

An Intelligent Hybrid Decision Support System for the Management of Water Resources

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Abstract

During the last two decades the scarcity of water resources is exponentially growing worldwide and especially in semi-arid countries like coastal and island communities of the Mediterranean region. Cyprus is one of the countries in the Mediterranean where the water shortage problem is evident and very severe. This paper describes an intelligent and flexible, hybrid decision support system, for the management of water resources in the regions along the South Conveyor Project, the largest water development project in Cyprus. In particular, the paper presents the integrated system and its architecture, together with detailed descriptions of the hybrid components synthesizing it.

Introduction

During the last twenty-five years the scarcity of water resources is exponentially growing worldwide. As a result, there has been a serious and growing concern about the water shortage problem, resulting in substantial progress in different aspects of water resource development and management in different parts of the world (Lintner 1996, Rahman 1998). The problem of the scarcity of water is especially severe in the semi-arid countries and in particular, in the coastal and island communities of the Mediterranean region, where water demand satisfaction is not possible (World Commission on Water 1999). Cyprus, situated in the northeast part of the Mediterranean region, is among the countries facing a severe water shortage problem (Hendawi 1998) and focusing in finding efficient and systematic ways for effective water management (Tsiourtis and Kindler 1995, Christodoulou and Socratous 1995). Considering the constant reduction in the water supply available, extraordinary efforts are needed to satisfy the demand for water, which increases proportionally with development. This task becomes even harder, due to the lack of a global view of the water situation in Cyprus, the nonexistent long term planning for its management and the utilization of ad-hoc approaches based solely on the

expertise of engineers and not on scientific facts. Such approaches result in unduly conservative or over-optimistic utilization of water, which may either lead to under-utilization or to large deficits of water. Consequently, there is a need for a methodological approach for supporting decision-making.

Such a methodological approach has been realized in terms of an interdisciplinary, intelligent and flexible, decision support system for the management of water resources in the regions along the South Conveyor Project (SCP), the largest water development project in Cyprus (Water Development Department 1983). The proposed system aims to support water managers face effectively the drought, and hence to minimize the water restrictions imposed on consumers and generally to use the water supply infrastructure effectively.

The final system will be installed at the Water Development Department (WDD) in Cyprus. Its benefits are expected to be highly significant, not only for Cyprus but also for other countries with similar problems. The architecture and the associated methodology can be applied not only to water management problems but also to other supply and demand problems of similar content.

The development of the proposed decision support system started under the INCO-DC project MEDWATER, funded by the European Union and is now continuing under project NHREYS, funded by the Cyprus Research Foundation. These projects are examples of a number of research projects in the area of decision making for water management. Other noteworthy examples, which in some aspects are closely related to the decision support system described in this paper, are the EUREKA project (Eureka Project EU487 1990) that generated the WaterWare system (Environmental Software and Services 1998), providing an integrated framework that provides easy access to advanced tools of data analysis, simulation modeling, rule-based assessment and multi-criteria decision support and a FAO project for the river Nile (Georgakakos 1997) developed in USA.

The rest of the paper describes the system and the architecture underlying it, elaborates on the individual system components, describes the state of the evaluation of the system and outlines future work.

Integrated System and System Architecture

The decision support system developed is based on a flexible, adaptive and hybrid architecture composed of a number of heterogeneous components originating from a variety of technologies and disciplines. The architecture allows the system to embody deep knowledge in the form of causal loop modeling and to use systems dynamics and simulation modeling for predicting behaviour under different water allocation strategies. It also involves relational databases for data storage, analysis and representation, and employs data pre-processing and standard statistical techniques for intelligent data analysis and forecasting. Its components can evolve on the basis of input data and expert knowledge. All these disciplines equip the system with intelligence and allow it to reason under uncertainty, thus increasing efficiency and accuracy in the management of water. The system's interactions are achieved through a Graphical User Interface that utilizes a number of communication and integrating techniques.

In particular, the architecture proposed is made up of four modules (Fig.1): the data module, the decision-maker, the manager and the display module. The data module manages the data and information required by the overall system. The decision-maker simulates the different water allocation strategies under various assumptions, whereas the manager controls the overall system. The display module stores and displays all the resulting information.

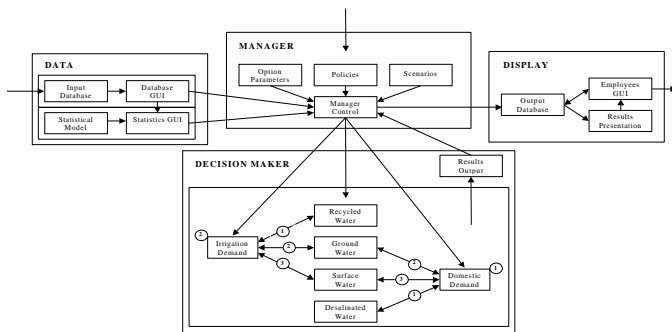


Figure 1: System Components

The four modules communicate among them and cooperate in exchanging data, information and knowledge in order to achieve their tasks.

Data Module

As data becomes the heart of any information system, database technology gets very closely tied to several other disciplines, which come up with their own unique set of applications. Such an application is the proposed decision support system, which is designed with a DBMS as a central component. The data module converts the raw data stored in the database to valuable information, through the use of statistical models. The database stores all the relevant input information such as the inflow to the dams,

the rainfall, the catchment areas characteristics, the demand for each area, the penalties for each type of demand, if not satisfied, etc. Collected data involve meteorological, hydrological and operational data for the seven river basins within the SCP.

The statistical models combine inflow models based on multiple regression analysis and meteorological/climatic models based on different statistical techniques with emphasis on time series analysis and probabilistic distributions. Their main objective is to forecast the inflow to the catchment areas along the SCP. The necessity of statistical models is evident, if one considers the uncertainty in the prediction of water resources.

For the construction of the multiple regression models, the runoff data were related to the factors affecting them (depth area rainfall, climatic conditions and upstream use). Considering the case of the Kouris catchment area, the largest catchment area along the SCP, this relationship suggested the existence of a four-month lag for the upstream use. This lag is due to the fact that the extraction mostly occurs during the summer time when there is no runoff due to drought. Thus, the effect of the extraction during the summer should be taken into account during wintertime. Furthermore, stepwise regression indicated the variables that best explained the data (depth area rainfall, maximum temperature and groundwater extraction) and a transformation of the original data eliminated the non-linearity that was detected. A remedial action was also taken, through some form of transformation, for the elimination of the positive correlation over time (autocorrelation) of the random error terms (residuals), to avoid inefficiency for the least square coefficients, underestimation of the variance of the error terms and non-applicability of certain statistical tests. The Durbin-Watson test ensured no further correlation between the error terms.

Multiple regression analysis on the new data set computed a new regression model. The results obtained indicated a strong enough linear relationship between the response and the predictor variables. The equation of the line fitting the data is: $\log(\text{runoff} + 1) = 0.0893 \cdot \text{DAR}^{0.5} - 1.1060 \cdot \text{MaxTemp}^{0.5} - 0.0601 \cdot \log(\text{IrrBoreholes} + 1) + 2.5690$. For this model, 77.43% of the variation of the runoff is explained by a variation on the factors affecting it. Both the coefficients and the total regression appear to be significant. A set of diagnostic plots further established the quality of the regression model. In particular, they: (1) verified linearity, independence and normality of the distribution of the residuals as well as the presence of only few outliers, (2) gave a good idea of how well the model has captured the broad outliers of the structure, compared the spread of the residuals and of the fitted values, finding the latter greater and (3) measured the influence of individual observations on the regression coefficients which turned out to be insignificant.

During the evaluation of the model, the error involved in it was also estimated. This activity ensured the reliability of the model and allowed its use for predicting the runoff when an estimate of the predictors involved in the model

was given. For doing so the original data set was split into two data sets. The first data set was used for the computation of a regression model after the procedure described above was followed. The resulting model was then used in combination with the second data set to predict the runoff given the values of the predictor. For this set of predictions the error turned out to be quite small and about 50% of the actual runoff data lie in the confidence interval constructed for the mean values, suggesting a valid model.

After establishing the validity of the model, the monthly trends for each of the predictors involved in the model were computed by the use of time series analysis. Thus, a forecast of the values of the predictors for the coming years could be calculated. These values were then passed to the model for the estimation of the corresponding runoff. For a probabilistic approach the same method was used, but instead of using the monthly trend, the cumulative frequency distribution functions of the predictors were used.

Decision Maker Module

The decision maker module embodies deep knowledge based on Forrester's approach (Forrester 1961) that human minds contain representations (models) of reality and use these models in all aspects of decision making. This approach led to the use of the system dynamics discipline, which facilitated the study of feedback characteristics (circular interconnections among elements) for the activities of the WDD, via computer simulation models, and showed how organizational structure, amplifications (in policies) and time delays (in decisions and actions) interact to influence the success of the WDD operation.

The model constructed is a simplified representation of the SCP system at some particular point in time, intended to promote the understanding of the system. Initially, this model was represented in the form of causal loops, modeling positive (type S) and negative (type O) interactions between water supply and demand (Fig.2) to understand the causal relationships among the elements composing the system. Every loop in the model is characterized either as reinforcing (even number of type O interactions) or as balancing (odd number of type O interactions), leading to exponential and goal-seeking behaviours respectively, which in turn lead to growth and change, in the former case, and to balance and stabilization in the latter. The reinforcing loops are represented by *F* and the balancing loops by *B*. Some of the interactions are based on the physical decomposition of the SCP, but others are based on (abstract) variables that control the allocation of water.

Even though system thinkers use Causal Loop Diagrams (CLDs) extensively and they believe that much can be learned from understanding the feedback structure of the system, simply having constructed the CLDs does not imply as much inference on the system behaviour as

desired. To study the system behaviour a collection of information and data that quantify the model are necessary,

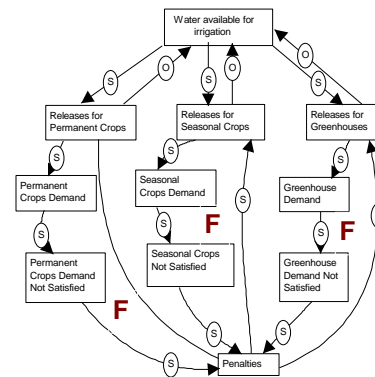


Figure 2: Causal model depicting the relationships involved in the distribution of water for irrigation needs

together with the description of the entities and the operational rules involved. Consequently, the CLDs were implemented as system dynamics models, using stocks (accumulations) and flows (distributions of water) (Fig.3) that allow the quantification of the models. The uncertain, initial conditions for the simulation, e.g. the inflow of water in the dams, are provided by the statistical models as well as by other assumptions. The integration of the subsequent system dynamics models resulted in a unified model simulating, with the aid of the Powersim constructor tool, the current physical transfer of water together with the current operational rules while enabling the investigation of alternative policies on the instruction of the manager.

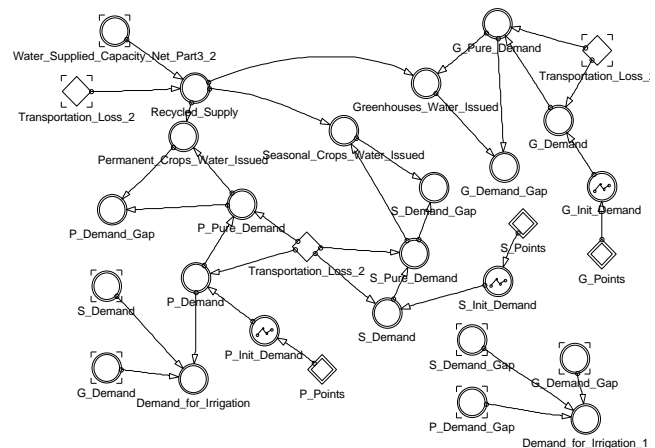


Figure 3: Implementation of the irrigation demand causal model in terms of system dynamics

Overall, the decision-maker is partitioned into two demand types and four source types, namely: the domestic demand, the irrigation demand, the desalinated water, the recycled water, the groundwater and the surface water. Each of them constitutes a distinct model, which is then integrated with

the rest according to a communication protocol (Fig.4) to form the overall model.

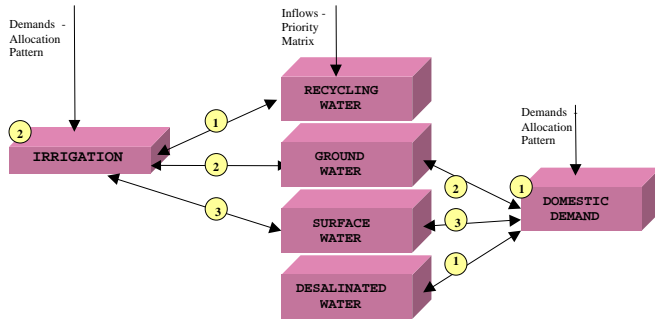


Figure 4: Decision-maker Sub-modules

The *domestic demand* sub-module simulates the demand for domestic use (urban, rural, industrial and commercial demand as well as demand for tourism). In particular, this sub-module reasons as to how much of the domestic demand can be satisfied, from which resources it can be satisfied, what the penalties for not satisfying the demand are, etc. The *irrigation demand* sub-module simulates the demand for irrigation. That is, what the irrigation demand points are, how much the monthly demand is at each demand point, what types of demand there are for irrigation, what the priorities of satisfaction of those demand types are, how much of the demand of each type is satisfied, what the penalties are for not satisfying the demand, etc. Irrigation demand is broken into three categories: the permanent crops, the seasonal crops and the greenhouses. These categories are processed with their corresponding priorities and rules. The *desalinated water* sub-module simulates the provision of water for domestic use and reasons according to the demand and the constraints imposed, such as the conveyor capacities and how to allocate the water available to the demand points that get supplied by desalination plants. The *recycled* sub-module simulates the provision of water for irrigation and reasons on the basis of the demand, in order to decide how much water to allocate for each demand type at each demand point. The *groundwater* sub-module simulates the provision of water for both irrigation and domestic use and decides on how to allocate it according to the demand not satisfied from the desalinated and recycled water respectively. The *surface water* sub-module simulates the provision of water for all the demands left unsatisfied, provided of course that the reservoirs can provide water to those particular demand points according to the structure of the SCP.

Among the demand types, domestic water supply has priority over irrigation. The allocation policy dictates that the absolute minimum demand is satisfied first, for all regions, according to an allocation pattern. Then there are three more allocation turns considered in sequence for all the regions. The priority with which a region is satisfied first during an allocation turn is defined through a priority matrix.

As far as the water resources are concerned, the priority goes as follows. If the demand to satisfy is for domestic use, water is requested first from the desalination plants, then from the ground water and then from the surface water. On the other hand, if the demand to satisfy is for irrigation, water is requested first from the recycled water, then from the ground water and then from the surface water. At each source type, issues such as source capacity constraints, network capacity constraints, transportation losses, evaporation losses etc, are also considered.

The results of the simulation are a set of time-series representing the behaviour of a number of variables at the granularity of month (Fig.5). These sets of time-series are passed to the display module and get stored in a database that keeps all the simulation output results.

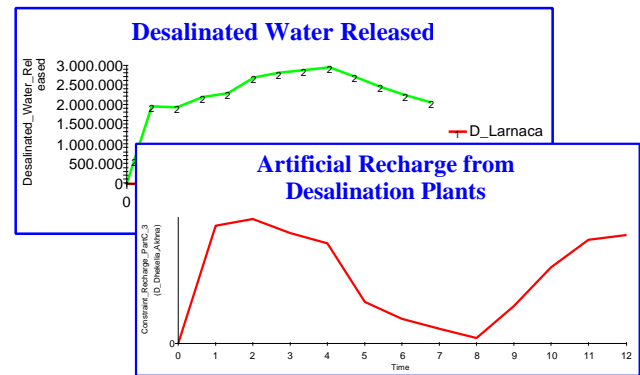


Figure 5: Water production rate and artificial recharge for the desalination water supply model

The system dynamics model went through a sequence of refinements until it provided an acceptable representation of reality. This was verified through a number of tests and scenarios that analyzed and verified the structure of the model and investigated the behaviour of the individual components. The artificial recharge supplied from the particular desalination plant (Fig.5), for example, is significantly decreased during the summer time, when the need for water is much higher and therefore the water available for source supplies is drastically reduced.

Manager and Display Modules

The manager module constitutes the top-level module of the system. In collaboration with the manager user, it successively formulates strategies for the management of water and instructs the decision-maker to simulate them. A strategy is a temporal plan defined through an allocation policy, an allocation pattern and a set of allocation priorities. At each simulation time step there are four allocations to be made according to some allocation pattern. The allocation pattern defines the percentage of demand that has to be satisfied in each allocation round.

The first allocation round defines the absolute minimum required for survival, whereas the rest of the allocation

rounds indirectly define the priority among the various demand types. The allocation priorities are given in a priority matrix, which defines the source to source and source to demand relationships with the corresponding priorities (given using numbers in a decreasing order), and the inflows available from the various sources.

The effects of a strategy, i.e. the results of its simulation, constitute the central aspects of the what-if reasoning performed by the manager. The database storing the results in the display module forms a knowledge base for the manager, aiding the analysis of the effects of the simulated strategies through the use of heuristics, with the purpose of selecting the best water allocation for the immediately following year. The system runs at the beginning of the hydrological year and suggests the water allocation for the following 12 months. The manager module communicates with the user in order to select the preferred policy, the allocation pattern and the allocation priorities.

System Evaluation

So far the database system, the statistical models and the decision-maker have been evaluated, as described in the previous sections, in close collaboration with the WDD,

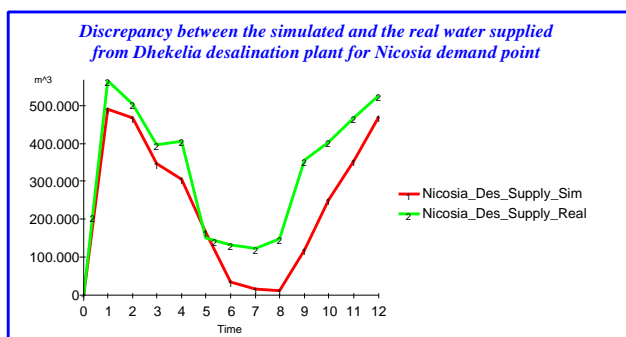


Figure 6: Discrepancy between simulated and real data

based on a bottom-up evaluation methodology that has been defined. In particular, real data have been used to ensure that the operations each component performs are valid (Fig.6). Following the validation of the individual components, the communication and cooperation among them was tested under normal and extreme conditions to ensure the success of their common tasks.

Presently, the evaluation of the integral system and more specifically the manager module is underway using scenarios and case studies for assessing the quality and reliability.

Future Work

The future work involves various enhancements concerning mainly the functionality of the manager. The immediate

task is to develop a learning mechanism that will incrementally enhance the manager's capabilities and knowledge, as more simulation runs are being performed and tested in practice. This is a substantial and critical step for the overall functionality of the system, for it will allow the manager to evaluate the (ongoing) application of a selected water allocation against the evolving reality and to incrementally enrich the base of water management strategies with their predicted and actual effects. Another intention is to extend the application to an internet-based distributed application that will be used by different departments of the WDD, primarily for the collection of new data and the subsequent updating of the statistical and mathematical models.

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