CENTRAL ISSUES IN THE COMBINED MANAGEMENT OF SURFACE AND GROUNDWATERS

N. BURAS and S.C. NUNN*
Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona 85721, U.S.A.

ABSTRACT

An overview of the major problems encountered when regional water resources consisting of surface streams and aquifers are to be developed and managed conjunctively is presented. The dynamics of complex hydrologic systems are discussed, including stream-aquifer interactions and some possible alternatives to groundwater mining. Most of the paper is devoted to a discussion of the economic aspects of managing complex hydrologic systems in a mature water economy. Following a presentation of water supply problems from the vantage point of water users and a brief discussion of opportunity cost of water use in complex hydrologic systems, a number of externalities generated by water resources development activities are brought into focus. Three methods for managing complex hydrologic systems are mentioned: (a) development of transferable property rights; (b) regulatory powers of agencies involved in water resources development and utilization; (c) centralized control of regional water sources. The paper concludes with a brief assessment of the current status of the area of conjunctive use of surface and groundwater, and ventures to indicate some possible directions for future studies.

1 INTRODUCTION

By the nature of things, management of regional water resources is based on trade-offs between competing demands. The satisfaction of these demands relies on the development and utilization of surface streams as well as groundwater aquifers. It is the ingenuity and skill of water resource systems analysts and managers that provide solutions to the complex problems of managing regional water resources.

It is quite clear that a successful method of managing water resources should have the capability of balancing competing demands so that actual operating policies optimize the net benefit to the region, as perceived by its inhabitants. Similarly, the management of regional water resources must address the advantage inherent in the integrated use of both surface streams and aquifers, considering also the time variability of several of the variables involved (hydrologic parameters, value of water used, water demand, value of

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*Currently with the Department of Economics, University of New Mexico, Albuquerque, New Mexico 87131, U.S.A.

water stored, etc.). In other words, effective management of regional water resources must recognize the dynamic character of natural hydrologic systems and formulate alternative policies based on this property (Buras and Hiessl, 1987).

Management of stream-aquifer systems in an arid environment differs markedly from that in a more temperate climate. Whereas in temperate regions surface water supplies appear to be more abundant, in the arid zone the reliance on groundwater supplies is much greater. The almost inevitable result is that in a growing economy such as Arizona's, for example, the depletion of groundwater resources outstrips by far their natural replenishment. In due time, a regional water crisis occurs, which generates primarily technological solutions, some of them involving the importation of surface water into the region. Referring again to the Arizona example, the Central Arizona Project will transfer substantial amounts of Colorado river water to agricultural lands and metropolitan areas in the central and southern parts of the state. The implementation of this federally funded project was linked very closely with the enactment by the Arizona legislature of the Arizona Groundwater Act in June 1980 (Arizona Revised Statutes, 1980). This exemplifies the institutional dimension of regional water resources systems, which, most often, has a controlling role in their development and operation.

Traditionally, in most countries surface streams and groundwater aquifers were developed by different agencies, each having separate objectives. Most public investments were made in developing large-scale surface water projects. Groundwaters were developed mostly by individuals, small-scale organizations, or as part of larger infrastructure systems. The reasons for this dichotomy are varied, and some of them were summarized recently (Sahuquillo, 1985). The combined and coordinated management of surface and groundwaters has to cancel this dichotomy in order to develop and utilize more effectively regional water resources.

2 DYNAMICS OF COMPLEX HYDROLOGIC SYSTEMS

2.1 Stream-Aquifer Interactions

Surface waters and aquifers are intimately connected in nature. They interact in the sense that fluctuations of streamflow in a river may have a direct--even if not an immediate--effect on the adjacent water table. A rise in the river stage can induce water to move from the surface stream into the aquifer, and a lowering of the river stage can cause drainage of the aquifer into the river. Intensive exploitation of the aquifer adjacent to river banks can result in a decreased stream discharge. In addition to these quantitative aspects of the interaction between groundwater and surface water, quality of water may be affected by its movement from aquifers into surface streams and vice-versa.

The complexity of the stream-aquifer interactions emerges from two major factors. In the first place, flow in open channels, including streams and rivers, occurs in a time frame that is expressed in meters per second, while movement of water in aquifers is measured generally in velocities that are several order of magnitude smaller. Thus the dynamics of hydrologic systems that are comprised of both surface streams and aquifers are complex, a complexity that is reflected in their mathematical models. In addition, the stochastic aspects of streamflows and the uncertainty connected with the areal extent of the physical characteristics of aquifers contribute to the complexity of stream-aquifer interactions. The scientific literature is rather meager with regard to studies of stream-aquifer interactions that include hydrologic uncertainty.

Of considerable interest is the quantification of the interaction between surface waters and aquifers. Specifically, one desires to determine in an explicit form the relationships that may exist between controllable decision variables (such as diversion of surface streams and pumpage from aquifers) and known existing conditions (river stages and piezometric elevations) on the one hand, and the ensuing state of the combined stream-aquifer system as expressed by river stage and water table levels on the other. These relationships are sometimes expressed by a set of coefficients referred to as influence coefficients (Illangasekare and Morel-Seytoux, 1982). The influence coefficients can be used in modelling regional water resources management issues as problems in mathematical programming. The mathematical models of stream-aquifer interactions may be as simple or as complicated (Sahuquillo, 1986), depending on the actual problem on hand.

Stream-aquifer interactions have important outcomes regarding water quality. Traditionally, we think of water quality in terms of water chemistry, for example, as expressed by concentration of total dissolved solids (TDS). Concentrations of other contaminants, such as synthetic organic solvents, acquire increased importance even though their concentrations can be expressed usually as parts per billion (ppb) or parts per trillion (ppt). The behavior of these trace organic micropollutants moving across a stream-aquifer interface is still poorly understood, although some progress was achieved in the past ten years. The main interacting processes that affect the movement and fate of organic compounds during percolation through the soil profile are dispersion, sorption, chemical reactions, and biological transformations. The extent to which contaminants are influenced by these processes depends on their physicochemical properties, the properties of the porous medium, and the nature of the micro-organisms present in the soil mantle. A recent study in Central Europe (Herrmann et al., 1986) has shown that the movement of some specific contaminants is retarded in comparison with that of conservative tracers. The magnitude of the retardation is estimated from the organic carbon content of the aquifer itself and the octanol-water partition coefficients of the micropollutants. The retardation factor thus calculated appears to be a useful yardstick for estimating spatial and temporal movement of organic microcontaminants. The results of this study indicate that only polycyclic aromatic hydrocarbons are completely removed from the percolating water during infiltration, the other organic pollutants presenting a high risk of contamination of aquifers adjacent to streams.

2.2 Alternatives to Groundwater Mining

(i) Artificial recharge of aquifers. Groundwater mining is an activity undertaken in many parts of the world where regional development outstrips the available surface water resources. This activity is prompted by the relatively low investment necessary to deliver a unit of flow (e.g. $10^6 m^3/yr$) with a very high probability, and by the slow response of the natural system. Thus groundwater mining appears to be an attractive proposition in the short-term since the immediate investments are rather modest and, in addition, the full price of excessive pumping will be borne by future users. However, the combined management of surface and groundwaters must consider alternatives beyond near-term solutions of the water scarcity problem. One such solution is the artifical recharge of aquifers.

Precipitation recharges aquifers when it exceeds the rates of runoff and evapotranspiration. The natural recharge rate may be considerably lower than that of aquifer exploitation, particularly in arid environments where water demands may be substantial. Parts of Israel and regions in Arizona are examples of this situation. Artifical recharge is practiced in Israel, in Southern California, and in other locations in the world, using one or another of the technologies currently available. A main point in most of these operations is the temporary storage within aquifers of surface water not currently delivered for use, originating from a number of possible sources. Examples of these sources are imported waters from other hydrologic units, enhancement of infiltration of flood waters in ephemeral streams, and treated effluent from wastewater treatment plants.

The engineering techniques used in groundwater recharge are known and their relative merits and shortcomings are abundantly treated in the scientific and professional literature. However, many important issues related to artificial recharge of aquifers are not related to the techniques employed, but are rather derived from environmental and other concerns (Coe, 1979). For example, the following questions are often raised: (1) How is the recharging water going to affect the quality of groundwater in the recharged aquifer? (2) What are the priorities between the individuals owning land overlying an aquifer artifically recharged and public agencies to available storage space in the aquifer, and what are the priorities between the public agencies? (3) Who owns the water after it is stored in the aquifer? (4) How should governmental and regional groundwater recharge programs be made compatible with local water management operations? Some of these issues will be discussed briefly in Chapter III of this paper.

(ii) Reclamation and reuse of wastewater. Treated municipal wastewater appears as an increasingly attractive alternative to groundwater mining, especially as a possible irrigation water source. At the same time, depending on the level of wastewater treatment, reclaimed effluent is a potential environmental pollutant and may present a serious hazard to public health. Provided that municipal wastewater is treated adequately, the effluent can indeed be used for irrigating agricultural crops. The integration of treated effluent within a regional water resources system requires the optimization (or at least quasi-optimal solutions) with respect to treatment plant capacity, level (or degree) of treatment of the municipal wastewater, allocation of the treated effluent to various users in the agricultural sector, and the cropping pattern of each user of treated effluent. A distinction is made in this discussion between municipal wastewater, which has a substantial load of organic material (living or inert), and industrial waste which may be rich in heavy metal cations such as chromium, molybdenum, copper, and others.

Viewed from a regional point of view, the integration of reclaimed wastewater within the water resources systems raises a number of inter-related problems (Dinar and Yaron, 1986), such as (1) establishing the geographical boundaries of the system considering (a) capacity of the wastewater treatment plant and (b) capacity and layout of the wastewater and effluent conveyance networks; (2) determination of the level of wastewater treatment; (3) allocation of the treated effluent to users within the region; (4) selection of alternative cropping patterns for each user; (5) allocation of costs to the users; (6) level of government subsidy, if needed. The approach to these problems was through the formulation of a long-run mathematical programming model, and the area to which it was applied was an agricultural region in Israel that included a town and several farms. The objective specified in this analytical model was to maximize the regional income subject to a given amount of municipal wastewater, public health standards, the capability of the agricultural production systems to use the effluent given the availability of land and of other imputs, the prevailing price system, and the existing technology. In addition to these constraining conditions, considerations of environmental quality and decreasing groundwater mining, i.e. freshwater savings, may induce governmental subsidies for the treated effluent.

The generalized model--without reference to the specific geographical region under analysis--had two major components: (1) the town (as the source of municipal wastewater) and the treatment plant including the alternative levels of wastewater treatment; and (2) the agricultural users of the treated effluent. The decision variables of the model are (1) the level of wastewater treatment; (2) capacity of conveyance facilities from generators of municipal wastewater to the treatment plant and/or for treated effluent from the plant to agricultural users; (3) treatment plant capacity; and (4) the areal extent of a given crop in an agricultural production unit (farm) using wastewater treated to a specified level. Decisions exogenous to the model are the location of the treatment plant and the rate of government subsidy. In addition, the model was used to obtain a solution under the assumption that users of treated effluent act independently; then it was expanded to include the possibility of cooperative action.

The results of the analysis of the specific region in Israel indicate that in the absence of governmental subsidy there is no incentive to the farmers to use treated effluent. A subsidy of 15% of the overall treatment and capital investment in the effluent conveyance systems is threshold incentive for the use of treated effluent. A 50% subsidy is an incentive for all farmers to use the treated effluent and leads to full regional cooperation. A residual problem that needs to be considered separately is that of redistribution of income at regional level.

(iii) Desalination. Considering that about 97% of all water on planet earth is in the oceans, desalination appears to be a tempting alternative to groundwater mining, particularly in coastal areas. However, the process of desalination involves substantial amounts of energy, which is a costly resource whose price will probably rise steadily beginning in the next decade. Consequently, desalination of sea water is carried out only in special cases (such as the island of Aruba in the Dutch West Indies), and more attention is given to the partial desalination of brackish waters.

Brackish waters, even those with a low salinity level of about 1,000 ppm TDS, can cause serious economic damage to both farmers and municipalities. The precise quantification of these damages is rather difficult, but it is estimated that salinity increase by one ppm TDS at the Imperial Dam on the Lower Colorado in the United States will increase costs of agricultural production by about $100,000 per year in the Imperial Valley in Southern California and will generate damages to water users in the Los Angeles Metropolitan Area of about $250,000 yearly (Svenson, 1980). An important source of soluble solids reaching the Colorado River is the irrigation return flow upstream from the Imperial Dam. Since irrigated agriculture uses very large amounts of water, it can cause considerable contamination of the regional water supply due to its low efficiency. Consequently, improved irrigation efficiency will reduce salt in the water supply, could help alleviate water shortages for other purposes provided that there exists sufficient storage capacity in the system, and may increase crop yield. However, improving irrigation efficiency to the point of reducing substantially the soluble matter reaching water supplies may be a time-consuming process, while the need to maintain regional water supplies at a desirable level of salinity may be immediate. To resolve this conflict in time, desalination technology may be used.

A specific example is the situation in the Lower Colorado River Basin. According to its treaty obligations, the U.S. has the responsibility of releasing to Mexico 1.5 million acre-feet on the average annually ($1{\cdot}8 \times 10^9 m^3$), with an average salinity content of not more than 115 $\pm$ 30 ppm more than the water at the Imperial Dam (salinity of about 850 ppm). Irrigation projects between the Imperial Dam and the Mexican border raise the salinity of the Colorado River water to 1,300 ppm. In order to meet the requirements of the Mexican treaty, the U.S. is making an effort to improve irrigation efficiencies downstream from the Imperial Dam and is constructing one of the largest reverse-osmosis desalination plants in the world for the treatment of irrigation return flows. The plant will have a capacity of 96 million gallons per day ($133 \times 10^6 m^3/yr$), and the investment is in excess of $330 million. Observe that this represents an average investment of about $2.50/m^3/yr, which should be added to existing investments in dams and reservoirs that regulate the flow of the Colorado and ensure the annual release to Mexico of $1.8 \times 10^9 m^3$ on the average.

(iv) Weather modification. Cloud seeding technology has developed over the last 35 years as a means of augmenting precipitation. The augmentation possible is fractional and, where successful, is in the range of 5%-20% (Committee on Weather Modification, 1983). However even these small increases in precipitation may generate important economic benefits. It is estimated that an additional 10% precipitation in Montana would increase farm revenues by $10 million (1973 dollars), while in Kansas these benefits could range from $99 million to $127 million.

An interesting aspect of cloud seeding is that minute amounts of nucleant have large physical effects in clouds. Silver iodide (AgI), which is the best known nucleant, consists of particles ranging from 0.01 mm to 0.1 mm, so that one gram can have as many as 10^{14} particles, enough to seed several cubic kilometers of cloud. However, AgI will probably accumulate in the soil, but it is unlikely to affect biota of most ecosystems. Some microorganisms, sensitive to silver poisoning, may be affected by concentrations of AgI in excess of 10 ppm. This concentration may be reached following 50,000 years of cloud seeding. Most crop plants do not seem to absorb AgI, and the absence of absorption suggests that, at least at the initial level, there is little possibility of concentration of silver up the food chain. In the cases that silver was observed to have been absorbed by vascular plants, it is apparently not transported to shoots. Thus, even if silver were to reach the utilizable parts of these plants, its effect is unlikely to be detectable within the first 1,000 years of seeding (Weaver and Larich, 1973).

A weather modification (cloud seeding) program involves the collaboration of a number of scientists and professionals. Meteorologists predict changes in precipitation due to cloud seeding; hydrologists estimate the resulting increase in runoff and streamflow; hydraulic engineers consider the effects on streams and reservoirs downstream from the target area; and water resources systems analysts and planners evaluate the potential overall changes associated with the program (Changnon et al., 1979). The planning, implementation, and management of the program require an interdisciplinary team.

(v) Demand modification. Modification and management of demand is probably one of the least considered alternatives to groundwater mining. All too often we seem to forget that optimal regional development and utilization of water resources requires an equilibrium between three major components: available supply, water demand (in terms of both quantity and quality), and the price we are willing to pay for water delivered with a specified probability. It is only lately that demand management and modification was considered seriously.

Estimation of water demand in a region is at best a difficult problem, and much of the difficulty stems from what appears to be the inherent inaccuracy of the data ("noisy data"). Thus it appears that a necessary step in the analysis of regional water demand is the formulation of a model capable of handling noisy data. A recent study (Kher and Sorooshian, 1986) considers the monthly municipal water demand in Tucson, Arizona, Q, as a function of the monthly family income I_t, the average price of water P_t, monthly average rainfall R_t, monthly average temperature T_t, and monthly effective evapotranspiration E_t. Thus

$$Q_t = f(I_t, P_t, R_t, T_t, E_t) = a_0 + a_1 I_t + a_2 P_t + a_3 R_t + a_4 T_t + a_5 E_t. \qquad (2\text{-}1)$$

Assuming a noise level of 10-30% in the independent variables, an algorithm is developed to give bounds on model parameters a_i $(i=0,1,\ldots,5)$ and on the noise covariance matrix. Thus the model can yield a range within which future demand is expected to lie.

Water demand, especially for urban residential use, is highly inelastic over a broad range of prices, particularly in the short-run. However, long-run price elasticity for residential water is about -0.5 (Martin and Thomas, 1986). Thus the potential for the long-term demand modification through price adjustments is significant.

Alternatives to groundwater mining are neither simple nor easy. Those mentioned in this chapter are the major ones, yet not exclusive. In the short run, mining of groundwater seems to be a least cost solution for the development of regional water supplies; yet, it is a myopic solution. In a more distant time horizon, depletion of regional groundwater resources may present a formidable problem. The problems of Tucson, Arizona, a city of about 600,000 inhabitants entirely dependent on aquifers for its water supplies, is an excellent example of the complex issues raised by continous mining of groundwater over a long period of time. (Metzger, 1986).

3 ECONOMIC ASPECTS OF MANAGING COMPLEX HYDROLOGIC SYSTEMS

3.1 The Maturing Water Economy

Interest in conjunctive management is characteristic of the maturing water economy, where scarcity values of water are high and rising. Other characteristics of the mature water economy are (Randall, 1981): (a) long-run supply of impounded water is inelastic; (b) demand for delivered water is high and growing; (c) physical condition of impoundment & delivery systems are decaying; (d) competition among agriculture, industrial, and urban uses, and instream flows is intense; (e) externality problems are pressing; (f) social cost of subsidizing increased water use is high and rising.

In the "young" water economy, management focuses on supply, developing impoundment and delivery systems and perfecting secure claims to water supplies. The maturing economy, with inelastic long-run supplies, increased competition among users and intensifying externality problems, shifts the focus towards demand management and coordination of the use of available supplies, or conjunctive management of demand with ground, surface, atmospheric and low-quality water.

The pressure of increasing economic scarcity is felt in both the technological and the institutional water-management arenas. When traditional sources of new water supplies have been exhausted and demand is still rising, water management technologies turn to conservation and supplies that can be developed by conjunctive management technologies--artificial recharge, effluent reuse, weather modification, and desalination--enter the set of economic alternatives.

Water management institutions, on the agency level as well as in the area of property rights, experience a similar shift in focus. Demand management agencies, using regulation, zoning, moral suasion or price, replace the traditional supply agency as the leading water institution. The "young" water economy's property-rights institutions usually do not recognize the external impacts of water use among hydrologically related water users. The costs of these effects are magnified when existing supplies are fully utilized, and property rights systems are pressured by injured third parties to account for external effects.

Finally, increasing competition among users creates pressures to replace public water-development policies with market-like water-allocation institutions in order to satisfy high-valued uses. Market-based reallocation requires property concepts that account for the relations among hydrologically interrelated sources, or conjuctive management.

3.2 Water Supply in a Complex System from the Water-user's Point of View

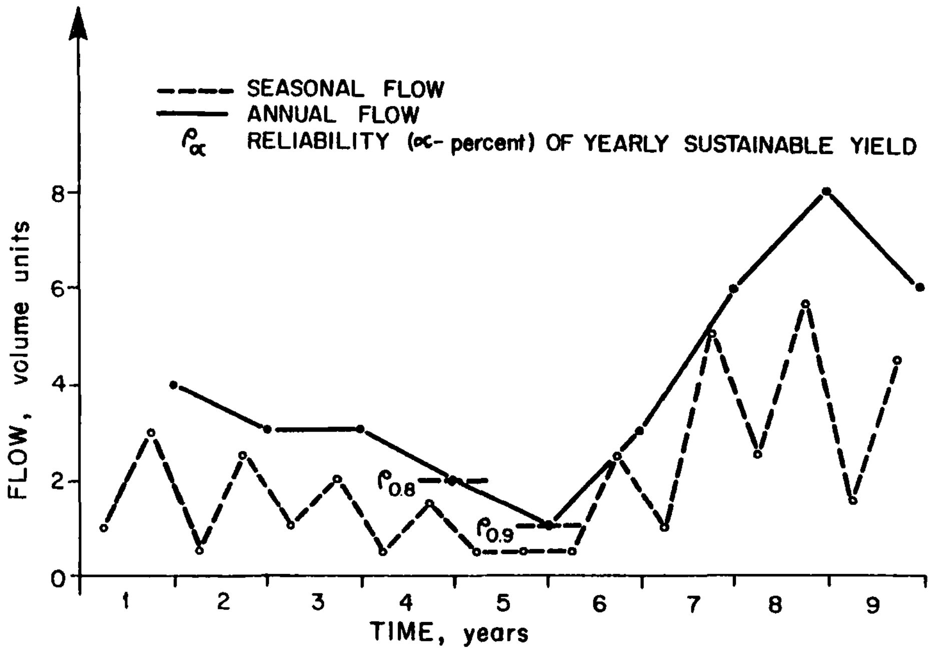
Water availability is a natural phenomenon with a highly stochastic element. Water demand, in contrast, is relatively constant, or predictably seasonal. The viability of a social or economic activity over its expected lifetime depends strongly on the availability of dependable supplies of water within the range of "reasonable" substitution for the duration of the community or the activity. While there are substitutes for water (capital investment in conservation, for example), elasticities of substitution tend to fall rapidly as low levels of water use are approached. Because of supply variation and the high cost of substitution, water users are motivated to seek secure water supplies over the entire planning horizon, and claims on water are most often held in the form of "water rights" or perpetual claims on periodic flows--acre feet/year, 10^6 m^3/yr, ft^3/sec, gallons per minute, m^3/sec--and not in volumes--acre feet, ft^3, gallons, cubic meters. The reliability of a water source can be expressed as the fraction of years that a given level of periodic flow will be equalled or exceeded.

The effective planning horizon over which these periodic flows are to be secured is different for different types of water users. For community water needs, it is generally quite long--in excess of 100 years could be taken as a guideline. For economic enterprises it is at least the period required to recover capital investment and a reasonable return--probably more like 20-50 years. For mixed endeavors such as agriculture, which is often both a social and an economic enterprise, it may be something between these extremes.

Quality is another important dimension of the water claim. Different users have different quality requirements--irrigation can utilize water that is too high in nitrates for municipal use; water for cooling a generator may contain toxins, but some cooling plants may have higher standards for total dissolved solids than even domestic users.

A community or an activity is as interested in the quality and reliability of its periodic water claim as in its magnitude. We shall call the periodic flow of a given quality which can be expected for the pertinent planning horizon with an "acceptable" degree of certainty--the supply's sustainable yield. Sustainable yield has four components: a periodic flow rate (e.g. 250 million cubic meters/year), a degree of certainty (e.g. 92%), a time horizon (e.g. 100 years), and an index of quality (e.g. above the U.S. Environmental Protection Agency standards). A source or combination of sources is expected to yield at least 250 million cubic meters/year of acceptable drinking water for 92 of the next 100 years.

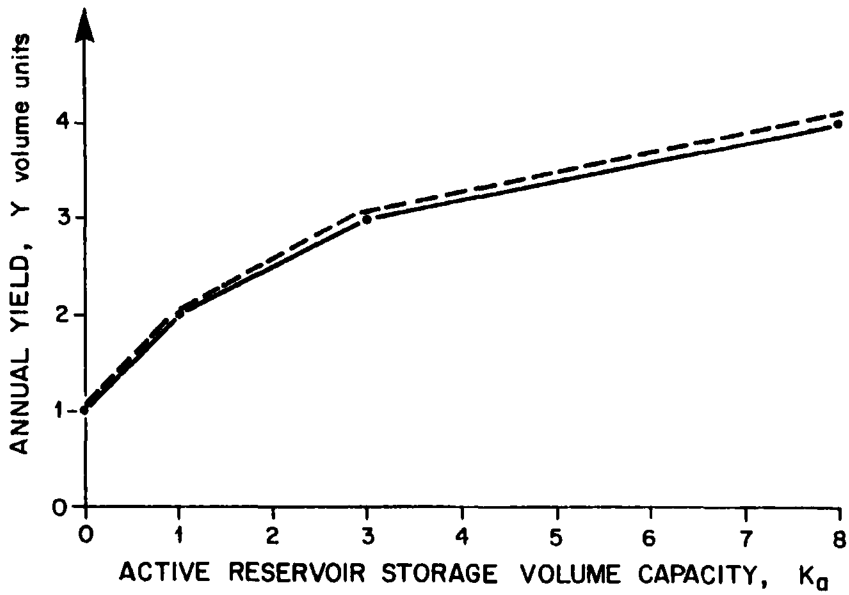
In the absence of storage the sustainable yield of periodic surface flows is the minimum flow that can be expected with the requisite degree of certainty. An example is shown in Fig. 1.



Source: Loucks et al., 1981

Fig. 1. Periodic streamflow with two levels of sustainable yield.

A water user who is dependent on surface flows with a water demand above the minimum flow level will find its needs are not met more frequently than is acceptable. Sustainable yield can be increased by building storage facilities; the theoretical upper limit to this increase is the average flow of the river, and the actual upper limit is below that, depending on the capacity of physical storage sites, annual surface evaporation, seepage losses, etc. Weather modification techniques, which tend to increase flows in peak years rather than in drought years, can increase sustainable yield only if adequate storage exists. Fig. 2 shows the variation in sustainable annual yield as a function of the active storage capacity of a surface reservoir.



Source: Loucks et al., 1981

Fig. 2. Annual sustainable yield as a function of active storage capacity. Broken line indicates possible effect of weather modification.

An example of a reservoir yield function indicating also the probability of sustainable yield is shown in Fig. 3 (Buras, 1985).

Sustainable yield takes on quite a different meaning for groundwater stocks. An aquifer with negligible annual recharge containing a million acre feet of recoverable groundwater stocks has a zero sustainable yield if the planning horizon is infinite. For a 100-year time horizon, the same aquifer has a 10,000 acre-foot sustainable yield; for a 10-year horizon, a 100,000 acre-foot sustainable yield. Groundwater stocks, however, offer a high degree of reliability over the recovery period. Fig. 4 indicates the sustainable yield of one million acre-feet of recoverable groundwater with planning horizons varying from ten years to infinity.

Reclamation and reuse of wastewater can reduce the required sustainable yield from the conventional water resource by providing a substitute for demand on the resource. The amount of potential reduction depends on how much of water used is available for reclamation.

Let x be total periodic water use, and the period considered be the interval between first delivery of fresh water and redlivery of treated effluent. Then volume of waste water available for reclamation and reuse is βx, where

$0 < \beta < 1$. Some of this potentially usable reclaimed wastewater is lost in collection, treatment, and transmission/distribution.

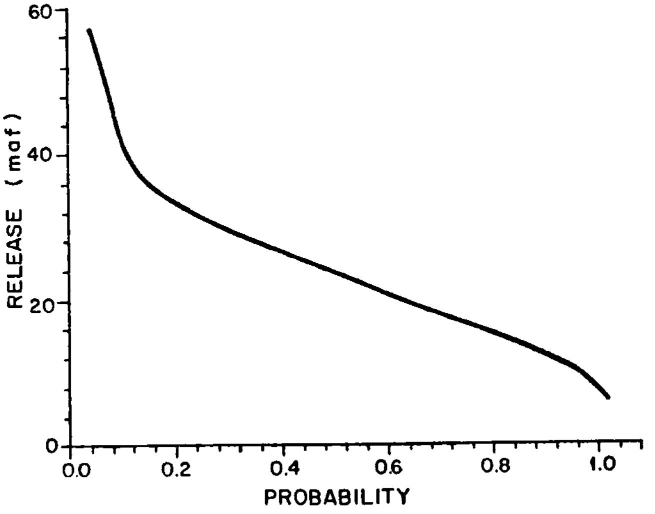


Fig. 3. Reservoir yield function.

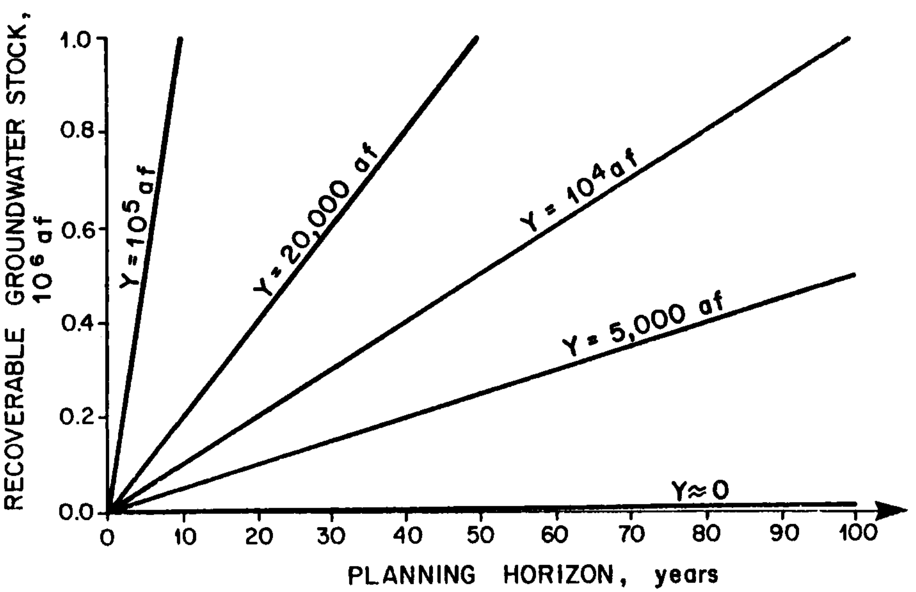


Fig. 4. Groundwater depletion for various sustainable yields.

Let γ be the proportion of these losses, $0 < \gamma < 1$. Then the maximum periodic yield of reclamation of wastewater is:

$$\alpha x = \beta \gamma x. \qquad (3\text{-}1)$$

Since reused water itself becomes wastewater and subsequently available for reuse, the total potential for substitution of wastewater for claims on the water resource is the sum of the infinite series:

$$\alpha x + \alpha^2 x + \alpha^3 x + \ldots = \alpha x / 1-\alpha. \qquad (3\text{-}2)$$

This fraction represents the supply-side limit on effluent reuse potential. On the user's side, reuse potential is limited by the capacity of existing users to utilize this lower quality water. Supposing uses exist for all the wastewater produced by the community, then fraction (3-2) can be called the "sustainable yield" of effluent as a supply source. Note that unlike other supply sources, this one depends on the level of water use, x.

In a hydrologic area where various alternative sources are present, joint management can improve sustainable yield in terms of periodic magnitude, quality, reliability, the planning horizon or all four. For example, a surface source of high variability (without storage) can be managed jointly with a groundwater stock by using the groundwater only when surface flows are insufficient to give a higher-magnitude, more reliable sustainable yield than the two sources together would have if they were managed independently. Similarly, a surface source with high concentrations of total dissolved solids (TDS) can be blended with a groundwater source with low concentrations to reduce the level of delivered TDS. Fig. 5 shows a very simple example, based on the same surface flow data as Fig. 1, of independent and joint management sustainable yield.

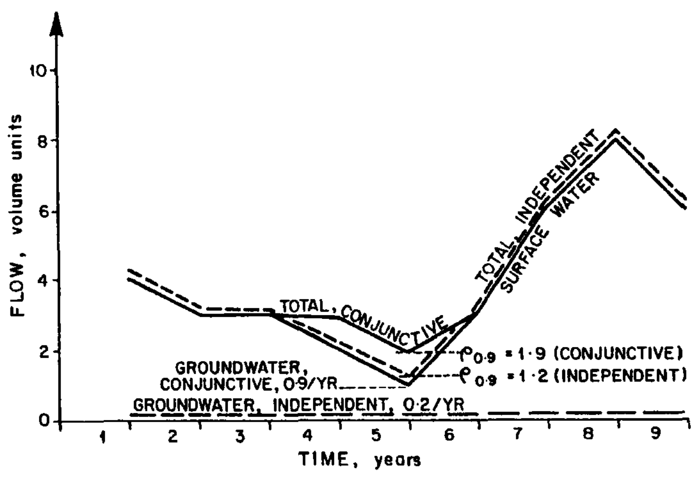


Fig. 5. Independent and joint management sustainable yield.

Water demand, the amount of water users will actually seek to acquire, is a function of the value of water in economic and direct-consumption activities, the cost of acquiring water, the cost of the substitutes and complements of water, and habits, tastes and preferences. Some fluctuations of actual yield below sustainable yield can be absorbed by reductions in demand, in response to increases in price or cost, subsidization of substitutes (water-conserving capital) or conservation exhortations which may affect habits and preferences. In periods of water shortage, excess demand that is not absorbed by these mechanisms must be shut off by restrictions on water deliveries.

Each water provider may satisfy its water demand with a portfolio of sources in conjunction with demand-management policies. A municipality may hold claims on surface flows, for example, large enough to satisfy its water demand 60% of the time, and enough reservoir capacity to store excess flows for 20% of the years of shortfall, supplemented with claims on groundwater stocks adequate to meet demand during the remaining 20%. As these reserve groundwater stocks are drawn down, the city may choose to invest in artificial recharge during high-flow years. If demand grows over time, dependence on the resource can be reduced by implementing reuse systems, in order to maintain sustainable yield requirements within levels of claims on the resource base. If the municipality operates its water-supply policy close to the margin, it may find it necessary to employ special pricing or conservation campaigns during short-supply years. Each of these policies is costly; even demand-management is a high-cost policy, though most of the costs are borne by the water consumer and not by the provider. The relative costliness of the policies is site-specific. Some general observations, however, can be made.

Storage is an investment activity, and the higher the effective discount on future returns the more costly storage activities are.

Since much surface storage produces hydropower as a joint good, while underground storage is energy-consumptive, the preference of surface to underground storage alternatives increases as energy prices rise. On the other hand, since surface storage experiences losses to evaporation, while subterranean storage does not, the higher expected future values for stored water are, the more attractive is artificial recharge relative to behind-dam storage.

Effluent reuse is among the more costly means to secure water supplies. However, some of the costs of reuse of wastewater are incurred with the growth in demand in any case--growing cities replace cheap septic tank systems with sewers; as sewage volumes overcome the assimilative capacity of the environment, highter treatment standards are imposed for disposal of raw effluent--the capital investment required for disposal of nonreused sewage in growing municipalities reduces the marginal cost of treatment and distribution for reuse. In addition, growth of demand tends to create more water uses that can be satisfied with low-quality water, giving rise to a market for effluent.

Finding the minimum cost portfolio to satisfy a given sustainable yield requirement (with the requisite degree of certainty as a choice variable as well) is a challenging but well-defined economic optimization problem. This problem is vastly complicated by the fact that there is more than one water user on a hydrologic system, and the effects of these users on the resource are deeply interdependent. The allocation problem of a hydrologic system with multiple users is not an optimization problem, but a problem in game theory (Buras and Hiessl, 1987).

3.3 Opportunity Costs of Water Use in a Complex System

The phases of the hydrologic system are in a dynamic balance with one another, so that changes in the flows, periodicity, or quality in one phase impact all related phases, see Fig. 6. This schematic representation of a regional hydrological cycle identifies some of the physical interrelationships in the context of water management activities.

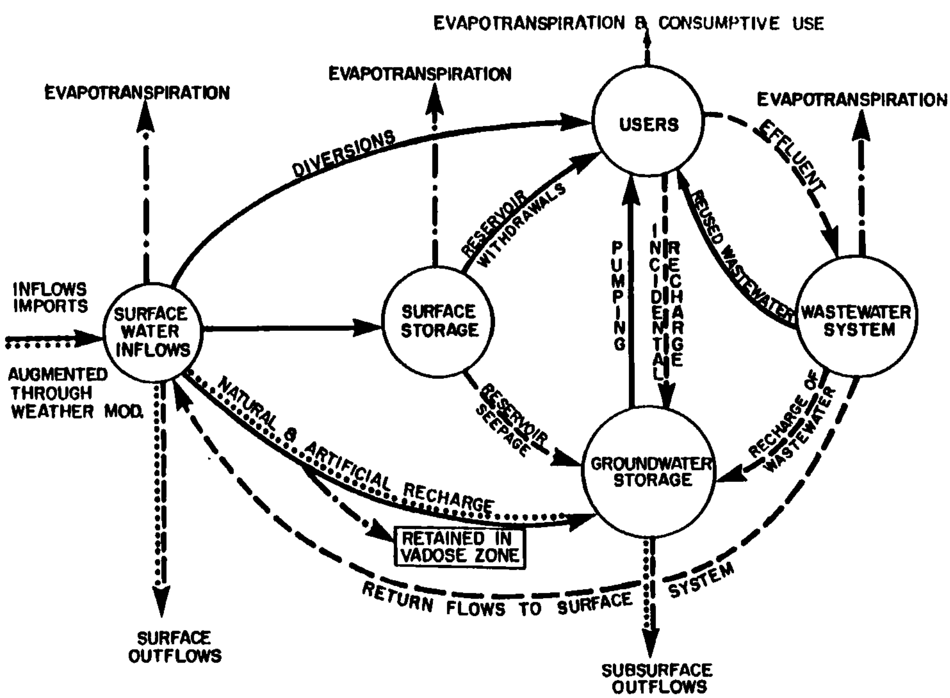


Fig. 6. Schematic representation of a regional hydraulic cycle.

The blue lines--surface diversions, surface storage, reservoir withdrawals, pumping, imports, artificial recharge and reused wastewater--indicate sources of water supply. Some type of legal claim is usually attached to these water uses. The green lines--effluent, wastewater recharge, return flows to surface systems and incidental recharge--indicate return flows to the system from water users. These return flows may be legally encumbered, as they represent an element of water supply to which water users in the subsequent phases of the cycle may have a legal claim. The red lines--evapotranspiration, water retained in the vadose zone in the recharge process, and consumptive use--represent potential losses to the system. Reductions in these elements represent a net addition to the total water available in the cycle. The yellow lines--inflows, natural recharge, and subsurface and surface outflows--represent nature's portion of the system. Surface and subsurface outflows may, however, be legally encumbered by water claims outside the region in question, as indicated by the dotted green lines.

What can be seen here is that it is impossible to define a water claim apart from the use to which it is put, because the use affects return flows to the system; it is impossible to define surface inflows or groundwater stock outside the context of water claims, because inflows and stocks depend on water uses and the nature of claims on water; it is impossible to consider wastewater reuse outside the context of claims to surface and groundwater, because wastewater that is not reused contributes to surface and groundwater flows. Only so long as water is not scarce, that is so long as changes in the flows through various parts of the system do not affect the legal claims of water users, can this system be managed as disjoint surface supplies, groundwater, wastewater, and surface storage systems. In economic terms, changes in water uses create opportunity costs in terms of their effect on other parts of the hydrologic cycle. Before looking at the management implications of these opportunity costs, we should itemize some of these opportunity costs and identify who will pay them.

(i) Groundwater pumping. The opportunity cost of pumping groundwater is felt in physical effects of removing the water from the aquifer as well as the disinvestment in stocks for future use. These effects include the increase in pumping lift for all future pumping, a cost borne by other pumpers on the aquifer; land subsidence as a result of removal of subsurface support, a cost borne by affected landowners; changes in surface vegetation that is dependent on the water table; infiltration of saline or other low-quality water as barriers to their inflow from other subsurface water bodies are removed (e.g. sea water contamination of coastal aquifers); and reductions in surface flows as surface water is diverted to replenish the cones of depression created by groundwater pumping (Young et al., 1986). To the extent that these costs fall on persons other than the pumpers, they are external.

(ii) Surface diversions. The opportunity costs of surface diversions arise from reductions in instream values such as hydropower generation (Frederick, 1986), the cost of which is borne by those who pay higher power prices for power generated by fossil fuel; fisheries, wildlife and riparian fauna, with costs borne by the public and the customary beneficiaries of the fish and wildlife population; and in diminished assimilative capacity of the stream and degraded quality (Miller et al., 1986), with costs to downstream water users and the environment dependent on the stream. In addition, recharge to the aquifer may be reduced and downstream diversions foreclosed, the costs of which can be borne by the affected water users. It is common for surface diverters to be confronted with the costs of foreclosed downstream diversions; however, many of the instream losses and reduced recharge costs of diversion are external to the decisions of the diverter.

(iii) Surface storage. Surface storage also has its opportunity costs. A full reservoir provides less flood protection, with costs to those with investments on the floodplain and perhaps to the public if flood damages are publicly indemnified. Reservoir management for storage often conflicts with management for hydropower, and many reservoirs have a policy which is spelled out in negotiated compromise between the two interests. Reservoirs experience high rates of evaporation, a sort of annual rent charged by the atmosphere. These costs are borne by those with claims on the stored water. Finally, of course, the opportunity cost of storage is the sacrificed current-period uses of water stored.

(iv) Artificial recharge. Current-period uses are also sacrificed for subsurface storage. In addition, the opportunity cost of artificial recharge includes the value of the land used for recharge in its next-best use, which since recharge is often carried out in aquifers in heavily populated areas, may be considerable. This cost is borne by society, in general, which loses the land as a resource, and by whatever group bears the cost of recharge in particular. Finally, storing surface water below ground involves creating an energy cost to pump it back up to the surface again, a cost which is borne by the water users who recover the recharged water.

(v) Effluent reuse. The opportunity cost of effluent reuse includes the loss of return flow or recharge from the wastewater if it is not reused. While reclaimed effluent often constitutes an important source of water supply (that is, this opportunity cost may be significant), raw wastewater in the absence of a reuse program creates a quality problem in the environment with an opportunity cost that may be negative. These costs, if uncompensated, are borne by the water users whose supplies are affected.

(vi) Weather modification & desalination. Like groundwater utilization at the turn of the century, these technologies are at too early a stage in their development and implementation for opportunity costs to be well-defined or understood. Among the possibilities for weather modification are the loss of precipitation in other watersheds as a result of cloud seeding, and the costs of increased snowpack and heavier runoff in the benefitted watershed. Most large-scale desalination processes are capital and energy-intensive, with opportunity costs set by the next-best use of the capital and energy required for the desalination. If desalination is publicly-sponsored or subsidized, these costs are dispersed over the general citizenry, with the resultant concern that desalination investments may be made for political reasons where the water improvement achieved may not be the best available use for the capital and energy invested.

3.4 Internalizing Externalities in a Complex System

(i) Groundwater pumping. The resource economics literature is replete with studies of the common pool externalities in groundwater pumping and suggestions for internalization through the perfection of well-defined property rights in the stocks and flows (Anderson et al., 1983; Smith, 1977; Burt, 1970). Some institutional studies suggest that actual groundwater rights institutions do an adequate job of internalizing the common pool externality (Nunn, 1986).

The more interesting problem of accounting for the effects of groundwater pumping on surface flows has been addressed in Colorado and New Mexico in different ways. In Colorado, rights to surface waters and tributary groundwater have been integrated by allowing surface diverters to use wells to satisfy their surface claims, and by classifying wells as to the delay time from the well for a cessation of pumping to cause an increase in river flow. Junior wells which would, if shut down, contribute to the flow to a senior surface right, can be "called" to cease pumping if the senior right is threatened (Morel-Seytoux et al., 1973). This has given rise to groundwater users together to purchase claims on stored water to be used to satisfy such senior grouping rights in times of shortage (Young et al., 1986). By internalizing the costs of the effect of pumpers on surface flows, not only were ground and surface waters subjected to integrated management, but stored waters as well.

In New Mexico, the relation between ground and surface uses was first recognized by giving surface appropriators the right to "follow their water to its source" in a related groundwater aquifer (Flint, 1968), and then by requiring the pumpers that affect surface flows to purchase and retire surface water rights to compensate for those effects (Morel-Seytoux et al., 1973). The magnitude of the effect is calculated on the basis of a hydrologic model of the aquifer-stream relationship.

Management to counteract the effects of pumping on saltwater intrusion has generally taken a more collective approach in contrast to the property-rights approach used in the examples above. In West Basin, California, on the western edge of Los Angeles, water producers threatened by saltwater contamination of their water source first formed an association, then created a Municipal Water District, sued to curtail groundwater production, and finally formed a special Replenishment District to carry out wastewater spreading operations to build a barrier against saltwater intrusion and to coordinate the water supply activities of a number of districts that affect the quality of the basin (Ostrom and Ostrom, 1972).

Another effect of sustained overdraft of groundwater is land subsidence. Serious problems were created in the Central Valley of California and in parts of Arizona where aquifers were overpumped continuously for several decades. These problems were analyzed from a legal-institutional point of view only recently (Bradley and Carpenter, 1986).

(ii) Surface diversions. The internalization of the costs of surface diversions on other aspects of the hydrologic cycle has been a major motivator in the development of water rights law. Under the riparian system of England, surface water users were simply prohibited from imposing costs on other surface water users. As developed in the eastern United States, this "natural flow" doctrine evolved to permit a "reasonable use" of the surface flow, which was interpreted to mean that "reasonable" costs could be imposed on other water users. In an effort to encourage investment in mills, New England states went so far as to grant special powers equivalent to eminent domain to mill owners, allowing them to flood upstream properties in order to store water for power (Horowitz, 1973). In the western United States, the prior appropriations doctrine evolved in order to permit early investors in water diversion to impose costs on those who came later to the stream.

Most western states have recognized that return flows from water uses make up an important component of the water supply and have burdened the water right with an obligation to maintain those return flows: this means that only the quantity of water consumptively used can be transferred, in order to protect water users who rely on return flows. This was an early form of conjunctive management--management of two different diversions from the same stream.

However, many problems remain unresolved. The effects of diversions on in-stream flow uses, which in the case of hydropower, may be even economically more significant than the diversion uses, have not been internalized (Butcher, Wandschneider and Whittlesey, 1986). The lack of a mechanism to internalize the effects of diversions on water quality has given rise to the United States' huge investment in a desalination plant in order to comply with treaty obligations to Mexico to provide water above a fixed quality (Miller, Weatherford and Thorson, 1986). Finally, subsidies on surface water provided by federal projects has created a "two-tiered" water system in the western United States, in which surface water developed at high cost is applied to low-valued uses, thus distorting the relative costs of ground and surface water and making rational scarcity-responsive conjunctive use on the basis of water-user decisions impossible (Ellis and DuMars, 1978).

(iii) Surface storage. Water released from surface storage may cause flooding and damages in the lower parts of a river basin. Reservoir managers may therefore become liable for such damages. For this reason, the responsibility for flood control operation of surface storage facilities is often assumed by a centralized authority, hierachically higher than the individual reservoir managers. For example, in Texas the U.S. Army Corps of Engineers is responsible for the flood control operation of tens of reservoirs which include its own projects as well as those constructed by the U.S. Bureau of Reclamation (Wurbs, 1987).

Water stored in surface reservoirs is liable to evaporation losses. These losses, which vary with climate, may be considerable. For example, in the Upper Colorado River basin, average yearly evaporation losses from surface storage exceed 600 million m^3, which are about 14% of all the consumptive uses (Water for Energy Management Team, 1974). Evaporation losses from the Aswan High Dam Reservoir are estimated at 10 billion m^3 annually, on average (Whittington and Guariso, 1983).

Surface storage is used also to regulate flow for hydropower generation. In multipurpose reservoirs, hydropower demands may conflict with releases for other uses, such as irrigation or water supply. The conflicting claims of hydropower on water stored in surface reservoirs are sharpened when water is scarce. In those cases, a risk analysis approach appears indicated (Palmer and Lund, 1986). Risk based approaches incorporating hydrologic uncertainties complementing critical period analysis seem an effective way to deal with this problem.

These are only a few examples of externalities generated by storing water on the land surface in reservoirs created by dams. The internalization of these externalities is neither simple, nor can it be formulated in one all-embracing statement. It appears that first we need to define storage rights with respect to every one of the different actors influenced by water stored in surface reservoirs and its subsequent release. Next, storage rights have to have the attribute of transferability, i.e. holders of these rights should be able to dispose of them, and other actors should be able to acquire them. Finally, some measure of quantification of storage rights has to be agreed upon.

(iv) Subsurface storage. Here we must mention that only phreatic aquifers are potential candidates for subsurface storage. A phreatic (unconfined) aquifer has a storage capacity that is independent of the amount in storage at the time.

An important institutional issue related to subsurface storage is that of establishing rights to the water stored in an aquifer, and to the aquifer itself. Questions arise regarding the right to use an undergound formation to store water artificially recharged, and the right to prevent others from abstracting the stored water. In other words, can one identify the owner (whether an institution or an agency) of a subsurface storage facility?

A literature search does not yield completely satisfactory answers, so that a generalized solution cannot be offered at this time to this problem. Several particular solutions, however, seem to emerge from legal precedents. As an example, a conflict arose between the cities of Los Angeles and San Fernando in California over a portion of surface water stored by Los Angeles in the aquifers underlying the San Fernando valley and not used by Los Angeles. The city of San Fernando, although it did not recharge the aquifer, wanted to exploit the amount unutilized by Los Angeles. The California courts in 1975 decided that the city of San Fernando has the right to appropriate the "upcaptured return flow," i.e. water that Los Angeles had imported and stored in the aquifer, provided that Los Angeles did not or could not recapture it and would otherwise go to waste (Trelease, 1982).

An additional problem arising out of subsurface storage of waters is that of changes in groundwater quality. Mineral composition of recharging waters is almost always different from that of the water existing in an aquifer, and in most cases it has a higher concentration of total dissolved solids (TDS). This situation creates a problem which may be of immediate concern or of a longer-range timeframe, depending on the relative concentrations of TDS in the recharging and groundwaters. Of considerably greater concern, however, is the microbiological quality of recharging waters. Contrary to some beliefs, the soil mantle overlying an aquifer is not an effective filter in the long range, and evidence exists to the fact that viruses--and probably other microorganisms--can survive and remain virulent over long periods of time in the groundwater at depths of tens of meters.

(v) Effluent reuse. Reusing effluent, i.e. treated wastewater, involves risks that are little understood yet very real. Using inadequately treated effluent, whether irrigating agricultural lands or urban landscaped areas, may place the public health in serious jeopardy even in the absence of an immediate outbreak of disease on a large scale. Recently, with the increased scarcity of water resources in many regions, effluent has been gradually introduced into the category of regional resources capable of satisfying water demand. Hence, the analysis of effluent reuse has to be performed at the regional level.

An efficient solution to the problem of effluent reuse considers the maximization of the regional net benefit derived from the reuse and its redistribution among the various categories of users in the region (Dinar et al., 1986). However, the economically efficient solutions at the regional level may be rejected by prospective users unless acceptable cost/benefit allocations are established. Additional questions which may be raised by users refer to the fairness and reasonableness of these allocations. Of course, these questions are not restricted only to cases of effluent reuse; they may be relevent to many other activities related to regional development and utilization of water resources.

In addition to the economic aspect of effluent reuse, there is also the institutional dimension. Certain categories of uses may be required to use effluent by local regulatory statutes. For example, ornamental fountains and water bodies in public parks may be mandated by municipal laws to use effluent. In such cases, safeguards must be provided so that individuals do not have body contact with the treated effluent. Similarly, golf courses and other landscaped areas in areas of water scarcity may be required to use effluent, provided that the wastewater has undergone treatment and disinfection at an advanced level.

(vi) Weather modification. There are two major points to be considered when dealing with issues generated by weather modification: (a) who has the rights to the water developed by weather modification; and (b) what kind of liabilities are incurred when inducing precipitation artificailly. So far, there have been very few large-scale projects with sufficient documentation to reach any generalized conclusions on these points (U.S. Bureau of Reclamation, 1987).

There is little, if any, incentive for a private party or public agency to engage in weather modification if they will not reap the benefits of the project. A major question is whether the additional water will belong to the developer or will it be divided to users along a stream (or pumping from an aquifer) in accordance with existing water laws. The additional runoff developed by activities aimed at weather modification depends on the amount of added snowpack and/or rainfall and the percentage of this added amount that reaches the surface hydrological sytem or percolates into aquifers. The physical processes related to precipitation events are usually analyzed using cloud models and/or statistical relationships. The outcome of these analyses is that the physics of cloud seeding are not fully understood, and statistics cannot prove cause and effect (Foote, 1978). Thus, the answer to the question of who has the rights to the water developed by weather modification does not have a clear and unambiguous answer. It seems, therefore, that this issue will be resolved from a legal standpoint in courts of law.

The question of liability of individuals or agencies involved in cloud seeding operations is concerned with possible floods, with other downwind effects, and with rights of landowners. Weather modification may cause deeper snowpacks than usual, so that the probability of flooding during the snowmelt period is increased. Given the variability and uncertainty of weather phenomena, it seems that the solution to this problem is to suspend the cloud seeding operations according to criteria predetermined for each watershed so effected. It might happen, however, that following the suspension of cloud seeding operations, an abnormally wet period could occur resulting in flooding. In such an event, although the cloud seeding operator is clearly liable for damages caused by additional runoff due to weather modification, the party damaged must prove that the damage was caused by the augmented flow.

Finally, uncertainty exists regarding whether landowners, by modifying clouds passing over their property, interfere unreasonably with land use in another area. The uncertainties are mostly uncertainties of fact, rather than uncertainties of law (Kirby, 1978).

(vii) Desalination. A major externality generated by desalination is related to the disposal of brines. Desalination plants, even on a large-scale, located on the sea coast are in a position to return the brine to the ocean with practically no undesirable effects. Inland desalination plants may have significant problems of brine disposal (Viessman and Welty, 1985). Alternative methods of disposal include evaporation ponds, transport by pipeline, deep well injection, and central stockpiling of dry salts. In this case, desalination plants must be operated subject to a regulatory agency overseeing the environmental quality. The power that such an agency needs should be very similar to that vested in a land-use authority.

Desalination on a small scale, satisfying the needs of a single family, is practiced in some parts of the world, including Southern Israel. It is accompanied by the same type of externalities as large-scale desalination plants, albeit of lower intensity.

3.5. Tools for Managing a Complex System

(i) Property rights. The complexity of a regional water resources system is due not only to the fact that the natural component has well-defined surface and groundwater hydrological subsystems, but also to the apparent inperfections in the socio-economic component. Consider, for example, the price charged for water pumped from an aquifer and delivered to users. Essentially it covers only the cost of drilling wells, pumping, distributing and managing the water system, while there is no charge for water itself. By implications, water stored in an aquifer has no value, is not priced, and is made available free of charge. One alternative approach to this problem is to establish specific property rights for groundwater (Smith, 1977).

The establishment of specific property rights appeared in the socio-economic history of man every time that a resource became too scarce to be managed effectively as common property. For example, when pre-historic man replaced gathering by cultivation, property rights with respect to land (and to crops) were invented. Similarly, it is conceivable that property rights for water could be established both with respect to water stored (in surface reservoirs and/or aquifers) and to water flowing into a region during a yearly cycle. These rights would be marketable (transferrable) in the same way as rights to real property (land).

(ii) Regulation. Regional water resources systems may become complex to manage when demand increases beyond the currently available supplies and a situation of scarcity develops. Under these conditions, disputes may arise between users, which need to be settled through some form of regulation. Regulation may be oriented toward reducing demand of one class of users so as to attain a management policy that will meet the regional development goals. One method of reducing demand for water in irrigated agriculture is to use the concept of water duties (Emel and Yitayew, 1987).

Prior to the emergence of scarcity, water availability is ample with respect to demand, a situation that does not lead to efficient use. Reduction of use (and demand) may be accomplished through proportional reductions of historic water withdrawal, pro rata reduction of water supplied per unit of area, reduction or termination of users having lower legal priorities to the source of water, improvements in irrigation efficiency, or by administrative fiat. The concept of water duty seems to embody several of these alternatives. As defined in Arizona, "The irrigation water duty shall be calculated as the quantity of water reasonably required to irrigate crops historically grown in a farm unit and shall assume conservation methods being used in the state which would be reasonable for the farm unit..." (Arizona Revised Statutes, 1980). Thus,

$$\text{Irrigation water duty} = \frac{\text{Total irrigation requirements/Total cultivated area}}{\text{Assigned irrigation efficiency}} .$$

The level of assigned efficiency to an individual farming operation, including the uniformity of water application, ranges from 70% to 85%.

(iii) Central and regional control. The management of complex water resources systems can take place locally, on a regional basis, or under a broader central authority. Each of these three modes has its advantages and shortcomings and none of them is sufficiently general to cover all possibile contingencies. Under specific conditions, however, one alternative appears superior to other two.

Recent studies regarding water supply to the metropolitan area of Washington, D.C., indicate that regional management and control seem to be preferrable to the fragmentation of the decision-making process into local subunits (Crews, 1983). The major supply of water to the U.S. capitol city is the Potomac, a stream with variable flow. The increase in demand resulted in the situation that the maximum one-day withdrawals exceeded the minimum one-day flow more and more often. A superficial examination of this situation revealed that the problems stemmed primarily from the fragmented management of the metropolitan Washington area water resources system which prevented the establishment of a political consensus of what ought to be done to alleviate the water shortage. Consequently, the solution to these problems did not lie with an "engineering fix" that would provide additional water supply; instead it centered around the institutional framework of managing agencies. Within the metropolitan Washington area there are 25 independent water supply systems, ranging in size from less than 3,500 m^3/day to about $2x10^6 m^3$/day, each of whom guard jealously their prerogatives to make independent decisions. A further study commissioned by the U.S. Congress formulated a range of plans which allow the local authorities to make better decisions and yet reach some degree of regionalization.

A centralized authority has, at least theoretically, the possibility of making institutional changes that might lead to more efficient management of regional water resources. Yet vested economic interests and political expediency may pose considerable obstacles (Sadan and BenZvi, 1987).

Institutional arrangements have a certain value (otherwise they would not have been made) and also involve a certain social cost. If we are able to quantify the potential of institutional change, we could evaluate their worth and thus their capability to form alternatives to further engineering and structural development of additional water supplies. Sadan and BenZvi examined the situation in Israel, especially under the assumption that new arrangements will evolve following relaxation of institutional barriers. The study utilized an advanced version of a linear programming algorithm simulating the functioning of Israel's water supply system which is closely interconnected with the agricultural sector. Historically, the institutional framework in Israel succeeded in establishing orderliness and stability in the development and distribution of irrigation water. After about half a century, it exhibits considerable rigidity in the allocation process which led to inefficient use of water in agriculture. In addition, it its "mature" phase, the water sector in Israel faces sharply rising incremental costs of additional supplies, such as reclamation of wastewaters and desalination.

The study has shown that institutional change--like any social change--seems to generate its own resistance. More specifically, the resistance to change was motivated in part by the preservation of vested interests, and in part by the tendency to achieve certain goals reflected by public sentiment, such as the settlement of the southern frontier of Israel. Because of these obstacles, institutional changes face difficulties in many parts of the world.

4 SUMMARY AND CONCLUSIONS

4.1 Where are we now?

The combined management of surface and groundwater resources in a region is becoming increasingly more complex. Much of the complexity appears in the area of water-related institutions, primarily with regard to policy decision-making. The problems arise when the growing demand for water exceeds the availability of surface supplies and groundwater resources begin to be exploited. As demand continues to increase, so does the pumpage from aquifers. The onset of groundwater mining, i.e. abstracting from aquifers quantities in excess of natural recharge, signals the beginning of the mature phase of the regional water economy. A salient characteristic of a mature water economy is that externalities, stemming from physical interdependence among classes of water users, are not only more obvious, they also lead to inefficient allocations of water. Under these conditions, the water-related costs perceived by the individual user are different from the social costs involved in the development and distribution of regional water resources. Among the approaches proposed by economists to remedy this undesirable situation are (O'Mara, 1986): (a) establishing well-defined transferrable water rights; (b) instituting a certain degree of regulation that includes levying of taxes and/or payment of subsidies with the object of adjusting private costs to the level of social costs; (c) centralizing the control over the regional water resources so that the external effects can be fully internationalized when calculating costs.

4.2 Quo vadimus?

To answer this question, we must determine three things, none of them easy: (a) the coordinates of the current position; (b) the azimuth of the direction of progress; and (c) the velocity of motion.

Regarding current status, generally we can say that there is a lively interest in the broad issue of conjunctive development and operation of regional surface and groundwater resources. More than that, we observe that actual work is being done to clarify the possibility of using aquifers in conjunction with surface water supplies, as exemplified by the current situation in Arizona (Mitchell and Putman, 1987). Some of the central issues faced today when managing surface streams in coordination with aquifers are highlighted in this paper. Moreover, this very symposium and workshop on groundwater economics is probably the best way to identify the current position, even if it varies from place to place.

The direction in which we should progress seems fairly clear. We seem to need closer interaction between the scientific disciplines involved in the resolution of the complex issues of conjunctive management of regional surface and groundwater resources. In particular, better and more informative dialogs should be initiated between hydrologists, engineers, and social scientists.

Finally, the speed with which we shall make progress depends primarily on us, the hydrologists, engineers, economists, and other scientists studying these problems. Curiosity is a powerful motivating force; it may still push us to greater interactions between disciplines.

5 REFERENCES

Anderson, T., Burt, O.R., and Fractor, D.T., 1983. Privatizing groundwater basins: a model and its application. In: T. Anderson (Ed.), Water Rights: Scarce Resource Allocation, Bureaucracy, and the Environment. Ballinger Press and Pacific Institute for Public Policy Research, Cambridge, MS, pp. 223-248.

Arizona Revised Statutes, 1980. Groundwater Code, Sec. 45.

Bradley, M.D. and Carpenter, M.C., 1986. Subsiding land and falling groundwater tables: public policy, private liability, and legal remedy. Econ. Geogr., 62(3): 241-253.

Buras, N., 1985. An application of mathematical programming in planning surface water storage. Wat. Res. Bulletin, 21(6): 1013-1020.

Buras, N. and Hiessl, H., 1987. Management of dynamic water resources systems with multiple decision makers. (In preparation)

Burt, O.R., 1970. Groundwater storage control under institutional restrictions. Wat. Res. Research, (6): 1540-1548.

Butcher, W.R., Wandschneider, P.R., and Whittlesey, N.K., 1986. Competition between irrigation and hydropower in the Pacific Northwest. In: K.D. Frederick (Ed.), Scarce Water and Institutional Change. Resources for the Future, Wash., DC.

Changnon, S.A., Huff, F.A., and Hsu, C.F., 1979. On the need to evaluate operational weather modification projects. Bull. Amer. Metero. Soc., 60(7): 770-774.

Coe, J.J., 1979. Ground-water storage for California water project. J Irrig. & Drain. Div., ASCE, 105(IR3): 305-315.

Committee on Weather Modification of the Irrigation and Drainage Division, 1983. *Guidelines for cloud seeding to augment precipitation.* J Irrig. & Drain. Div., ASCE, 109(1): 111-182.

Crews, J.E., 1983. Regional versus local water supply planning. J Wat. Res. Plan. & Manage., ASCE, 109(2): 179-185.

Dinar, A. and Yaron, D., 1986. Treatment optimization of municipal wastewater and reuse for regional irrigation. Wat. Res. Research, 22(3): 331-338.

Ellis, W.H. and DuMars, C.T., 1978. The two-tiered market in western water. Nebraska Law Review, 57(2): 333-367.

Emel, J.L. and Yitayew, M., 1987. Water duties: Arizona's groundwater management approach. J Wat. Res. & Plan. & Manage., ASCE, 113(1): 82-94.

Flint, F.H., 1968. Groundwater law and administration: a New Mexico viewpoint. Proc. of XIV Annual Rocky Mt. Mineral Law Institute, Tucson, AZ, pp. 545-568.

Foote, G.B., 1978. Weather modification: a technology in its infancy. In: R.J. Davis, L.O. Grant (Eds.), Weather Mod., Tech. & Law. Westview P, Boulder, CO, pp. 85-94.

Frederick, K.D. (Editor), 1986. Scarce Water and Institutional Change. Resources for the Future, Wash., DC.

Herrmann, R., Kaa, W., and Bierl, R., 1986. Organic micropollutant behavior in a river water-groundwater infiltration system. In: S.M. Gorchick (Ed.), Conjunctive Water Use, IAHS Publication #156, pp. 189-198.

Horowitz, M.J., 1973. The transformation in the conception of property in American law, 1780-1860. U of Chicago Law Review, 40: 248-290.

Illangasekare, T. and Morel-Seytoux, H.J., 1982. Stream-aquifer influence coefficients as tools for simulation and management. Wat. Res. Research, 18 (1): 168-176.

Kher, L.K. and Sorooshian, S., 1986. Identification of water demand models from noisy data. Wat. Res. Research, 22(3): 322-330.

Kirby, J.W., 1978. Judicial regulation of weather modification. In: R.J. Davis, L.O. Grant (Eds.), Weather Modif., Techn. & Law, Westview P, Boulder, CO, pp. 55-63.

Loucks, D.P., Stedinger, J.R., and Haith, D.A., 1981. Water Resources Systems Planning and Analysis. Prentice-Hall, Englewood Hills, NJ.

Martin, W.E. and Thomas, J.F., 1986. Policy relevence in studies of urban residential water demand. Wat. Res. Research, 22(3): 322-330.

Metzger, P.C., 1986. Challenges for water management in Tucson, Arizona. J Wat. Res. Plan. & Manage., ASCE, 112(2): 250-264.

Miller, T.O., Weatherford, G.D., and Thorson, J.E., 1986. The Salty Colorado. The Conservation Foundation, Wash., DC.

Mitchell, K.R. and Putman, F.G., 1987. Preliminary feasibility study of groundwater recharge potential of surplus Central Arizona project water in Aqua Fria River. Ariz. Dept. Water Res., open-file rpt.#3, Phoenix, AZ.

Morel-Seytoux, H.J., Young, R.A., and Radosevich, G.E., 1973. Systematic design of legal regulations for optimal surface-groundwater usage, phase 1. Fort Collins: Environmental Resources Center, Completion Report Ser.No.53.

Nunn, Susan Christopher, 1985. The political economy of institutional change: a distribution criterion for acceptance of groundwater rules. Nat. Res. J, 25: 867.

O'Mara, G., 1986. Some economic and institutional aspects of efficient and sustainable conjunctive use. In: S.M. Gorchick (Ed.), Conjunctive Water Use, IAHS Publication #156, pp. 463-473.

Ostrom, Vincent and Elinor, 1972. Legal and political conditions of water resource development. Land Econ., 48(1).

Palmer, R.N. and Lund, J.R., 1986. Drought and power production. J Wat. Res. Plan. & Manage., ASCE, 112(4): 469-484.

Randall, A., 1981. Property entitlements and pricing policies for a maturing water economy. Austr. J Agri. Econ., 25: 195.

Sadan, E. and Ben-Zvi, R., 1987. The value of institutional change in Israel's water economy. Wat. Res. Research, 23(1): 1-8.

Sahuquillo, A., 1985. Groundwater in water resources planning: conjunctive use. Water Interntl., 10(2): 57-63.

-----, 1986. Quantitative characterization of the interaction between groundwater and surface water. In: S.M. Gorlick (Ed.), Conjunctive Water Use. IAHS Publication #156, pp. 3-16.

Smith, V.L., 1977. Water deeds: a proposed solution to the water valuation problem. Arizona Review (Jan.): 7.

Svenson, G., 1980. Multimillion-acre tea bag. Civil Engineering, (50)4: 47-50.

Trelease, F.J., 1982. Conjunctive use of groundwater and surface water. Rocky Mt. Mineral Law Institute, 1853-1894, 27.

U.S. Bureau of Reclamation, 1987. Feasibility study on wintertime cloud seeding to augment Arizona water supplies. Final rpt. for AZ Dept. Wat. Res.

Viessman, W.Jr. and Welty, C., 1985. Water Management: Technology and Institutions. Harper and Row, New York.

Water for Energy Management Team, 1974. Report on water for energy in the Upper Colorado River basin. U.S. Dept. Interior, Denver, CO.

Weaver, T.W. and Klarich, D., 1973. Ecological effects III, silver iodide in terrestrial ecosystems, a preliminary study. Bulletin 670, Montana Agriculture Experiment Station, Montana State U., Bozeman, MT, pp. 16-17.

Whittington, D. and Guariso, G., 1983. Water Management Models in Practice: A Case Study of the Aswan High Dam, Elsevier, Amsterdam, 1983.

Wurbs, R.A., 1987. Reservoir management in Texas. J Wat. Res. Plan. Manage., ASCE, 113(1): 130-148.

Young, R.A., Daubert, J.T., and Morel-Seytoux, H.J., 1986. Evaluating institutional alternatives for managing an interrelated stream-aquifer system. Amer. J Agri. Econ., 787.