J. ENVIRONMENTAL SYSTEMS, Vol. 16(3), 1986-87

ENVIRONMENTAL PATTERNS OF WATER MANAGEMENT

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ABSTRACT

Water is managed in a wide variety of ways to fulfill a wide variety of purposes, amidst a wide variety of constraints. This article attempts to provide a framework for understanding what a range of water management steps are trying to do and the approaches available for doing it. The framework is built upon previously suggested concepts of "landscape hydrology," which sees the hydrologic landscape as a combination of surface, soil, groundwater, atmospheric and cultural "mantles" in which different types of hydrologic processes occur. Major aspects of the framework are the types of functions that management steps perform and the types of environments in which they are practiced. Uses of water demand that water have specific characteristics of quality, quantity, time and place. Water management aims to produce those characteristics in water either before use, to make water suitable for designated uses, or after use, to make it suitable for discharge into the environment. Not all management occurs in artificial pipes and tanks. Management makes use of existing processes in unmodified environmental mantles. It also makes use of the mantles' potential capacities for altering water's characteristics. Technologies are media that man interposes to stimulate natural processes to perform closer to demanded levels. Highly developed management systems are analogous to modern agriculture's modification of and interaction with natural soil and plant processes. Thus the means of managing water include symbioses of natural and cultural systems.

Regional management of water resources forms complex labyrinths of objectives, constraints and methods. Among the many purposes for which people manage water are irrigation, flood control, industrial and domestic uses, land drainage, mine dewatering, hydropower, navigation, aquaculture, fish and wildlife, insect control, recreation, aesthetics, soil salinity control, wastewater disposal, dilution and assimilation of pollutants, saltwater intrusion control, soil subsidence control, cooling and defense. Techniques of water management are as varied as rainwater harvesting, wastewater land application, stormwater infiltration and

doi: 10.2190/G5JK-6CDV-6F5A-P08D
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direct recycling. They are practiced in environmental backgrounds that vary from the arid to the humid, the upland to the lowland, the permeable to the impermeable, the vegetated to the unvegetated, the urban to the rural, the natural to the artificial. Concerns about quality, availability and cost of water resources have demanded full consideration of all potential management alternatives [1, 2].

In trying to understand and plan for water resources in a region, it is useful to ask what overall patterns management activities form now and could form in the future. Are there parallels among them? Do they relate systematically to the climatic, soil and other environmental backgrounds where they are practiced?

It is easy to find discussions of individual types of hydrologic activities such as those aimed at groundwater [3], management of soil moisture by irrigation and drainage [4], control and treatment of surface waters [5] or flood control [6]. However, few of those references touch with equal emphasis on other types of hydrologic processes.

This article attempts to offer an orderly framework for characterizing a wide range of water management activities with respect to the types of functions they perform and the types of environments where they are practiced. Such a framework can be of value to those who are trying to understand the management opportunities and constraints of the regions where they work. It could help to guide early planning decisions by helping to recognize the natural patterns of regions, to conceive clusters of alternatives and thus to accelerate the development of most appropriate solutions.

Previous papers set a stage for the development of this framework by suggesting basic concepts of "landscape hydrology" [7] and identifying ways in which hydrologic processes can vary from landscape to landscape [8]. The framework was developed by inventorying the types of management activities mentioned in a wide range of literature and aligning those activities with the functions they perform and their relationships to the hydrologic environments where they occur. Stimulus for refining concepts has come from a series of graduate seminars in the University of Georgia's School of Environmental Design.

There are two major aspects of the framework: the purposes that management serves and the environments in which it is practiced. The application of the framework suggests interesting concepts of the relationship between man and nature.

PURPOSES OF WATER MANAGEMENT

Let us distinguish water "management" from water "use." The *use* of water is a very specific and brief, sometimes even instantaneous event, such as the entry of soil moisture into the root hair of a crop plant, the contact with a cooling surface in a power plant or the half hour or so of sloshing in a laundry machine.

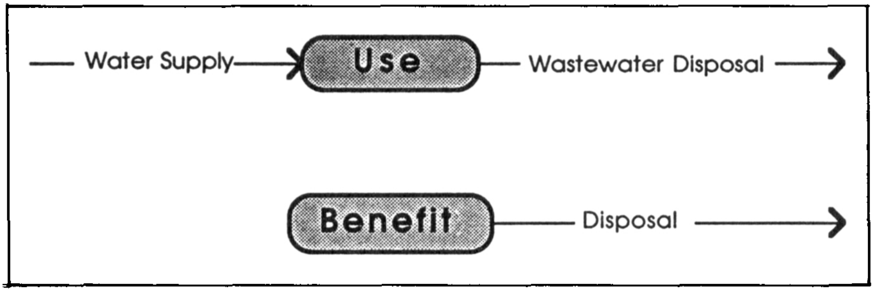

Figure 1. Sequential relationships of water use (or benefit) and water management. The upper diagram shows a use to which water is supplied and from which it is disposed, such as municipal, industrial or agricultural uses. The lower diagram shows a benefit from which water is removed without a prior supply, such as flood control, land drainage or stormwater disposal.

Uses or benefits of water include both those to which water is supplied such as irrigation, hydropower, wetland maintenance or cooking; and those from which it is removed such as flood protection, agricultural soil drainage and effluent disposal. In contrast, water *management* comprises all the great variety of steps that enable water to be used for chosen purposes, in chosen amounts, and in chosen times and places, or to be disposed afterward.

As illustrated in Figure 1, sequences of water management surround water use. Management of water *before* use enables water to be used by converting its characteristics in nature to those it will have during use. Management *after* use gives water characteristics necessary for desired types of discharge. Although some purposes of water disposal, such as diversion of flood water from industrial districts, removal of excess soil moisture from croplands or drainage of storm waters from city streets, are not preceded by a positive "use" of the controlled water, they are done to benefit the protected area or population.

As suggested in part by Hall *et al.* [9] and the U.S. Office of Technology Assessment [2], the demands that users or beneficiaries may impose on water, and thus on water management, are in terms of quantity, quality, time and place. Many water "supply" projects actually produce smaller flows of water at the points of delivery than are available at the points of intake. Their objectives are actually involved with the assurance that water of a certain quantity and quality will be available when and where needed. A million gallons of water *per se* has little value; those same million gallons delivered to a city every day with assured quality can have great value. Table 1 lists the requirements of five very different types of water uses. The table shows that quantity, quality, time and place are in fact demanded by all five uses, and that each specific use demands specific types of results from the management sequences that serve it.

Table 1. Characteristics of Water Demanded by Five Specific Uses or Benefits in the U.S. in Recent Years.

Type of Use or Benefit	*Quantity*	*Quality*	*Time*	*Place*
Publicly supplied domestic	120 gal/day/person [10].	$<$500 ppm TDS; $<$0.5 ppm BOD5 [11, p. 312].	Flow fluctuation .4 to 3.0 ratio to mean [5, pp. 99, 127].	Individual home: 150 in/yr on 1% of area: 2.5 in/yr on 5 percent of area (estimated from data on quantity).
Crop irrigation	.007 gal per $ receipts [10, 12].	$<$500 ppm TDS; $>$40 deg F. [11, p. 313; 13, p. 65].	0 to .3 in/day [14, p. 23].	35 in/yr on 2.5 percent of area (estimated from data in [10]).

Freight navigation	2 cfs per 1,000 tons/ day (estimated from data for lowest-use canal in [11, p. 295]).	(No limiting demand?)	>2 cfs at all times (assumed).	<1 percent of land area (assumed).
Urban stormwater drainage	Storm of 1 to 50 year recurrence interval [15] .	Site-specific [16] .	Drainage within 1 to 3 days after storm [17] .	<1/2 street lane [15] .
Catfish acquaculture	88,000 liters per kg yield (estimated from data in [18, pp. 180, 824]).	<2,000 mg/1 TDS; 70-80 deg F. [11, p. 335; 18, p. 164] .	(Pond flushing at intervals.)	3,400 in/yr on <1 percent of U.S. area (estimated from data in [18, pp. 180, 824] .

Note: Sources as shown. Assumptions in making estimates are that U.S. land area is 3,615,123 sq. mi., U.S. population is 225 million persons in 75 million homes, and typical home is 1,500 sq. ft.

These tangible types of demands are related to the money value of water. In a free market the money value of water tends to reflect the aggregate types and intensities of demands for quality, quantity, time and place. Money value is a means of establishing an equilibrium between demand and supply.

In a complex region many different actors may be involved in completing management sequences. Some public agencies may be involved with large-scale storage and distribution for the benefit of many (U.S. examples are the Army Corps of Engineers, the Bureau of Reclamation and the Soil Conservation Service). Other agencies, public or private, may be involved in withdrawing, treating, storing and distributing water to individual users. Private users or beneficiaries may add their own supplemental storage, treatment, conveyance and augmentation if their demands exceed those of the water being supplied to or discharged from them (examples may be hospitals, isolated farmsteads and certain industries). Each management step brings water closer to the quantity, quality, time and place of intended use or benefit.

WHERE MANAGEMENT OCCURS

A previous paper suggested that the hydrologic landscape consists of "mantles" or layers where different types of hydrologic processes occur [7]. The surface mantle is characterized by overland flows and surface water bodies; the soil mantle by vadose moisture and capillary tension; the groundwater mantle by phreatic water and hydraulic pressure; the atmosphere by vapor and spray, evaporation and precipitation; the cultural mantle by confined pipes and tanks. Each mantle in a region has its own water balance characterizing its inflows, outflows and storages; the sum of the balances for all the mantles is the region's overall water balance. A more recent paper outlined the ways in which the particular combinations of mantles, and thus of hydrologic processes that occur, can vary from place to place [8].

Artificial water supplies and dispositions amount to diversions into and out of the environmental mantles. Each of the mantles produces flows and storages which can be evaluated in terms of quantity, quality, time and place, and which might be used at the levels at which they are found. Table 2 summarizes ranges of quantity, quality, time and place that are typically encountered.

When demanded, the mantles, both natural and cultural, can be induced to produce altered levels of quantity, quality, time and place. Consider a river valley. As suggested in Table 2, a natural surface stream is likely to have relatively brief storage duration. Without significant natural storage the stream's rate of flow fluctuates relatively widely in response to changing weather in its drainage basin. However, a stream's *potential capacity* for storage is fixed by the overall topography of its valley. When a dam is built across the valley the river's actual storage volume and duration are enlarged. Discharging flows are relatively

Table 2. Ranges of Quality, Quantity, Time and Place of Water Typically Found in the Five Hydraulic Mantles in the Unaltered Environment. Sources as Shown.

Characteristic of Water	*Atmosphere*	*Surface Mantle*	*Soil Mantle*	*Groundwater Mantle*	*Cultural Mantle*
Quantity	Precipitation 1 to >400 in/yr; evaporation 0 to >140 in/yr. [19, pp. 23, 97].	Runoff <.25->80 in/yr; 20-40 percent of precipitation [11, p. 75].	Specific yield 2 to 40 percent by volume [13, p. 9].	Specific yield 2 to 40 percent by volume [13, p. 9].	120 gal/cap/day average in U.S. [10].
Quality	Precipitation 10 mg/1 TDS typical [5, pp. 4-5]; evaporation about 0 (assumed).	Runoff 100-2,000 mg/1 TDS; seawater 35,000 mg/1 TDS [5, pp. 4-5; 20, p. 81].	0 to >3 percent salt content [21, p. 110].	1,000 mg/1 typical [5, pp. 4-5].	Raw municipal effluent 700-1,000 mg/1 TDS [5, pp. 4, 28]; municipal supply <500 ppm TDS [11, p. 312].
Time	Precipitation occurs <20 to 300 days/ year [19, pp. 23-24];	Streamflow occurs 0 to 365 days/ year (assumed);	Flow occurs 1 to >300 days/ year (assumed);	Flow occurs 1 to >300 days/ year (assumed);	Municipal flow fluctuates .4 to 3.0 ratio to

Table 2. (Cont'd)

Characteristic of Water	*Atmosphere*	*Surface Mantle*	*Soil Mantle*	*Groundwater Mantle*	*Cultural Mantle*
	storage about 10 days [11, p. 61].	storage 1 to 10 days [11, p. 61].	storage 1 to 100 days [11, p. 61].	storage 1 to 200 years [11, p. 61].	mean [5, pp. 99, 127]; storage 1-3 days (assumed).
Place	Precipitation and evaporation on >90 percent of land area (assumed); travel 10-10,000 mi (assumed).	Ordered streams on about 1 percent of land area, wetlands on about 10 percent of land area; travel <3,000 miles (assumed).	Unsaturated soil on about 85 percent of land area; travel <1,000 ft (assumed).	Significant groundwater occurs under about 75 percent of land area; travel <1,000 mi (estimated from data in [13]).	Irrigated + municipal areas equals about 7.5 percent of U.S. area (estimated from data in [10]); travel <400 miles [22].

Table 3. Some Relationships Governing Capacities of the Hydrologic Mantles for Altered "Management" of Water by Responding to Imposed Artificial Stimuli

Demanded Characteristic of Water	*Atmosphere*	*Surface Mantle*	*Soil Mantle*	*Groundwater Mantle*	*Cultural Mantle*
Quantity	Potential saturation per vapor-pressure relationship [23, pp. 391-392].	Potential flow rate per Manning relationship [24].	Potential flow rate per Darcy's relationship [25].	Potential flow rate per Darcy's relationship [13, p. 12].	Flow rate per demand of specific use [10].
Quality	Assimilative capacity (assumed).	Reaeration rate [26, p. 747].	Cation exchange capacity [27, p. 102].	Mineralization rate [13, p. 64].	Constituent increment per cycle [5, p. 158].
Time	Potential storage per saturation vapor-pressure relationship [23, pp. 391-401].	Stage-storage-discharge relationship [26, pp. 351-355].	Storage coefficient [13, p. 28].	Storage coefficient [13, p. 28].	Various
Place	Potential transport per vapor-pressure relationship [23, pp. 399-401].	Potential velocity per Manning relationship [24].	Velocity per Darcy's relationship [28].	Velocity per Darcy's relationship [13, p. 25].	Various

Note: Some of the listed relationships exist in theory although they are not widely monitored or exploited.

Table 4. Some Types of Technologies for Inducing Water Management Processes in the Hydrologic Mantles

Managed Characteristic	*Atmosphere*	*Surface Mantle*	*Soil Mantle*	*Groundwater Mantle*	*Cultural Mantle*
Quantity	Cloud seeding, evaporative disposal [29]. Watershed management [30].	Roofing, water harvesting [31]. Surface intake, Surface discharge.	Soil cover, plant root uptake [32]. Irrigation infiltration [17].	Well, land drainage [22]. Recharge [3].	Reduction of use [33]. Increase of use, Direct recycling.
Quality	Air treatment, cloud seeding.	"Overland flow" treatment [34].	"Slow-rate" treatment [34].	"Rapid infiltration" treatment [34].	At-source elimination, direct recycling, Artificial treatment.
Time	Cloud seeding [2].	Surface impoundment, snowpack enhancement [2], flood attenuation [8].	Fallow, mulch [27].	Aquifer storage [35].	Artificial storage (tanks).
Place	Cloud seeding, snowdrift trapping, evaporative disposal [29].	Wetland and flood-plain preservation and maintenance [36], channelization [37], diversion [32].	Irrigation.	Aquifer transmission [35], land drainage.	Aqueduct [22].

Note: Some of the listed technologies have theoretical potential but are not necessarily widely used. Many of the technologies apply to more than one mantle and more than one characteristic of water. For instance, "recharge" is listed for quantity in the groundwater mantle, but it involves removing water from some other mantle and influences quality, time and place in the groundwater and in the donor mantle.

stabilized, with likely consequences for downstream users and beneficiaries. A dam is the fourth wall of a new reservoir, the first three of which were the preexisting valley walls. The qualitative *types* of flows and storages occurring in a dammed valley are the same as under natural conditions, but their quantitative *rates* have been modified. The artificial dam has no storage capacity; the dam's role is to *induce* the natural valley to fulfill more of *its* potential for storage. The new reservoir is neither entirely natural nor entirely man-made. It is an integrated system, encompassing dam and valley together.

The same type of thing happens when man recharges an aquifer, irrigates a soil, erects snowfences, treats sewage, diverts floods or manages water in many other possible ways. He uses the natural capacities and constraints of the preexisting environment. He provides stimuli, to which the mantles of the environment respond according to their native properties. Relationships governing the mantles' capacities to produce altered levels of quantity, quality, time and place are listed in Table 3. Each relationship is a measure of the rate of response of a mantle to various types of loads or stimuli placed upon it. These potential responses are different from the rates of flows and storages that may actually occur under natural conditions.

The hydrologic mantles comprise a list of the physical resources available to man for managing water. Each of the mantles, whether natural or cultural, has some level of output in its native condition, and some further capacity to manage water in response to artificial stimuli. Each mantle is capable of transforming an inflow of water having certain characteristics of quantity, quality, time and place, into an outflow with those characteristics altered.

Technologies are the media that man can interpose to induce the mantles to perform closer to demanded levels. Some types of technologies for inducing demanded levels are listed in Table 4. In efforts toward meeting demands, man's water resource technologies interact with the processes in each of the mantles. Each technology is aimed at stimulating a native type of process in one of the hydrologic mantles to perform water management closer to demanded levels.

Thus not all water management occurs in artificial pipes and tanks. Many steps happen in the soils, streams, vapors and aquifers of the "natural" landscape. The sequence of transfers through the mantles that evolves or should evolve in a region is a union of human demands and hydrologic potentials. Water management involves an integration of man's affairs with the capacities and constraints of the natural landscape.

TWO EXAMPLES

An example of a region with a low level of management intensity is at the city of Athens in the Piedmont region of Georgia. The city takes its water supply from the Oconee River, a perennial stream with flow relatively constant from

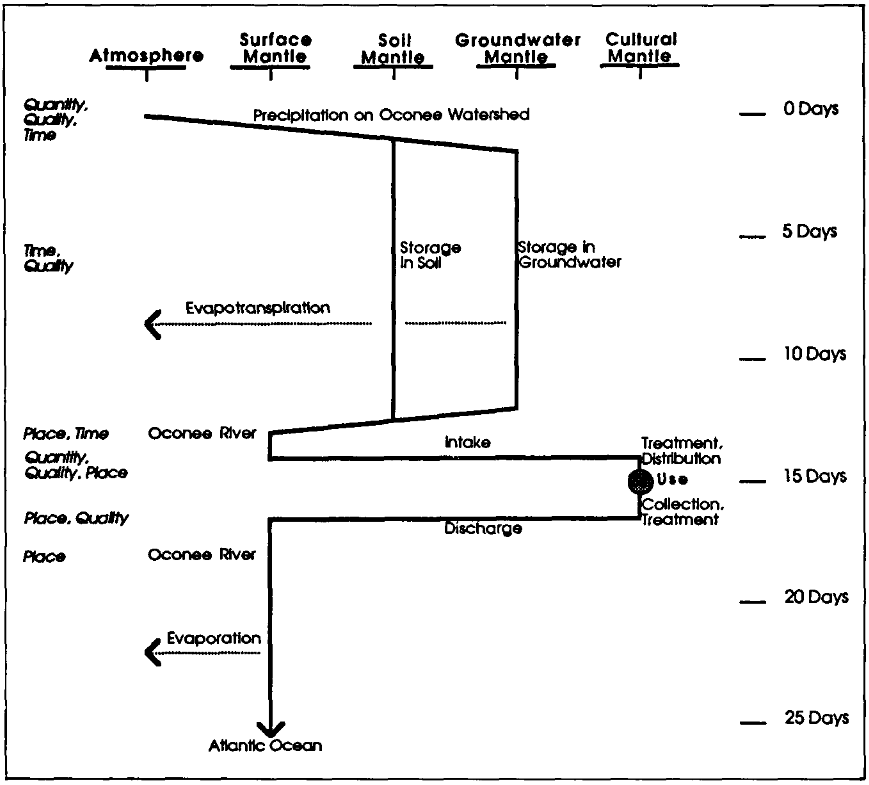

Figure 2. Management of water for the city of Athens, Georgia, beginning with precipitation on the watershed of the Oconee River. The lines follow the path of a typical drop of water through the hydrologic mantles listed on the top of the diagram. On the right is elapsed time. On the left are listed the characteristics of water that are controlled at each step.

season to season. The diagram in Figure 2 follows the path of a typical drop of water through the city's water management system. The vertical scale is approximate elapsed time in days. Along the left side are noted the characteristics of water that are controlled at each step. The system starts with precipitation on the mostly forested watershed upstream from the city. Rainwater mostly infiltrates the soil and is stored in the subsurface, where relatively brief, intense pulses of rain are transformed into more steady stream discharges [25]. There are evapotranspirative losses before water exfiltrates to surface streams. The river system concentrates the discharges of tributaries into higher-order streams where the city, with a highly concentrated population, can benefit from the hydraulic subsidy of the upstream watershed. The city's withdrawal seldom exceeds a few percent of the river's natural flow. Within a few hours after leaving the river, the water has been artificially filtered, distributed through pipes and used by city residents. Wastewater is collected to sewage treatment plants where it may reside for as long as a couple of days before it is discharged back into the river, about five miles downstream from where it is withdrawn. The river carries the effluent away to the Atlantic Ocean, where it mingles with salt water and becomes unusable to most people until evaporation of ocean water begins the global hydrologic cycle again.

One can see from Figure 2 that the 70,000-person city of Athens is directly dependent upon its 130 square mile watershed. Through the actions of a combination of relatively natural environmental mantles, the watershed acts as a catchment, treatment medium, storage tank and collection system. Athens does little more than take water out of the river, treat it, use it and put it back. Athens is to the Oconee River like an insect gall is to the branch of a cherry tree: the branch, supported by a large root system, provides all the energy, while the parasite feeds upon the passing flow. Athens can afford to operate at this low level of intensity of water management because its demands for water are small in relation to native supplies.

An example of a region with more intense management is the San Joaquin Valley in California [38]. Its diagram, in Figure 3, is more complex than Athens' and includes a much longer time scale. The valley is filled with deep permeable alluvium washed from the surrounding mountains. It is home to some of the world's most productive agriculture as a result of the warm, sunny climate of the level valley floor. Copious volumes of irrigation water are required to support the agriculture because local precipitation is small and occurs mostly in the winter when it is least needed. Most of the valley's irrigation water originates in rain and snowfall on the adjacent Sierra Nevada Mountains (where precipitation is greater due to the higher elevations, although still seasonal) and from northern California (which is in a generally more humid climatic zone). In those distant areas drifting winter snows collect in deep, slowly melting packs, partly due to artificial snowfences. The snowpacks, soil moisture and groundwater release water gradually to rivers, at the mouths of which reservoirs have been located to further stabilize and prolong outflow. Sierra reservoir waters then pass through a series of artificial conduits to individual farmers' holdings; northern waters flow down the "borrowed" channels of southward-flowing rivers before entering similar regional and local aqueducts. Other stream waters and local precipitation recharge the valley's groundwater, which is stored for a period of months while it spreads out to farmers' wells. Farmers spread waters from canals and wells over the soils where their crops are rooted. There it is stored for a few days more and moves toward plant roots by capillary tension. When water contacts the roots it is taken up by plants and finally used—transpired by the plants, contributing

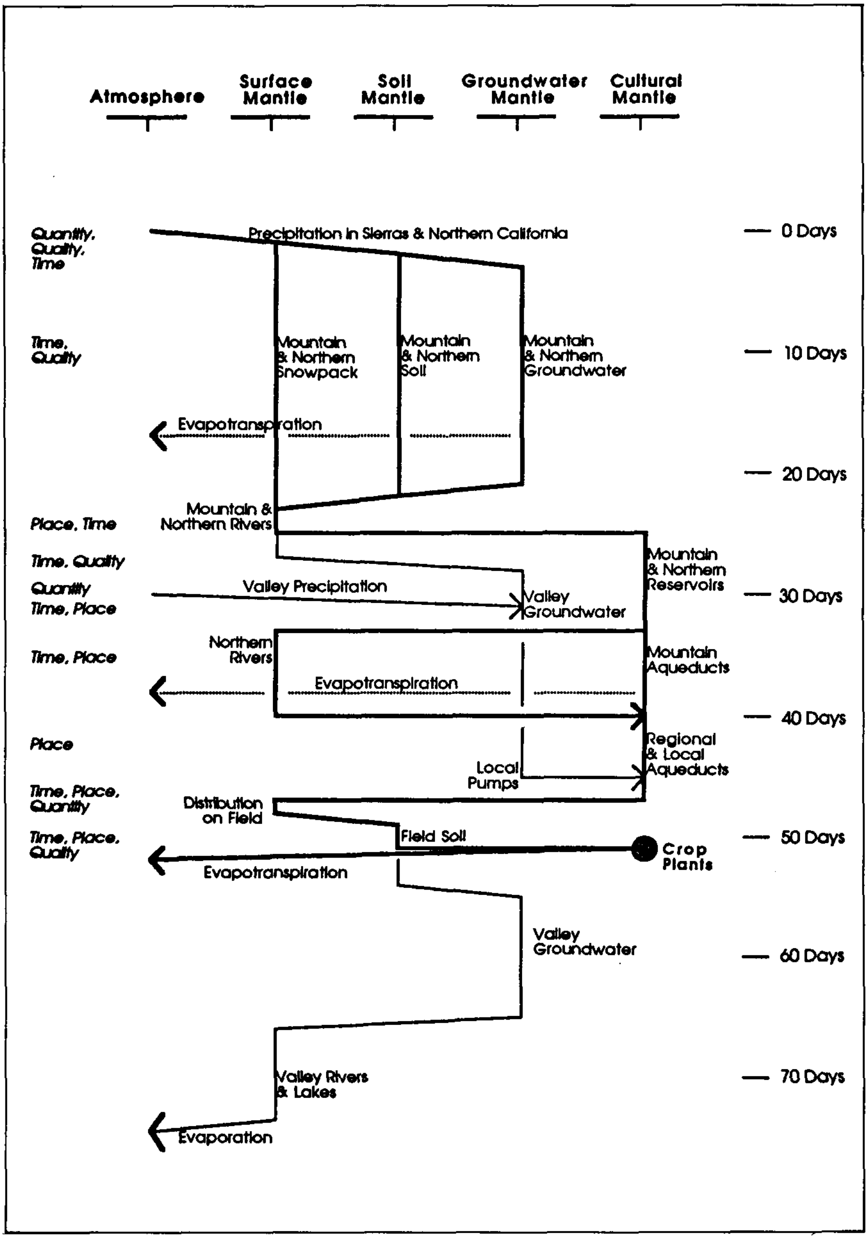

Figure 3. Management of water for irrigation in the San Joaquin Valley of California, beginning with precipitation in northern California and the Sierra Nevada Mountains.

to crop growth—in barely an instant of time compared to the lengthy preparatory management. Any water that escapes plants passes down the topographic gradient, ending up in ephemeral lakes where eventually it evaporates.

One can see from Figure 3 that farmers in the valley are as dependent on their "watershed" as the town of Athens is on the Oconee watershed. But here, where demands upon water in the summer fields far exceeds the levels of natural supplies, the hydrologic system is much more intensely developed. Water is induced to travel through the various environmental mantles in numerous cycles. Water passes through strictly cultural canals, wells, and crop plants three times, each time returning to some other environmental mantle. The atmospheric, surface, soil, groundwater, and cultural mantles are all called into play to convert distant, untimely precipitation to soil mositure when and where it can be most productive.

SUMMARY AND CONCLUSION

The type of framework described in this article can help to evaluate regional water management proposals and to point out otherwise unrecognized management opportunities. As water-related problems continue to become of more concern, and as man's use and management of water and related natural resources continues to intensify, such frameworks will continue to be valuable in clarifying the situations with which man is confronted, and guiding him through them.

Water management serves specific water uses by controlling the quantity, quality, time and place of water, either before or after use or benefit. It uses the natural capacities and constraints of the preexisting environment, as well as artificial pipes and tanks. Management technologies provide stimuli to which the mantles of the environment respond according to their native properties. Water management involves setting up feedback loops between man and his environment. Man and nature are interactive and symbiotic.

Any region is a "layer cake" of some combination of mantles having both existing, natural supplies and theoretical capacities for further management. Each region has its own combination of landscape features and its own combination of demands for quantity, quality, time and place. From the time rainwater falls on watersheds until evapotranspiration carries it away or it mingles with the salt of the oceans, water can be directed, stored, used and reused. That any of the mantles is or could be connected to any of the others can lead to complex combinations of management steps.

In the early years of the development of many regions, water supplies are obtained from rivers and aquifers simply by withdrawing and disposing amounts of water that are small in relation to natural flows. This is analogous to the hunting-gathering stage of agriculture, where the user gets whatever the natural environment provides. When regions become more developed and greater demands are placed on water resources, man modifies and interacts with natural flows and storages of water in a manner analogous to modern agriculture's modification of and interaction with "natural" soils and plants.

Water management is not limited to the edifices and engines of man, nor to the streams and aquifers that seem to be the immediate origins of many water supplies. Man's technologies are aimed at inducing the various mantles to perform at desired levels; each mantle responds to such stimuli in proportion to specific capacities. Water management can be guided by an understanding of the types of processes that water follows and could follow in the land. Water management can draw on the capacities of the atmosphere, surface water, soil moisture, groundwater and cultural devices to control the characteristics of water. In the process it integrates the "mantles" of the hydrologic environment. Water management integrates the natural and the artificial.

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