DEFINITIVE BASIN WATER MANAGEMENT

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ABSTRACT

The required level of management of the fresh water supply practiced within a given watershed is defined by all of the physical, chemical, economic, environmental, and sociological factors involved. Efficiency of water use, consumptive versus non-consumptive utilization of water, diversion requirements, and environmental requirements all need to be understood and balanced to optimize use of the available water. Where watersheds span states and sovereign nations, treaties and agreements are required for orderly use of the fresh water resource. Understanding of the nature of water use and the hydrology of the water resource system is a key element in rational utilization of the resource. Elevation, water quality, and temporal availability are some of the parameters that must be considered. Ground water and surface water need to be treated as a single resource for effective management.

INTRODUCTION

The shortest path in the hydrologic cycle occurs over the ocean. Water evaporates from the surface of the sea, rises into the atmosphere, condenses into clouds and falls directly back into the ocean as rain. The total hydrologic cycle time for a given drop of water over the ocean may be only a few hours. If the clouds move over a land mass before the rain falls, the hydrologic cycle may take years to complete. When precipitation occurs over a land mass, the hydrologic cycle is modified by many physical processes such as reservoir storage, aquifer storage, interception, evapotranspiration, and travel time in a stream or an aquifer. The quality of the water will be naturally degraded as the water moves toward an outlet. Part of the water will return to the atmosphere without ever entering an ocean. When rainwater falls on the land, the raindrops coalesce and become controllable liquid water. An area of land that contributes water to an identifiable outlet or measuring point is called a basin. The percent of the precipitation that arrives at an outlet or measuring point as liquid water is the yield of the basin and can generally be predicted statistically by correlating rainfall and runoff, using existing measured data.

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Water management (meaning management of the liquid water) in a hydrologic basin requires an understanding of the hydraulics of water movement in aquifers and open channels, and an understanding of the evaporative processes that occur. Evaporation is the only process that subtracts water from the hydrologic system, so identification and quantification of water uses should be made on the basis of whether a particular use has an evaporative component. For example, hydroelectric power generation on a river does not consume water as a result of its being passed through a turbine, but retaining the water in a reservoir until it can be routed through the turbine will result in evaporation that decreases the quantity of water remaining for downstream users.

Wherever a water use occurs, the quality of the remaining water will be reduced. Hydroelectric power generation generally consumes little water and does not significantly affect the chemical quality of the remaining water, however, elevation or hydraulic head is lost. Commercial production of salt will result in a total loss of the liquid water and no water will be available for subsequent reuse. Municipal use of water has a relatively low evaporative component, when lawn irrigation is not practiced, but the biological quality of the remaining water may be seriously degraded. Agriculture evaporates a relatively large proportion of the water it uses, and decreases the chemical quality of the remaining water by a natural concentration process. Therefore, definitive water management in a hydrologic basin requires that quantity, quality, elevation, timing, and volume all be understood in the context of evaporative and non-evaporative uses. The paths followed by the water on its way to an outlet or measuring point must be understood and the effect of the path on water quality and temporal availability must be included in the basin water management analysis. If wrong assumptions are made, serious errors will occur in prognostications.

One of the terms used to evaluate the appropriate use of water is the word efficiency. Efficiency was applied to on-farm use of water for irrigation by O.W. Israelsen (1932). He measured the amount of water applied to a field and determined the proportion of the applied water that was stored in the root zone. Water that left the field as deep percolation below the bottom of the root zone and water that ran off the surface of the field was considered to be "lost" in the calculation of irrigation efficiency. On a single field basis, an irrigation efficiency thus calculated can give an indication of how a given supply of water might be more effectively utilized. Irrigation efficiency analyses only gave recognition of the part of the water applied to the field that was evaporated and not to the unevaporated quantity that was still part of the basin supply. There was also no recognition of the difference in change of water quality between deep percolated water and surface runoff water. Irrigation efficiency is a term that can be used to evaluate the efficacy of a single irrigation application, but the term does not have applicability in definitive water management in a basin. Irrigation efficiency can also be used to compare irrigation application methods or practices on a field or a farm, but cannot be used to either analyze or manage a basin water supply.

It has been suggested (Willardson, Allen & Fredricksen, 1994 and Allen, Willardson and Fredricksen, 1997) that water basin management analyses can be made more definitive by the use of decimal fractions or percentages to better identify the disposition of water for any use within a basin. For example, if 60 percent of the water applied to a field is stored in the active root zone of the plants, all of that water will be eventually evaporated by the plants and the remaining 40 percent of the water applied will remain in the basin's liquid water supply. Any surface runoff water will have approximately the same chemical quality as the water that was applied, not considering any sediment picked up by the water. The deep percolation water, however, will have a salt concentration that may be measurably higher than that of the applied irrigation water because of the natural concentrating effect of evapotranspiration. Dissolution of any existing salt in the soil profile will further increase the salt concentration of the deep percolation water. If the surface runoff water and the deep percolation water happen to be remixed at some downstream point, the resulting water will always have a salt concentration that is higher than that of the original upstream water. This effect occurs naturally, even in the absence of irrigation diversions. In many basins, the salinity of the original water supply is low enough that concentration of salts through natural evaporation and evapotranspiration and by diversions for irrigation still leaves water that is quite acceptable for other uses. To definitively manage water in a basin, both the quality and quantity of the water before and after a given use must be evaluated.

Watershed management has legal and political components as well as physical and chemical components. Decisions on water management are sometimes taken in courts and legislatures that are not founded on the defined physical reality of the watershed involved. In the newsletter, Resource Law Notes, published by the Natural Resources Law Center of the University of Colorado at Boulder (Number 42, Winter Issue, February 1998) is a story entitled "The Watershed Approach," that contains the following statement:

> "Among those elements opened-up for scrutiny are: the determination of who should be involved in making management decisions, at what geographic locations should these decisions be based and what should be the evaluation criteria utilized to determine appropriate water uses and management philosophies."

The statement implies that watershed management can be based on philosophies and evaluation criteria, in the absence of the physical facts that define the hydraulic and hydrologic characteristics of the watershed. Decisions that are taken in the absence of the defined limiting physical parameters can have serious negative results, if they are not correlated closely with the hydrologic realities of the watershed. The physical facts must be known before effective management criteria are established.

The position of a given water use in a basin is another important factor that has an effect on the type and intensity of water management that must be provided to get an eventual full utilization of a given water supply. The following sections describe how water management differs from the top to the bottom of a watershed or basin.

HIGH WATERSHED AREAS

Extensive use of water in the upper parts of a watershed should not ordinarily be a concern from an efficiency standpoint. The use of water by plants is a function of the available evapotranspiration energy and is not a function of the amount of water applied. Research in the high mountain meadows of Colorado (Kruse, E.G. and H.R. Haise, 1974) found that water applications of ten times the amount of water consumed by the plants did not affect downstream water quality or quantity beyond the effect of the consumptive use. The water supply was only reduced by the fraction of the water that was consumed by evapotranspiration. The full unconsumed fraction of the water applied quickly made its way back to the stream either as surface runoff or as part of the ground water flow entering the stream. The flow paths were relatively short so that the temporal availability of the water was not modified significantly.

The studies by Kruse and Haise (1974) also showed that yields could be increased by reducing the amount of water applied and by planting better varieties of grasses that did not have to have tolerance to continuous flooding. Therefore, reducing the quantity of diversions and flow through the soil in the upper watersheds would have increased evapotranspiration losses to some degree, due to higher plant vigor and leafiness, as reflected in the higher yields. The result of "improved" water management in this case would be increased depletion of the downstream basin water supply.

The quality of the water in the upper part of the watershed is high because of the high natural leaching fraction. The salts that are generated naturally by the soil weathering process are leached away at low concentrations and the natural stream flows have a large dilution capacity. Higher watershed areas tend to have short growing seasons and limited land areas, and produce most of the water that is available.

Trans-Basin Diversions: Diversion of water high in one watershed into another basin not only removes the full amount of water transferred and some salt load, but it reduces the dilution capacity of the stream that normally maintains downstream water quality. If half of the water generated in a basin is removed by an upstream diversion, the runoff per unit area of the basin will be seriously decreased. The diverted water has a relatively low salt load and therefore will not be available downstream to improve downstream water quality. It is well known that decreasing the leaching fraction in an irrigated soil profile will reduce the quality of the total amount water that seeps below the root zone. The same principle applies to a watershed or hydrologic basin.

Every basin, as a result of the generation of soluble salts by soil weathering processes, has a potential salt load that is removed in the outflow from the basin (Drever, 1988). The salt load is a function of the area of the basin. Transporting that salt load in a smaller volume of water at the exit from the basin means a higher salt concentration in the water leaving the basin.

The change in salt concentration in a stream from the upper to the lower parts of a watershed is illustrated in Table 1 which was taken from river basin simulations published by the Utah Water Research Laboratory (1968). Table 1 shows the area in square miles, the annual runoff in Acre Feet, the runoff per unit area and the estimated electrical conductivity of the outflow in a downstream direction for the Bear and the Sevier river basins of Utah. The electrical conductivity of the water was estimated by assuming that new salt was generated by soil weathering at a rate of 300 kg/ha/year and that it was removed uniformly with the outflow. Table 1 shows that the annual outflow in acre feet per square mile decreases naturally as the area of the watershed increases in a downstream direction. This is primarily due to lower precipitation amounts at lower elevations. Since salt is generated on an area basis, the salt concentration in the water also increases in a downstream direction. The electrical conductivity values are theoretical calculated natural values and have not been compared with measured values that would take into account leaching of residual salts and diversion of water for irrigation. Actual values are known to be higher than those shown.

To illustrate the effect of diversion of water from a basin, it can be assumed that 100,000 AF are diverted from the Sevier Basin watershed in the first 10 percent of the area. The diverted water would carry some of the dissolved salt out of the basin and would reduce the outflow from the basin by 100,000 Acre Feet. The salt load in the river would be reduced by the amount carried in the diverted water, and the electrical conductivity (theoretical) of the basin outflow would therefore change from 1.03 dS/m to 1.12 dS/m. This occurs because the balance of the salt generated in the basin must be carried by the remaining 974,000 Ac Ft (1.12 = (1,074,000(1.03)-100,000(0.17))/974,000). If, instead of a complete diversion away from the upper basin, the same 100,000 AF of water were completely consumed by irrigation in the bottom 80 percent of the watershed, the water would be lost, but the full salt load would remain. Use of the water for irrigation would change the electrical conductivity of the basin outflow from 1.03 dS/m to 1.14 dS/m (1.14 = 1,074,000(1.03)/974,000). This example demonstrates that salt concentration naturally increases in a downstream direction, just due to basin hydrology and that any consumptive use of water within the basin or diversion of water from the basin will increase the downstream salt concentration by decreasing the basin leaching fraction.

Table 1. Increasing salt concentration in the downstream direction for the Bear and Sevier Rivers of Utah. Utah Water Research Laboratory 1968.

	Percent of Total Area					
	10	20	40	60	80	100
Bear River						
Area, Sq. Mi.	328	655	1,310	1,966	2,621	3,276
Runoff, Ac-Ft	342,900	561,100	812,600	943,500	1,017,300	1,039,100
Ac-Ft/Sq.-Mi.	1045	857	620	480	388	317
dS/m (est)	0.09	0.11	0.16	0.21	0.25	0.31
Sevier River						
Area, Sq. Mi.	1,129	2,259	4,518	6,776	9,035	11,294
Runoff, Ac-Ft	655,200	929,100	1,050,400	1,063,300	1,069,800	1,074,000
Ac-Ft/Sq.-Mi	580	411	232	157	118	95
dS/m (est)	0.17	0.24	0.42	0.63	0.83	1.03

Trans-basin diversions also reduce downstream potential for hydro-electric power generation. Irrigation diversions reduce downstream flow volumes, but only by an amount equal to the consumptive use that ensues. If a large proportion of the return flows travel back to streams via an aquifer, the temporal availability of the water supply downstream may be affected, but the total remaining volume discharged is relatively unaffected, since there are few water losses from a groundwater storage system. In some situations, especially where most of the water is derived from snowmelt, large diversions during large streamflows can reduce downstream flooding potential and the subsequent return flows may return to the surface water supply when they will augment low late-season stream flows, thereby improving fish habitat and streambed environments. The defining water management factors in the upper parts of a basin deal primarily with volume and timing of flows and not with efficiency of use and local water quality. The stream bed environment is generally not seriously affected by local water uses in the upper parts of the watershed. Biological pollution may occur if heavy human recreational use of the upper watershed area occurs, but the quantity and chemical quality of the water will generally remain high.

The definition of water uses in the upper portion of a watershed requires evaluation of the effect of any water uses or diversions on downstream water quality and quantity, with emphasis on the quality and quantity of the fraction not consumed or diverted outside the basin.

MIDDLE WATERSHED AREAS

Most water uses, natural and man-related, occur in the middle areas of watersheds. The land is relatively flat and readily adapted to irrigated agriculture and urbanization. Middle watersheds have less precipitation than high watersheds and their effect on the basin water supply is greater. Large amounts of water can be diverted for irrigation and all of the water not consumed by crops still returns to the groundwater and to the surface water supply, sometimes beyond any point of possible local reuse. When a large proportion of the applied irrigation water is consumed, the quality of the deep percolation fraction of the returning unconsumed water may be significantly reduced if the initial salinity of the water is high. The water diverted in the middle watershed usually has a higher salt content than water diverted higher in the watershed. However, the drainage water (return flow) from irrigation is almost always reusable downstream. In some extreme situations, such as the irrigation of saline soils, the drainage water may become too saline for reuse without dilution.

Water diverted for municipal use usually has a low consumed fraction so that most of it returns to the downstream water supply, although it may have a high biological oxygen demand because of the organic matter it contains. Municipalities, on average, consume from 10 to 15 percent of the water they divert (Fredricksen, 1992) so that 85 to 90 percent of the water remains available downstream in the basin from a mid-basin diversion. Tertiary treatment of municipal waste water usually makes municipal waste water safe for return to a natural stream if there is sufficient dilution and travel time for further natural biological purification to take place. Downstream reuse by other humans is then possible. Measurements of water diversions for municipal purposes does not define the hydrologic impact of such diversions. The consumption and dilution requirements for the recovered water need to be considered as well as the chemical and biological water quality.

The water supply in the middle part of a watershed should be considered to be a conjunctive use system, that includes both surface and groundwater, where quantity, quality, timing, and elevation are parameters of use. Any use of water for any purpose will affect one or all of the important middle watershed parameters. Again, only the fraction of the water supply that is actually consumed is no longer available downstream. All other water will eventually appear above or at the outlet of the system. Examining the fractional disposition of the water will define what is actually happening to the supply and what the final effect of use in the middle watershed will be on the quantity and quality of water downstream.

Environmental considerations of water management become important in the middle watershed. If diversions are too high, the stream may actually disappear for some distance along the natural stream course until surface and subsurface return flows replenish the stream. If wildlife preservation requires the maintenance of a minimum streamflow, then diversions may have to be restricted even though there is excess water available at the downstream end of the middle watershed. Definition of all water needs in the middle watershed, in terms of water consumed, water quality, required stream flow, and temporal availability are required for good management. Conjunctive use of groundwater must managed to prevent an undesirable loss of streamflow (due to seepage losses to groundwater or reduced inflow to the stream from groundwater) caused by lowered water tables. Control of groundwater extraction or recharge of the local aquifer will be required to prevent overuse of the conjunctively managed water supply of the basin.

LOW WATERSHED AREAS

Even under natural conditions, the quality of water in the lower part of a watershed may be relatively low. A natural stream that is undisturbed has a progressive decrease in chemical water quality along its length (Table 1). The flow rate may increase in a downstream direction, but the chemical quality will decrease because the basin leaching fraction decreases. The runoff rate per unit area is highest in the upper watershed and decreases in a downstream direction. The area of the watershed increases in a downstream direction, so that the apparent leaching fraction, defined as the outflow per unit area, decreases. Downstream water quality will always be lower than upstream water quality. In river basin management, the minimum downstream water quality must be set to some standard and the upstream water uses must be managed and controlled to preserve that standard. Any management practice followed in the lower watershed cannot have a physical effect on the watershed anywhere upstream, but it may have a defining effect on management of the upstream water. For example, downstream water rights may have priority over upstream water rights, in which case, upstream uses are restricted. Depending on the water needs (quality and quantity) and water rights in the lower watershed, careful definition of the hydrologic and hydraulic system for the entire watershed is required before management is undertaken. The fractions of water taken from the supply and the fractions returned must be known in terms of quantity, quality, elevation, and timing in order to define the kind of management required for a given system. If the groundwater part of the equation is not included, serious losses in surface-related investments can occur. The planning should take place in a manner that will make the water resource sustainable and usable for all interested parties and for the public good.

The hydrologic position of the lower watershed changes the management and costs (in terms of water volumes) so that they are different from those in the upper and middle parts of a watershed. In the upper watershed, quality is high and all of the water that is not consumed is available for downstream use. In contrast, a lower watershed may border on a saline sink into which any non-recoverable water from the watershed discharges and is, therefore, not reusable. Such locations may be a city or an irrigation project that borders on an ocean, such as the cities of San Diego, Los Angeles, and the San Francisco Bay area, or an irrigation project such as the

Culicacan project in Mexico, the Imperial Irrigation District in California, and the Sevier River system in Utah. All of the diverted water that is not consumed can readily enter the sink to be evaporated and eventually returned to the atmosphere but cannot be directly reused. In the lower watershed, every economically feasible effort should be made to productively consume as much of the water as possible before it is lost to a saline sink, unless there are important environmental reasons for not doing so.

Defining the quality of water that makes it no longer economically and physically useful and which therefore must be discharged into a sink is an important defining management parameter. Large cities that border the ocean have large diversion requirements, but consume only a small fraction of the water and often discharge their treated municipal wastewater directly into the sea. Los Angeles has made an attempt to recover some of their treated sewage water by recharging the groundwater between the ocean and the inland freshwater aquifers that were being pumped down to elevations below sea level. In the Imperial Valley, the groundwater is too saline for recovery, so that pumping groundwater for reuse as a means of recovery is not feasible. In the Imperial Valley, only irrigation water management that results in a high consumed fraction of the water diverted will minimize the loss of the water resource. This occurs because a high consumed fraction, given the relatively constant rate of consumptive use, translates into reduced diversions. This would require reducing the deep percolation to groundwater and reducing surface runoff that is otherwise destined for the Salton Sea. Any water transferred from the Imperial Valley, which currently consumes more than 70 percent of the water diverted, and that is used instead for municipal supplies in sea coast cities, which consume less than 20 percent of the diverted water, will result in net reduction in productively consumed fresh water. In the Salt River Project of Arizona, a middle watershed location, all of the deep percolation from irrigation and municipal treatment recharge facilities is recoverable with deep wells, a management alternative that is not available in a lower watershed.

CONCLUSIONS

Defining the hydraulic and hydrologic system of a given watershed is an important first step in the management of a basin water supply. The fractions of diverted water and the paths that they follow will enable rational decisions to be made concerning the importance of investments in infrastructure to manage water. High efficiencies of water use in an upper watershed are generally unimportant because water not consumed is not actually lost. High efficiencies in lower watersheds are imperative because any water not consumed is not recoverable. A true conjunctive use approach in the examination of the disposition of the total water supply from the top to the bottom of a watershed is necessary to define the management parameters needed to guide the disposition of a limited fresh water supply.

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