Site

The Mediterranean island of Cyprus is an example of a semi-arid country where water allocation policies have important impacts. Cyprus experiences water shortages but is expected to meet its 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. However droughts are common on Cyprus, typically occurring every two to four years (Haten-Moussallen et al. 1999). Being aware of this pattern, Cypriot water managers plan for droughts when allocating water. Despite this, managers acknowledge that they cannot sustain any significant increase in demand and that one or two years of lower-than-average rainfall will force stricter allocation polices (Grimble and Archimandritou 1982c).

The Kouris Dam Water District in southern Cyprus is an example of a semi-arid region that uses water allocation to manage system performance. International funding has provided resources for major supply management projects on Cyprus. As part of these improvements the Kouris Dam has created the largest reservoir (115 MCM[3]) in the Southern Conveyor Project and on Cyprus (Cyprus—Southern Conveyor Project Case Study 1986, Water Development in Cyprus 1996). Despite these supply management efforts, the Kouris Dam Water District experiences periods of inadequate water supply, and allocation is used continuously to manage water deficits and system performance. Access to managers of the District provided rich data concerning the information, parameters, and processes used to allocate limited water resources. Data was collected about water allocation policies through several extended interviews. In particular the chief system manager of the Kouris Dam Water District who sets allocation policies described the specific policies modeled here. This allowed the modeling and analysis of an important aspect of water resource management with a depth and richness not always possible.

Hypotheses and Research Approach

Interviews with managers in the Kouris Dam Water District repeatedly identified managerial expectations and risk as critical aspects of allocation decision-making. These concepts formed the basis for four hypotheses that relate water allocation policies in the Kouris Dam Water District to the performance of the system. The water managers at the research site are very aware of the apparent tradeoffs between using water for current needs and saving water for future needs. Therefore they attempt to anticipate available supplies and incorporate those expectations into allocation policies. The previously described requirement to make allocation decisions prior to the rainfall that provides some of the water to be distributed, the uncertainty of the amount of that rain, and the complexity of

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[3] MCM – million cubic meters

the impacts of allocation decisions preclude defining an optimal release policy. As one manager interviewed admitted, “We do not have an algorithm in helping us to decide on the best possible levels of restrictions per use.” (Andersen, 1998). The frequent generation of expected conditions and their use in decision-making processes suggest that managerial expectations have large impacts on system performance. Therefore:

> H1: The expectations concerning demand and supply of water allocation managers in semi-arid regions are important factors in the short-term and long-term performance of the water system.

Water managers were found to often adopt risk-averse policies in allocating water between present and future needs. As used here risk-averse policies are policies that managers believe will protect users from drought conditions (large water deficits and very reduced releases) during future droughts. These risk-averse policies take the form of restricting releases for current water use and saving the unused water for future (potentially drought-stricken) times. In contrast, riskier policies value filling current demand more than saving water for future use. A valuable issue addressed by this research is the degree of success in protecting users against future drought conditions that risk-averse policies provide. Water managers at the research site 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 reservoir and to all the reservoirs on Cyprus were unusually low. They consistently stressed the need to “assume the worst” about inflows and to consider the needs of the next few years, even in “good” (i.e. wet) years, in case a severe supply shortage happened again. This aversion to risk demonstrates the managers’ clear understanding of the system dynamics concept of policy resistance through the delayed impacts of unintended side effects. More specifically, the managers understand that risky policies that may increase short-term performance can cause severe drought conditions for users in the future and thereby destroy policy attempts for good short-term and long-term system performance. Because it shifts resources between the short-term goal (meet current demand) and long-term goal (future drought protection), risk aversion is expected to have large impacts on system performance. Therefore:

> H2: Managerial risk preferences in water allocation policies in semi-arid regions are important factors in the short-term and long-term performance of the water system.

Risk-averse allocation policies will impact performance in different dimensions and time scales differently. For the reasons described, more risk aversion is expected to increase long-term performance and decrease short-term performance. Therefore:

> H3: The long-term performance of the water system increases with increasing amounts of risk aversion in water allocation policies in semi-arid regions.

> H4: The short-term performance of the water system decreases with increasing amounts of risk aversion in water allocation policies in semi-arid regions.

To test these hypotheses a model that reflects the water allocation policies and decision-making processes in the Kouris Dam Water District was constructed. The model was then analyzed and used as the basis for experimentation, as described later. The need for a modeling methodology capable of accurately reflecting the explicit descriptions of the information and policies used in practice, the expectations developed, and priorities of uses make system dynamics an effective approach for these investigations.

A Water Allocation Model

The components of the system dynamics model and their interactions are based on existing water resource theories and field data collected at the research site. Examples of these theories include the structure of the water storage sector that is based on the conservation of mass, decision-making structures based on the theory of bounded rationality (e.g. Simon 1995), allocation policies based on resource management theories (e.g. Jacobs and Vogel 1998), and existing water resource models (e.g. Belaineh, Peralta, Hughes 1999). Consistent with previous research, realistic management practices are modeled, including the preservation of unavailable water (dead storage) and releases that exceed demand during flood conditions (Jacobs and Vogel 1998, Haten-Moussallen et al. 1999, Sheer, Ulrich, and Houck 1992). The focus of the model structure, behavior, and policies addressed here reflect the inadequate supply conditions that dominate water-stressed regions and water allocation policies. The model simulates three types of water use (agricultural, residential, and tourism) that differ in their volume, efficiency, timing of impacts on managerial decision-making, and contributions to performance. Figure 2 shows the interactions among the model sectors, representing the three types of demand, water storage, and water allocation. The Agricultural, Residential, and Tourism Demand sectors receive water release volume information from the Water Storage sector and provide information on unfilled demand levels to the Water Allocation sector.

Within the Water Allocation sector information concerning the supply from the Water Storage sector and demands from the three use sectors are used to predict available supply. Allocation policies are then applied to determine releases for specific uses, which satisfy demand and reduce supplies in the Water Storage sector. Equations that describe water demand and allocation policies are listed in the appendix and identified in the following description with numbers in parentheses. Complete model equations are available from the authors.

Insert Figure 2 here

Modeling Water Demand

Each of the three water use sectors models the demand for water and the performance of the sector. Total demand over which system managers have influence is the sum of the agricultural, residential and tourism demands for water (1). The agricultural sector models crop irrigation requirements and crop production. A generic model structure simulates the annual water demand for each of the three major crop types in the Kouris Dam Water District: citrus trees, greenhouse crops, and potatoes. The generic structure was calibrated to represent specific crop types. The structure is based on documentation provided by the water development department and interviews. Differences in growing seasons among crop types are important drivers of water demand. Therefore the annual demands for each crop are distributed throughout the year to reflect different growing seasons. The same monthly fractions were used as those used by the water managers in the system investigated. Unit (per hectacre) irrigation requirements are modeled as the product of the annual demand for water per hectare of the specific crop and the fraction of annual demand required in specific months.

Consistent with Belaineh, Peralta, and Hughes (1998) and others, water use efficiencies are included to reflect evaporation, losses during transit, etc. Crop-specific unit irrigation requirements are multiplied by the cultivated land area for each crop to estimate total irrigation demands. The water demands of individual crop types are aggregated to estimate the total agricultural demand (2).

To measure the agricultural performance of the system this sector compares the amount of water that each crop needs to the amount it receives. This ratio drives a nonlinear relationship that was developed prior to this study by water managers at the site for each crop type. The relationship is used by managers and in the model 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 water demand is water needed for basic household uses such as direct consumption, cooking, cleaning, laundry, lawn care, etc. Demand is modeled as the product of the resident population, water demand per capita per year, and a multiplier that adjusts demand for seasonal variations (3). Residential water management performance is measured by comparing the water demand to the water actually supplied to determine the average water volume per month that supply falls short of demand.

Water demand for tourism is modeled as the product of the number of tourist arrivals each month, the average water demand per tourist, and the average length of a tourist’s visit (4). Performance in the tourism sector is measured with the number of months in which rationing or other measures are required because releases do not completely satisfy tourism demand.

Modeling Water Storage

The storage sector is relatively simple but driven by the water inflow and use data at the research site (Kypris and Panayiotis 1994). Water stored in the single reservoir is modeled as the net accumulation of actual inflows, losses, and the combination of mandatory and managed water releases (5). This approach is consistent with previous approaches to simulating the impacts of different allocation policies (Wurbs 1997). The continuity of supply provided by a given policy reflects the performance of the storage sector. Due to the long delays in some water resource system feedback loops (Anderson 1998) this performance can change gradually over several years. Therefore the water available for future use at the end of the simulation period using different policies is compared to assess water storage management performance.

Modeling Water Allocation Policies

Two critical decisions were identified that impact short-term and long-term performance. First, managers decide how much water to release from supply for all combined uses. This is a form of load management that allocates water supply across time between filling demand in the current year and saving water for future use. Second, managers decide how to allocate the released volume among users. The 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 Water Release Volume Policy

One simple 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 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. Therefore managers base release volume decisions on forecasted supplies.

Consistent with the literature on decision-making (e.g. Simon, 1995) water managers' expectations about water storage are assumed to not change as abruptly as the real system, i.e. as quickly as changes in the water volume in the reservoir. Instead, as described previously, 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. This delay also captures the practice of managers reacting slowly to the onset of a drought to postpone difficult decisions to restrict releases. Because decision-makers typically consider recent experiences to be more important than older conditions the expected storage volume is modeled as an exponential adjustment over a period of eighteen months toward the current storage volume (6).

The field data revealed three policy features that describe risk aversion in release policies: the supply expectation adjustment time, the desired coverage of demands by supplies, and the response to supply volumes in release decisions. Longer supply expectation adjustment times reflect more conservative (risk-averse) policies as managers "remember" times of inadequate supply longer as current supplies increase. This causes them to expect and plan for inadequate supplies more than with riskier policies. Risk-averse policies for regions that also regularly experience periods of abundant supply (not addressed here) would also include short adjustment times when supplies decrease to reflect manager's quick "forgetting" of plentiful supplies.

When anticipating drought managers do not fill some current demands until they feel that adequate supply will be available for future needs. The concept of the "coverage" of demand by expected supplies is used to describe how much supply managers expect to have available in relation to releases. The system's Expected Coverage predicts short-term system performance by describing the expected ability of the system to provide water. It is defined as the ratio of the expected storage to the unfilled demand for the remainder of the year or in the next year as the current year nears its end (7, 8). The Expected Coverage also describes an expected short-term safety factor in the water system. For example, an Expected Coverage of 1.2 indicates a 20% surplus of expected supply over the expected unfilled demand in the near future. Expected Coverage values less than one indicate an expected water deficit if occurring in the dry season since additional supply would not be available soon. Notice that managers do not choose the Expected Coverage, but use it to consolidate system information for use in decision-making. In contrast, the Expected Coverage Ratio compares the Expected Coverage and the Desired Coverage, the second measure of aversion to risk, as a ratio. The Expected Coverage Ratio is a long-term indicator of operational safety, with lower values indicating more vulnerability to future droughts.

The third descriptor of aversion to risk is the managerial response to the available supply when deciding how much water to release. Releases are reduced from the levels indicated purely by the unfilled demand based on a nonlinear relationship between the Expected Coverage Ratio and releases (9). This relationship describes restrictions on releases based on managerial responses to the coverage ratio. Based on the fieldwork the shape of this relationship for water management at the research site is a horizontally stretched “S” between no releases if the coverage ratio is zero and unrestricted releases if the coverage ratio is 1.2 or greater.

The release volume policy structure described generates responses in three time scales, (Figure 3). High Unfilled Demand increases pressures to release more water, which immediately satisfies some Unfilled Demand (loop B1). Over a few years the satisfaction of this demand also increases the Expected Coverage Ratio, suggesting that more Releases are possible (loop R1). But the same Releases also decrease Current supplies and, over time, Expected Supply and Expected Coverage, thereby controlling Releases (loop B2). These Releases are also controlled over a long time scale as supplies alter the Historical (as remembered by managers) Supply and thereby Expected Supply, Expected Coverage, and the Expected Coverage Ratio (loop B3). Loop B3 is an example of a long time delay that can cause long term performance to evolve slowly.

Insert Figure 3 here

The Water Use Allocation Policy

Managers often prioritize the use of limited resources to facilitate allocation decisions (Ford 2002, Haten-Moussallen et al. 1999, Sheer Ulrich and Houck 1992). Policies incorporated into the model reflect managerial priorities among competing uses. Fieldwork found the following priorities during times of adequate or nearly adequate supply:

1. Preservation of "dead" (unavailable for use) storage in the reservoir
2. Mandatory uses dictated 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, with a higher priority given to keeping long-lived production plants (e.g. fruit trees) alive
5. Retention of water supply for future use

Note that the retention of water supply for future use only has the lowest priority when supplies are adequate. When supplies are inadequate this becomes a separate decision through the water volume release policy. When total releases are less than total demand discretionary releases are distributed among users after managers preserve dead storage and fill all mandatory uses (priorities 1 and 2). In the Kouris Dam Water District and the model this allocation process applies the priorities above in three steps. First, discretionary releases are 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 release volume and allocation policies described above capture the basic water allocation policy structure used at the research site, but remain generalizations. For example, actual policies varied from the model description during the first few years of operation of the Kouris Dam as managers initially filled the reservoir. Managers have also occasionally applied trial-and-error adjustments to the policy described in search of an optimal policy. For example in one year, after dead storage and mandated demands were met 80% of residential and tourist demand were filled, then a percentage of the demand for long-lived production crops, then the remaining 20% of residential and tourist demand, then other crop demands were filled. However, managers consistently used the order of priorities above and the policy of allocation proportionate to contribution to total demand throughout the simulation period. Therefore the model is considered potentially useful for policy analysis.

Model Calibration and Testing

The model was calibrated to the Kouris Dam Water District on the island of Cyprus. Parameter estimates were based on data from Southern Conveyor Project records and field studies of water management in the district. Records of estimated losses and mandatory uses were analyzed and found to average approximately 10% of total releases with relatively low variability over the eight years of available records. They therefore were assumed to not influence release policy conclusions. Extensive fieldwork generated reliable data for calibrating the majority of the model's exogenous variables, including time series data on rainfall, population, and tourist arrivals, as well as the nonlinear water-to-yield relationship for each crop type, maximum yields for different crops throughout the year and the average length of tourist visits. Eight years (1988 – 1996) of monthly historical data for storage volumes, evaporation and leakage estimates, and releases from the reservoir were collected and used to test the model's ability to replicate actual system behavior. By simulating and measuring performance over an eight year period that includes both times of adequate and inadequate supply the model captures the ability of policies to fill current demands and provide supply continuity in different naturally occurring supply conditions. Figure 4 shows the actual and simulated reservoir storage over the eight-year period.

Insert Figure 4 here

The simulated behavior reflects the behavior pattern (shapes, timing, and amplitudes) of the actual system behavior with acceptable error (R^2=96%). Disaggregating the error using Theil statistics (Sterman, 2000) reveals that the majority (92%) of the error is due to co-variation and not bias or variation. This indicates that differences between simulated and actual behaviors are due primarily to mismatches between individual simulated and system data points and not due to a vertical translation (systemic bias) or exaggeration of amplitudes (variation). This suggests that the model structure captures the drivers of behavior that drive the real system. Andersen (1998) describes additional tests of model structure and behavior used to develop confidence in the model's ability to simulate water system performance from the underlying structural drivers and for analyzing allocation policies.

Hypothesis Testing

Performance Sensitivity to Managerial Expectations and Risk Preferences

Hypotheses H1 and H2 were tested with sensitivity analysis of the model. Sensitivity tests were limited to parameters reflecting components of hypotheses and system components that managers could reasonably influence. For example performance sensitivity to managerial expectations was tested but sensitivity to population was not. Long-term performance was measured with the stored supply at the end of the eight year simulated period. Short-term performance was measured with crop production for each crop type, average monthly residential shortfall of supply from demand,

and months with tourist shortfall. Performance was simulated for a base case reflecting the calibration conditions and with pessimistic and optimistic values of parameters reflecting modeler estimates of the 90% confidence bands. Performance ranges 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 the approach used in sensitivity analysis and Anderson (1998) for details of the sensitivity analyses.

To test the portion of hypothesis H1 concerning the impacts of expectations on long-term performance nineteen parameters were tested that reflected five storage, demand, and risk components, eight crop components, four domestic use components, and two tourism components for their impact on long-term performance. In descending order of influence, long-term performance was found to be most sensitive to the total demand expected by managers, managerial response to coverage in determining release volume, the average crop efficiency of water use, and manager’s desired supply coverage. The high sensitivity of performance to the total demand expected by managers and managerial response to coverage in determining release volume (reflecting supply expectations) strongly support hypothesis H1 that the expectations of water allocation managers in semi-arid regions are important factors in the long-term performance of the water system.

To test the portion of hypothesis H1 concerning the impacts of expectations on short-term performance twenty one parameters were tested that reflected nine storage, demand, and risk components and eleven crop components. Although the crops vary in their degree of sensitivity, all three crop types were found to be sensitive to the crop’s maximum yield, cultivated area of the specific crop type, the crop’s efficiency of water use, expected total demand, and managerial responses to coverage in determining release volume. Among these five high-leverage components citrus and greenhouse crops were more sensitive to the three characteristics of crops, whereas potatoes were more sensitive to the two managerial components. These findings are consistent with those of researchers 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). Residential and domestic performance was found to be sensitive to demand expectations and unit demands for water by residents and tourists. These results support hypothesis H1 that the expectations of water allocation managers concerning demand and supply in semi-arid regions are important factors in the short-term performance of the water system. The sensativity analyses support hypothesis H1 concerning both long-term and short-term system performance.

The results above also provide the basis for testing hypothesis H2 concerning the impacts of risk preferences on performance. Two of the three parameters that describe managerial risk preferences were found to have a large impact on long-term performance. One of those three parameters (managerial response to coverage) was found to also have a large impact on short-term performance. These results support hypothesis H2 that managerial risk preferences in water allocation policies in semi-arid regions are important factors in the short-term and long-term performance of the water system.

Impacts of Risk Aversion on Performance

Hypotheses H3 and H4 address the impacts of risk aversion in allocation policies on system performance. These hypotheses were tested by comparing performance using allocation policies with different amounts of aversion to risk. A base case simulation was generated using the calibration conditions of the model except that mandatory releases were held constant to better expose the effects of allocation policies on discretionary water uses. To evaluate specific policies, performance was compared to the optimal performance possible in the model. The raw and relative performance of the system using the base case policy is shown in Table 1. Of the three crop types modeled citrus crops performed best in the base case. Citrus farmers lost 25.6% of maximum yield due to water shortages, compared to 67.0% and 65.6% for greenhouse crops 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 experienced shortages in 90.6% of the months (87 of 96). Reservoir storage for future use was 34.0 MCM, 70.4% below the reservoir capacity of 115 MCM.

Insert Table 1 here

System performance using several alternative policies were simulated and compared to the performance of the base case. Performance relative to the optimal performance was calculated in the same manner as for the base case policy (Table 1). The three previously described model parameters that describe aversion to risk in policies were used to design policies that were unambiguously more or less risk-averse than the base case policy. The performance of these alternative policies relative to the optimal performance and the base case are shown in Table 2.

Insert Table 2 here

The three policies on the left of the base case policy in Table 2 are riskier than the base case. The Release to Demand policy releases water in response to demand regardless of the amount in the reservoir by setting the effect of coverage on releases to 100%. This policy releases to match demand as often as possible. The Reduced Demand Expectation policy changes the total expected demand from 30 MCM per year to 20 MCM per year. The policy does not assume lower actual demands, only that managers limit their expectations of what the society needs in terms of water supply and therefore increases coverage and releases. The Lower Desired Coverage policy uses the same effect of coverage on releases as in the base case but reduces the Desired Coverage Ratio from the base case value of 3.0 to 2.0. This means that releases will be unrestricted when coverage is at least twice as much as the desired coverage. The two policies on the right of the base case policy in Table 2 are more risk-averse than the base case. The Constrain Releases policy uses base case policy parameter values but reduces the releases for any given supply by changing the relationship between the Expected Coverage Ratio and releases. The Higher Desired Coverage policy uses base case policy values except that the desired coverage ratio is raised from 3.0 to 3.5, meaning that releases will be restricted until coverage is 3.5 times larger than the desired coverage.

As shown in Table 2, long-term performance improves as policies become more risk-averse, from a range of 90.2%-96.4% variance from optimal for riskier policies, to a 70.4% variance in the base case, to a range of 62.2%-66.3% variance for more risk-averse policies. This supports hypothesis H3 that the long-term performance of the water system increases as the amount of risk aversion in water allocation policies in semi-arid regions increases. The range in variance from optimal performance (34.2%) also indicates that risk aversion is effective in protecting users against future drought conditions. Short-term performance is less consistent because the various performance measures respond differently to allocation policies. However, a review of Table 2 shows that short-term performance generally degrades as policies become more risk-averse. The increases in residential use deficits and decreases in greenhouse crop yields clearly illustrate this trend. This supports hypothesis H4 that the short-term performance of the water system decreases as the amount of risk aversion in water allocation policies in semi-arid regions increases.

Policies for Improved Total Performance

To investigate the potential of policy changes to simultaneously improve both short-term and long-term performance additional policies were designed and tested that incorporate features not used by the managers at the research site. Policies were chosen that include changes that are typically more difficult to implement due to the economic, social, and political environment in which system managers operate, but also include additional controls that can potentially improve performance. Table 3 shows the performance of three of these policies.

Insert Table 3 here

The Release to Demand with Sacrificial Crop policy assumes that a new type of crop with lower value (economically or politically) than the three crops modeled is introduced. This crop would be sacrificed to save the more valuable citrus, greenhouse, and potato crops in times of water shortage. If managers stop releases to this group of crops when necessary, they could be more liberal in releasing water in times of adequate storage. The Release to Demand with Maximum Release policy is the same as the Release to Demand policy described above (Table 2) with a limit on releases that prevents complete fulfillment of current demand during times of abundant water, saving the unreleased water for future use. The Release to Demand with Maximum Release and Sacrificial Crop policy combines the previous two policies. These three policies add new controlling feedback to the system by providing managers with additional information and incorporating that information into allocation decisions.

The new allocation policies generally improve short-term performance compared to the base case and the policies that do not add feedback controls (Table 2). However the long-term performance of these policies is very poor and is significantly worse than the long-term performance of the base case policy (96.6% average variance versus 70.4% variance). These policies appear to improve short-term performance slightly at the cost of significantly increased vulnerability to droughts in the future. Even the incorporation of more radical changes in policies that are difficult to implement such as the introduction of a new crop type appears unable to simultaneously improve both current and future performance.

Conclusions

This work has modeled water allocation policies in a semi-arid region and their effects on system performance. Both short-term and long-term system performance were found to be sensitive to managerial expectations and risk preferences. Performance using current policies was compared to the performance of more and less risk-averse policies. Riskier policies increase the satisfaction of current demands but significantly increase vulnerability to future droughts. This demonstrates the trade-off between the fulfillment of current demand and safety from future droughts. New policies incorporating additional feedback controls were designed and tested but not found to simultaneously increase both current and future performance. This illustrates the difficulty in improving total performance with allocation policies alone.

The results are limited by the degree of realism in the simulated system. For example, the optimum yield for any crop requires the proper mix of soil conditions, sunlight, evapotranspiration, etc. in addition to adequate water. Similarly, families, businesses, and tourist areas respond to water shortages 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. Future research can test the model's ability to reflect other water systems and their management, and expand the model to include additional factors that impact performance. Future versions of the model can also investigate the impact of increasing the efficiency of supply and situations in which water managers work closely with demand centers to improve efficiency, the timing of demand, and other factors not directly under water managers' control. Understanding the role of water management policies on system performance can continue to improve through the development of water resource models that describe the impacts of demand management, supply management, and their interactions. These integrated models can lead to improved water resource system management and performance.

This work has shown that modeling managerial expectations and risk preferences is critical to understanding the impacts of water allocation policy on performance. It has also demonstrated and explained how water allocation policies can have significantly different effects on performance in different time scales. This supports previous research that recommends the explicit incorporation of different time scales into tools to improve dynamic system manager decision-making (Ford and MacCormack 2000). The current work describes how managers in one practice attempt to incorporate the system dynamics tenet of policy resistance due to delayed and unintended side effects into policies and thereby satisfy objectives with different times scales. Their experiences and challenges in moving beyond recognizing that lesson to improving both short-term and long-term performance suggest that, to fulfill its potential, system dynamics must:

- Discover, recognize, acknowledge, and leverage dynamic insight in practicing managers when and where it exists
- Develop deep understand of the methods used and challenges faced in addressing dynamic management needs
- Develop implementable system solutions to the management challenges identified by system dynamics and faced by managers
- Develop tools and methods that expand and extend existing dynamic insight and skills in practitioners

System dynamics can increase its impacts on dynamic management practice by increasing its efforts to identify, understand, and expand existing managerial insight and experience in managing dynamic challenges.

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Appendix: Water Release Volume Policy Equation Listing

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

$$D_a = \sum_{i=1}^{n} (l_i * ((d_i * s_i) / e_i)) \qquad i \text{ å}\{1, 2, 3...n\} \tag{2}$$

$$D_r = p * d_r * s_d \tag{3}$$

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

$$dS / dt = I - L - R \tag{5}$$

$$dE / dt = (S - E) / \text{ô}_E \tag{6}$$

$$D_u = D - (R)\, dt \tag{7}$$

$$c = E / D_u \tag{8}$$

$$R = \text{Min}\,((S - S_d)/ \text{ô}_R, (D_u * f_C(c/c^*)) + D_m) \tag{9}$$

where: D – Total demand for water (m^3 / month)
D_a – Agricultural demand for water (m^3 / month)
D_r – Residential demand for water (m^3 / month)
D_t – Tourism demand for water (m^3 / month)
l_i – cultivated land area of crop i (hectacres)
d_i – annual water demand of crop i (m^3 per hectacre per year)
s_i – monthly fraction of annual demand for crop i ((m3/month)/(m3/year))
e_i – efficiency of water use by crop i (%)
n - number of crop types (e.g. citrus trees, potatoes, greenhouse crops)
p – population (residents)
d_r – unit annual residential water demand (m^3 per resident per month)
s_d – monthly fraction of annual residential demand ((m3/month)/(m3/year))
a – arrival rate of tourists (tourists per month)
d_t – unit tourism water demand (m^3 per tourist per month)
v – average length of tourist visit (months)
S – Current stored supply (m^3)
I - net inflows to water storage (m^3 / month)
L - Losses from storage (m^3 / month)
R – Total releases from storage (m^3 / month)

E – Expected stored supply (m^3)
$\hat{o}_E$ - Time to adjust water supply expectations (months)
S_d - "Dead" (unavailable) storage (m^3)
f_C – Effect of coverage ratio on releases (dimensionless)
D_u – Unfilled demand for water for remainder of season (m^3)
c - Expected coverage
c^* - Desired coverage
D_m - Mandatory releases
$\hat{o}_R$ - Time used to release available storage (months)

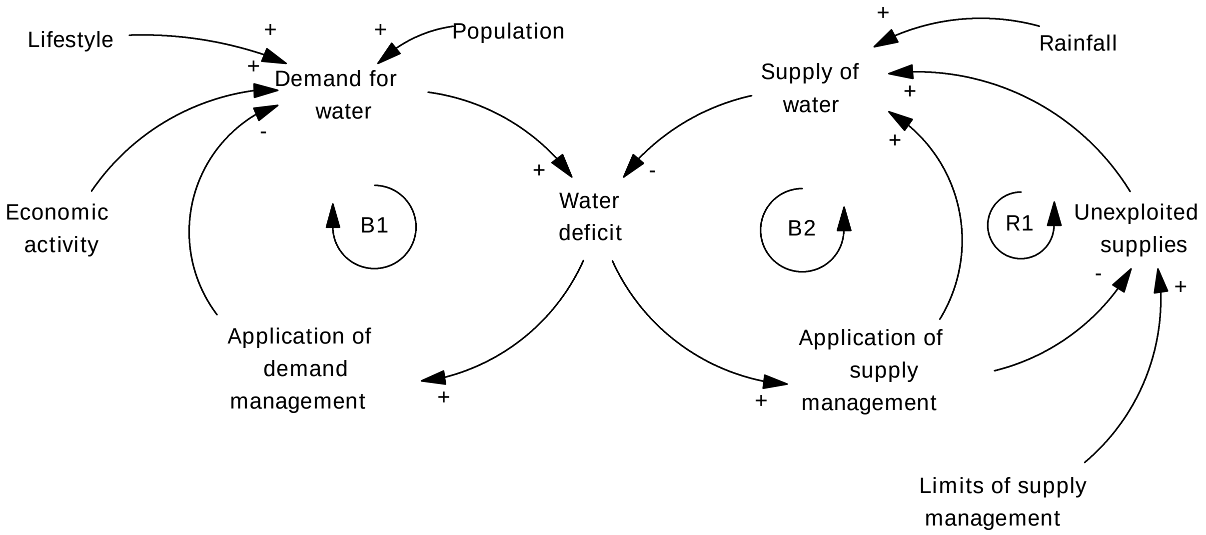

Figure 1: Demand and Supply Management of a Water System

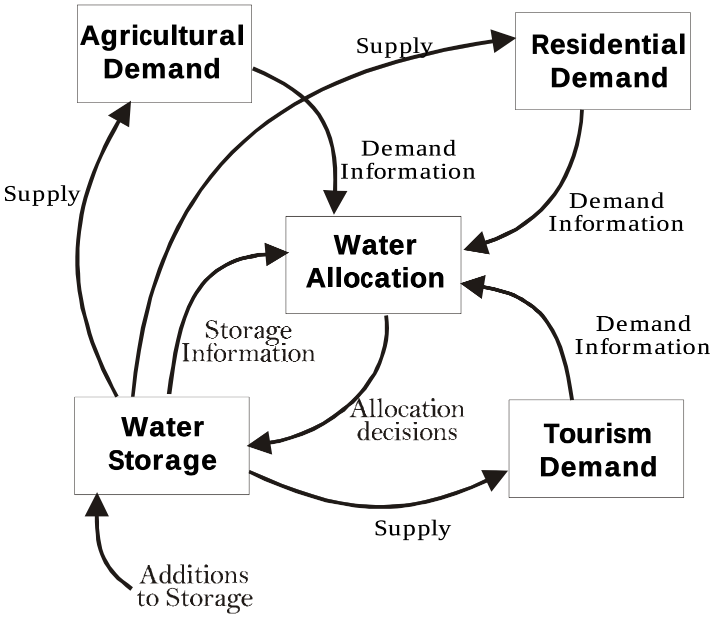

Figure 2: Water System Model Sectors

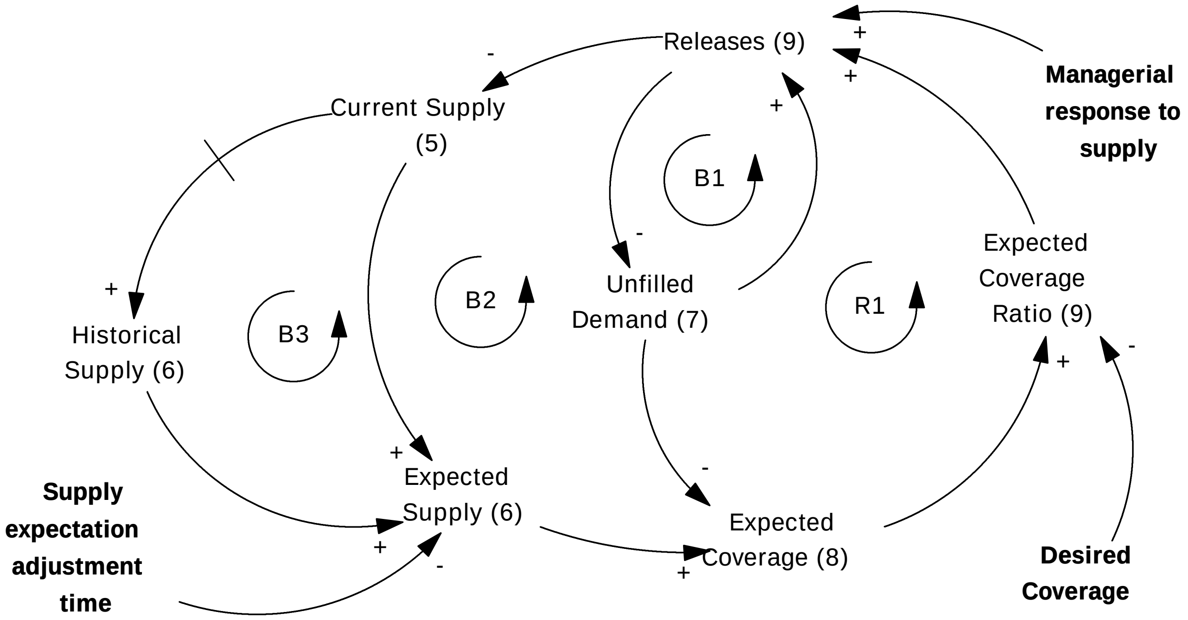

Figure 3: A Water Volume Release Policy Structure

Notes: Equation numbers shown in parenthesis. See appendix.
Descriptors of risk aversion shown in bold

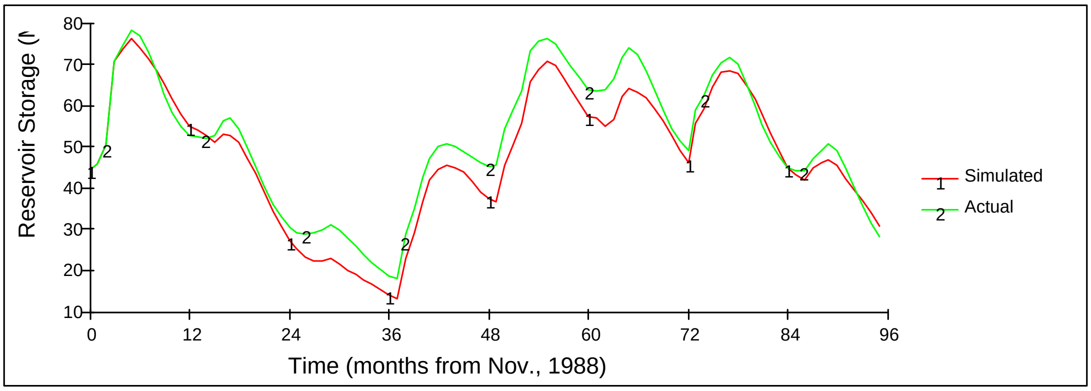

Figure 4: Simulated and Actual Reservoir Storage

Performance Measure	Units of Performance	Base Case Performance	Optimum Performanc	Variance
Agricultural Use Performance				
Citrus yield (8-yr average)	tons/ha	37.2	50	-25.6%
Citrus yield range	tons/ha	31.0	0	31.0 tons/ha
Seasons without citrus yield	each	0	0	0
Greenhouse yield (8-yr average)	tons/ha	12.2	37	-67.0%
Greenhouse crop yield range	tons/ha	18.1	0	18.1 tons/ha
Seasons without greenhouse yield		0	0	0
Potato yield (8-yr average)	tons/ha	12.1	35	-65.6%
Potato yield range	tons/ha	20.9	0	20.9 tons/ha
Seasons without potato yield	each	0	0	0
Residential Use Performance				
Avg. residential shortfall	m3/mo/capita	2.64	0	2.64 m3/mo/ca
Tourism Use Performance				
Months tourist supply shortfall	each	87	0	90.6%
Storage Performance				
Storage preserved for future use	MCM	34.0	115	-70.4%

Table 1: Performance using Base Case Policy

Legend: ha - hectacre (10,000 square meters)
MCM - million cubic meters

		Riskier Policies			Base-Case Policy	More Risk-Averse Policies	
Performance	**Units of Variance**	**Release to Demand**	**Reduced Demand Expectation**	**Lower Desired Coverage**		**Constrain Releases**	**Higher Desired Coverage**
SHORT-TERM PERFORMANCE							
Agricultural Use							
Citrus yield (8-yr avg.)	percent	-38.7	-26.3	-28.8	**-25.6%**	-30.5	-27.3
Citrus yield range	tons/ha	43.1	35.3	46.4	**31.0**	37.9	23.2
No-yield citrus seasons	each	0	0	0	**0**	0	0
Greenhouse yield (8-yr avg.)	percent	-34.8	-53.7	-55.8	**-67.0**	-68.0	-70.1
Greenhouse crop yield range	tons/ha	19.0	28.8	28.0	**18.1**	18.8	19.0
No-yield greenhouse seasons	each	0	1	1	**0**	1	1
Potato yield (8-yr avg.)	percent	-10.4	-47.1	-47.5	**-65.6**	-75.4	-69.9
Potato yield range	tons/ha	15.9	33.9	33.2	**20.9**	18.9	21.4
No-yield potato seasons	each	0	0	0	**0**	2	0
Residential Use							
Avg. shortfall	m^3/mo/cap	2.27	2.40	2.44	**2.64**	2.74	2.74
Tourism Use							
Months with shortfall	percent	62.5	84.3	88.5	**90.6**	85.4	96.9
LONG-TERM PERFORMANCE							
Storage preserved	percent	-96.4%	-94.1	-90.2	**-70.4**	-66.3	-62.2

Table 2: Variance of Performance from Optimal
Base Case and Alternative Policies

Performance	**Units of Variance**	**Release to Demand with Sacrificial Crop**	**Release to Demand with Max. Release**	**Release to Demand with Max. Release, Sacrificial Crop**	**Base Case Policy**
SHORT-TERM PERFORMANCE					
Agricultural Use					
Citrus yield (8-yr avg.)	percent	-21.6	-25.5	-21.1	**-25.6%**
Citrus yield range	tons/ha	36.1	28.3	28.1	**31.0**
No-yield citrus seasons	each	0	0	0	**0**
Greenhouse yield (8-yr avg.)	percent	-31.6	-31.7	-28.9	**-67.0**
Greenhouse crop yield range	tons/ha	19.0	25.6	25.9	**18.1**
No-yield greenhouse seasons	each	0	0	0	**0**
Potato yield (8-yr avg.)	percent	-18.1	-25.1	-22.2	**-65.6**
Potato yield range	tons/ha	15.9	21.4	22.8	**20.9**
No-yield potato seasons	each	0	0	0	**0**
Residential Use					
Avg. shortfall	m^3/mo/cap	1.76	1.75	1.53	**2.64**
Tourism Use					
Months with shortfall	percent	70.8	75.0	75.0	**90.6**
LONG-TERM PERFORMANCE					
Storage preserved	percent	-96.8	-96.5	-96.4	**-70.4**

Table 3: Variance of Performance from Optimal
Base Case and Designed Policies