Multiobjective Optimization Model for Water Allocation in the Aral Sea Basin

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ABSTRACT

Current conditions of political and economic development in the Central Asian Republics of Uzbekistan, Kazakstan, Kyrgizstan, Tadjikistan, and Turkmenestan require new systems of analyzing water management. A water allocation model for the Aral Sea basin based on multiobjective optimization and water balance principles is being developed which can be used to evaluate the efficiency and sustainability of water use in the region. The model will be a decision aid for water distribution planning and an instrument that will be sustainable by and useful to local specialists. The first step has been the construction of a multiobjective model to investigate annual allocations of water in the Amudarya River basin. The objectives considered in the model include maximizing the flow to the Aral Sea, maximizing the satisfaction of demands for water in the basin, and equalizing the distribution of water deficits in the basin.

INTRODUCTION

The Aral Sea basin, one of the most critical environmental zones in the world, is now facing serious ecological problems resulting from previous water use and diversion policies. The two main rivers of the Aral Sea basin, the Amudarya and the Syrdarya, once supplied the Aral Sea with 73 and 37 km^3 of water, respectively, every year. The flows from these rivers have now decreased substantially, due to the recent development of intensive irrigation along the rivers. The Aral Sea was once the fourth largest lake in the world by area. Today the sea is nearing one-half of its 1960 surface area, less than one-third of its previous volume, and it is still shrinking.

The effects of these changes reach far beyond the fate of the Sea. People who depend on the Sea and its tributaries for their life blood are now endangered by severe health and economic impacts. Reduced water flow has caused a myriad of problems including: increased salinity of the sea; a reduced moderating effect of the Aral Sea on local climate, resulting in hotter summers, colder winters, and a decreased growing season; exposure of over 20,000 km^2 of former sea floor; and increased irrigation requirements for salt-laden fields in order to achieve the same level of production as before. To accommodate this increased irrigation water need, more fresh water must be taken from rivers that otherwise would feed the Aral Sea, resulting in a cycle causing even greater depletion of the Aral Sea.

Everyone agrees that something must be done to save the dying Sea. Of course, the most direct solution would be to guarantee that the sea receive more water from its source rivers. Unfortunately, there are serious obstacles in the way of this alternative. Another might be to constrain the flow of the rivers into the sea to be no less than some specific values, such as the 1925-50 annual average (~45 km^3/yr). The consequences of this would be to severely limit the amount of water available for irrigation. Clearly, the people in the five newly independent Central Asian Republics in this basin (Kazakstan, Kyrgizstan, Tadjikistan, Turkmenestan, and Uzbekistan) can not give up their irrigated fields. Some of these republics have even begun to lengthen the canals from the rivers, and build new reservoirs on the tributaries so that even more fields can be irrigated.

On the other hand, the international political conditions also make water management in this region very complex. The five republics share the water in this basin, but water management in each country is developing in different ways, e.g., hydroelectric power generation in Kyrgizstan and irrigation in Turkmenestan and Uzbekistan. In March 1992, the republics of the basin agreed to equal rights to water use, as well as equal responsibility for its conservation, however, few concrete measures have yet been developed to achieve these goals.

A new system of analyzing regional water management may aid the republics of the Aral Sea basin in making decisions and developing policies for managing the water resources of the region. Several models of the Aral Sea water resource systems have been reported, including SHI (1991), Voropaev et al. (1984, 1989), and Raskin et al. (1992). Only the models of Voropaev et al., consider the mathematical optimization of system performance, the others rely exclusively on simulation and a user must use trial and error to find regions of optimal values of the decision variables of the models. In addition, except for the model of Raskin et al. The models are all reported in the Russian language with no known English translation or publication in the international water resources literature. Given the current worldwide interest in the problems of the region and the Aral Sea in particular, it seems beneficial to consider the construction of a new optimization based model of the allocation of water resources in this region.

We report here on the initial development a multiple objective optimization model for water allocation in the Aral Sea basin. It is difficult to express the water management goals of a complex situation such as the Aral Sea basin as a single objective. While the Aral Sea needs more inflow and the agricultural sector needs more irrigation water, each republic attempts to satisfy its own demand to the extent possible. Even in a year with larger than normal rainfall, conflicts among the various planning objectives will exist. Therefore, it is appropriate to deal with the problem using a multiple objective modeling approach.

OBJECTIVES AND USES OF THE MODEL

The model developed here is expected to promote the understanding of, and aid in the development of, efficient and sustainable water allocation options for the republics that rely on Aral Sea basin for their water resources. The goal is to construct a screening tool which can be used to easily identify good alternatives for water management that can then be discussed, debated, modified, and simulated in greater detail. With this goal in mind, three objectives are considered in the model: (1) Maximize flow to the Aral Sea. Clearly this is a desirable objective given the precipitous drop in the surface area of the sea and the resulting ecological and economic consequences of the sea level decline. (2) Satisfy existing or projected water demands, primarily for irrigation, to the extent possible. In order to preserve the irrigation based economy of the region, it is necessary to maintain the flow of water to the irrigation districts of the area. (3) Ensure an equitable distribution of water deficits to all demand sites. It seems reasonable to distribute water deficits, in the event that they occur, evenly to all irrigation districts.

MODEL DEVELOPMENT

Monthly operational time steps are considered in the model. There are three linear objectives which have been included in this preliminary model using a weighting method: (1) Maximize the annual inflow to the Aral Sea from the Amudarya River. Since the inflow to the Aral Sea is the river source amount minus any diversions and losses, the ratio of all diversions in a year to the total source in one year can be minimized. (2) Maximize the satisfaction of water demand at all demand sites in a whole year. This will satisfy the demands, to the extent possible. Equally, the ratio of supply over demand can be maximized. (3) Minimize the difference in water deficits among all demand sites. Equally, the minimum ratio of supply over demand in each month and each site can be maximized. This ensures that there is an equitable sharing of water at all demand sites and causes the water to be allocated evenly among the time periods. The constraint set for the model includes a mass balance for each river or tributary node in each time period, ground water pumping limits, local surface water limits, minimum flow requirement for downstream uses, lower bounds on the ratio of supply to demand at each site for all months and at all sites in each month.

The source of much of the data used in the model presented here is the data base of the Tellus Institute WEAP (Water Evaluation and Planning System) model for the simulation of water supply and demand in the Aral Sea region (Raskin et al., 1992). These data consisted of the water demand, including all losses and return flows, for the year 1987 (total demand = 74.7 km^3/yr), water availability for the basin in various years corresponding to different hydrological conditions (very-dry, normal, and very-wet), and available sources of ground water. These data indicate that the total demand exceeds the available supply for all months of the very-dry scenario (total supply = 39.2 km^3/yr) and for a large part of the normal scenario (total supply = 65.5 km^3/yr).

RESULTS

The model was programmed using the GAMS modeling language (Brooke et al., 1992) and run with the data described in the previous section. Model results are shown in Fig. 1 for the three hydrologic scenarios (very-wet, normal, and very-dry) and two sets of multiobjective programming weights. Weight set 1 (w_1 = 1.5, w_2 = 5.0, w_3 = 10) emphasizes the satisfaction of demand at the expense of Amu Darya flow to the Aral Sea. Conversely, weight set 2 (w_1 = 5.0, w_2 = 5.0, w_3 = 10) balances the satisfaction of demand and the Amu Darya flow to the Aral Sea. The results of the model allow us to examine the relationship between flow to the Aral Sea and the degree of satisfaction of the demand at each site. Fig. 1 shows that, even when the model emphasis is on satisfying demands, the upstream demands are not satisfied in some months, while the downstream demands are almost always satisfied. This is different from the results of Raskin et al. (1992), who found by simulation that the upstream demands could mostly be satisfied, but the downstream users suffered shortages. It is seen that the effect of the multiobjective weights is small in a very-wet year and slightly more pronounced in a very-dry year. In all scenarios, there is some shortage of water at the three largest demand sites.

Fig. 2 shows the monthly flow to the Aral Sea under the three different hydrologic scenarios and the two sets of multiobjective programming weights. The figure shows that the flow to the sea is significantly increased in the high flow months of June, July and August when the second set of multiobjective weights is applied.

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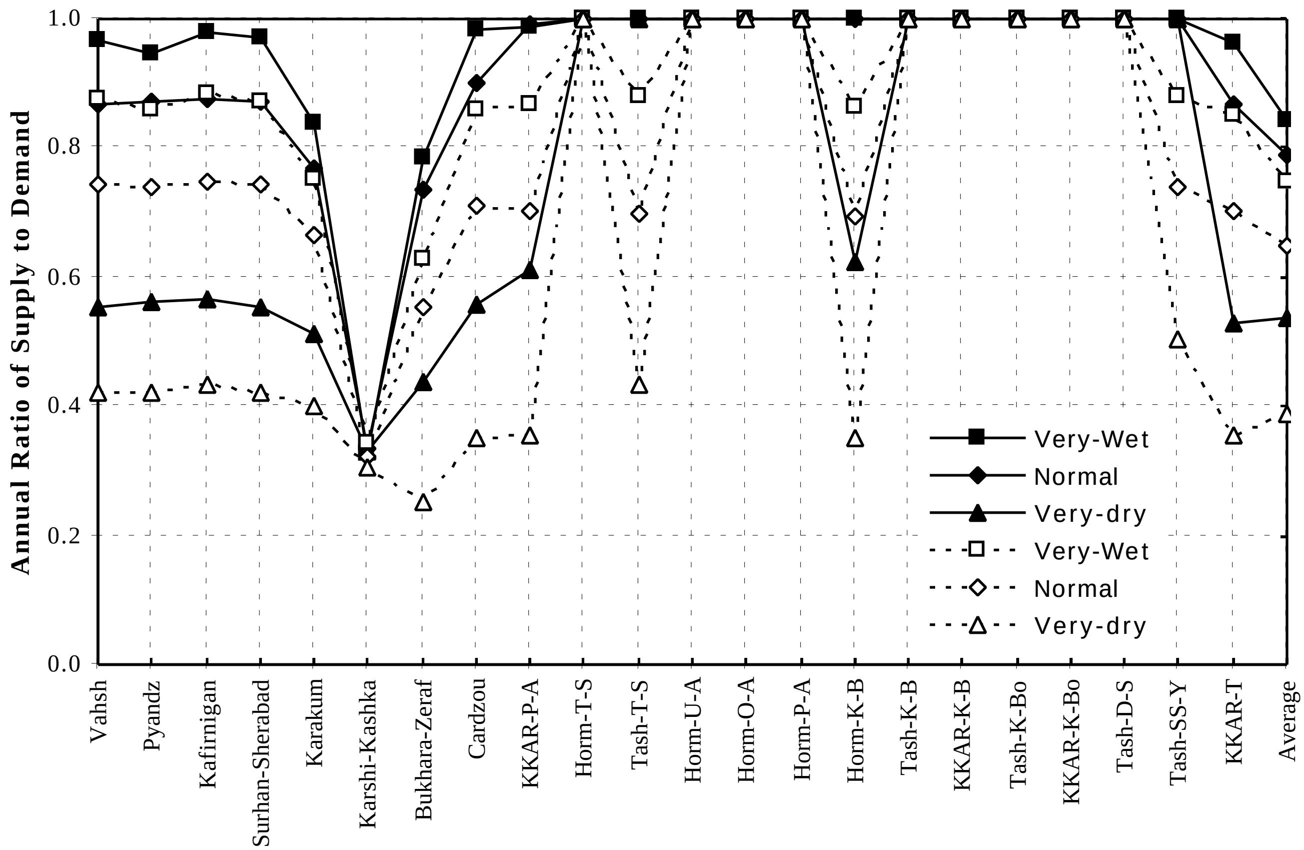

Figure 1. Ratio of supply to demand (three hydrologic years: very-wet; normal; and very-dry and two sets of multiobjective weights: filled symbols-w_1=1.5, w_2=5, w_3=10; open symbols-w_1=5, w_2=5, w_3=10).