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Phasen der wasserwirtschaftlichen Entwicklung und der Auswirkungen der Schließung eines Flußgebietes

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Stichworte
Flußgebietsentwicklung, wasserwirtschaftliche Analyse und Planung, Wassernutzungseffizienz, Konzepte des Wassermanagements in geschlossenen FluBgebieten

Keywords
River basin development, river basin analysis and planing, water use efficiency, concepts of water management in closed river basins

Zusammenfassung
In der Arbeit wird ein konzeptioneller Rahmen für die wasserwirtschaftliche Analyse und Planung von Flußgebieten vorgestellt. Ein genereller Entwicklungsverlauf von Flußgebieten wird aufgezeigt, dem diese mehr Oder weniger folgen, wenn deren Wasserdargebot erschlossen wird um die zunehmende Nachfrage zu befriedigen. Der spezifische Entwicklungsverlauf dem das einzelne Flußgebiet folgt, wird bestimmt durch die relativen Kosten und die gegebenen Optionen innerhalb des Flußgebietes, den Wasserbedarf für ökologische Bedürfnisse etc.. Das Konzept des geschlossenen Flußgebietes, welches vorliegt, wenn die Wassernutzung dem verfügbaren Wasserdargebot entspricht, wird erläutert und dessen Auswirkungen auf die Wasserressourcenplanung untersucht. Die Autoren kommen zu der Feststellung, daß es das Ziel des Schutzes und der Erhaltung der Wasserressourcen in geschlossenen Flußgebieten ist, tatsächliche Wassereinsparungen zu erzielen. Und zwar solche die in andere Gebiete transferierd und die anderen Nutzungen innerhalb des jeweiligen Flußgebietes zugeführt werden können. Das Konzept der effektiven Effizienz in der Wassernutzung wird erläutert im Kontext der Identifizierung und Quantifizierung realer Wassereinsparungen. Die Arbeit beschrankt sich auf die physikalischen Aspekte der Wassernutzungseffizienz.

Abstract
This paper provides a conceptual framework for river basin analysis and planning. A general development progression is described that all river basins will follow in some manner as their water supplies are developed to meet growing demands. The specific progression that any single basin will follow **is** determined by the relative costs and availability of the options in that basin, the amount of water reserved to meet ecological needs, and other factors. The concept of river basin closure, which occurs when water use approaches the available supply, is presented and its implications to water resource planning examined. Closure management zones are defined as areas in the lower portions of closing river basins where the last water use cycle can be designed to exploit the maximum consumptive potential of the water supply. The authors submit that the objective of conservation in closing river systems is to achieve

real water savings, which are savings that can be transferred to other locations and uses in the basin. The concept of effective efficiency in water use is presented in the context of identifying and quantifying real water savings. The scope of the paper is limited to physical water use efficiency, not the much broader concepts of economic and environmental efficiency.

1. Introduction

As the demands of agricultural, industrial and urban water users increase the water resources of river basins become stretched to the point that supplies remaining for environmental needs become marginal. In some cases, such as the Sacramento River Basin, the water remaining for environmental uses has been reduced beyond public acceptance levels. This has resulted in efforts to reduce the agricultural, industrial and urban demands in order to maintain greater in-stream flows, especially during drought periods. This full utilization of a river basins water resources is what we call a closed water system in which there is little or no margin for further development in one area without reducing demands in another area or augmenting the existing supplies.

We define a closing water basin as one in which the beneficial consumptive use of water is approaching the available effective supply (see KELLER et al, 1992). Typically, consumptive use is thought of as depletion by evaporation and transpiration, but consumptive use can also be by flow to a sink and by salinization or other pollution. We define the available effective supply as the renewable or sustainable equivalent freshwater supply. Since there may be some required outflow from the basin (for example to maintain estuary water quality or in observance of international treaties or water rights), the available effective supply is the total renewable supply less the required outflow.

As a water system begins to close, it becomes increasingly difficult, and hence costly, to conserve water; and tradeoffs emerge among the different water conservation opportunities. We call the planning, selection, and implementation of water conservation programs in a closing system, "managing the closure." The fundamental objective of water management in closing basins is to increase the sustainable output per unit of freshwater effectively consumed. This objective can be met either by increasing sustainable output, by decreasing freshwater consumption, or by increasing the effective supply.

The topics that follow include a synoptic way of viewing the various phases of river basin development, general water development costs, irrigation efficiencies, conservation planning, basin closure stages, and the policy implications as a basin approaches closure.

2. Basin Development Progression

There are considerable differences among the current resource development options. Contemplating the reasons for these differences leads to the idea that one could imagine a kind of *"river basin water development sequence"* and fit the various basins along it (see KELLER and FADL, 1993). This lead to conceptualizing the phases of basin development related to supply and utilization depicted in Figure 1. We realize that the development activities within a given basin usually involve more than one phase at a time. This is because water related stresses will differ throughout a basin and the incremental costs per unit of water ($ per cubic-meter or $ per acre-foot) developed have overlapping ranges across the development phases. But the real value of Figure 1 is to provide a conceptual structure for visualizing the natural progression of water development in river basins.

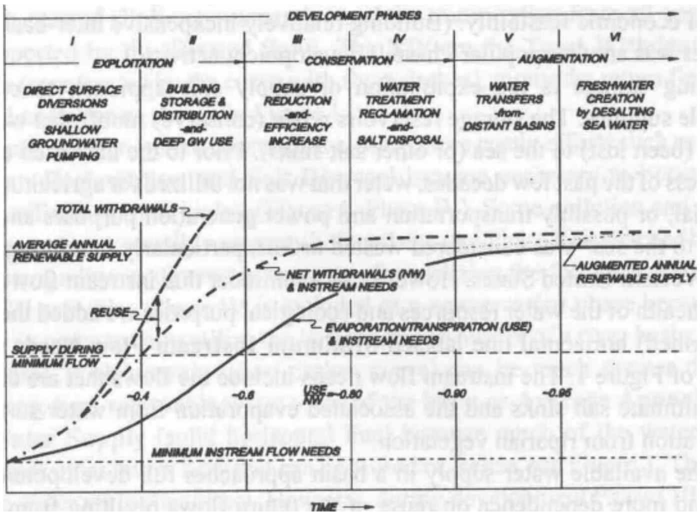

Figure 1:
River Basin Water Resource Development Phases Relative to Minimum Flow and Average Annual Renewable Supplies as Use Relative to Net Withdrawals (Demand Ratio or Use/NW) Increase

For systems in wide open basins the major means for satisfying increasing demand is simply to divert more supply and pump from shallow groundwater aquifers. There is little need to worry about increasing storage or conservation to reduce demand or exotic procedures such as extensive treatment of waste water to reclaim degraded effluent or desalinization to increase the usable supply. Furthermore, the main means for dealing with pollution is dilution. This is the **Direct Surface Diversion** phase of the ***exploitation*** of a water resource (see Figure 1, Phase I) during which there is minimal emphasis on demand reduction.

The next phase *of* ***exploitation*** is **Building Storage,** extending the distribution system, and pumping from deep aquifers (see Figure 1, Phase II). This becomes necessary when the **Net Withdrawals** plus **Minimum Instream Flow Needs** (dash-dot-dash curve) begins to exceed the available **Supply During Minimum Flow** periods (dashed horizontal line). The Net **Withdrawals** equal the **Total Withdrawals** (short-dashes curve) minus **Reuse** of return flows, see Figure 1.

Conserving the available freshwater supplies becomes increasingly important when the water supply is no longer adequate (in all or parts of the basin) during minimum flow periods. In the past the emphasis on building storage to increase the usable supply was considered to be a relatively "straight forward engineering solution". It was politically popular and could usually be given at least the appearance of economic feasibility. (Building relatively inexpensive inter-basin transfer facilities was another popular Phase II development activity.)

Adding storage is the exploitation or supply side approach to conserving available supplies. The storage reservoirs retain (conserve) runoffthat would have flowed (been lost) to the sea (or other salt sinks). Prior to the increased ecological awareness of the past few decades, water that was not utilized for agricultural, urban, industrial, or possibly transportation and power generation purposes and "simply flowed to the sea" was considered wasted or lost, particularly in arid regions such as the Western United States. However, as a reminder that instream flow is needed for the health of the water resources and ecological purposes we added the (short & long dashed) horizontal line labeled **Minimum Instream Flow Needs** along the bottom of Figure 1. The instream flow needs include the flows that are discharged to the ultimate salt sinks and the associated evaporation from water surfaces and transpiration from riparian vegetation,

As the available water supply in a basin approaches full development there is more and more dependence on reuse of the return flows resulting from each use cycle, and the system begins to close. For such closing water systems the typical lack of concern for reducing demand and salinity and pollution control to conserve freshwater supplies must change. This is because there is increased dependence on the reuse of return flows, but the increasing load of pollutants and salinity can no longer be adequately diluted, thus the water becomes unsuitable for reuse.

In this "closing water system phase of development" further exploitation is no longer a viable option and the development focus must shift from *exploitation* toward ***conservation.*** The most cost effective means for expanding or getting more benefit from the developed water supply is usually **Demand Reduction** and increasing the efficiency of water use (see Figure 1, Phase III). However, increasing water use efficiency requires careful integration of water quality with water quantity.

In dealing with conservation savings water quality and quantity must be tightly linked. Simply using dilution to deal with water quality is not sufficient. Mechanisms such as source control (that is keeping pollutants and salt loads out of the supply in the first place by treatment or direct disposal) must be utilized to maintain usable and safe supplies of freshwater. There are two forces at work that can rapidly increase pollution loading, these are the population and the added pollution per person. Unfortunately they are both increasing simultaneously in most regions of the world.

During development Phases II and III the proportion of the water consumed (or global water use) within a basin usually increases dramatically as expressed by the ratio of the **Evaporation and Transpiration (USE)** to the **Net Withdrawals (NW)**, **USE/NW** (see the solid and dash-dot-dash curves respectively in Figure 1). The **USE** is the sum of all direct evaporation and the transpiration from all vegetation being supported by the diverted flows. The **NW** are the **Total Withdrawals** or diversions (represented by the curve with short-dashes), minus the return flows that are reused or **Reuse** as shown in Figure 1.

As a basin's water system approaches closure more costly efforts such as **Water Treatment, Reclamation and Salt Disposal** become necessary to boost global water use efficiency even higher (Figure 1, Phase IV). Some pollution and salinity control measures are usually necessary before the end of Phase III is reached because of the water quality requirements necessary for realizing the full potential benefits of Phase III activities. Phase IV is included as a *conservation* phase because it is necessary in order to fully utilize the basic water resources of a river basin.

The **Total Withdrawals** (short-dashes curve) can be much greater than the average long term renewable water yield of the basin or **Average Annual Renewable Water Supply** (solid horizontal line) because much of the water that is diverted ends up as return flow that can be reused or **Reuse,** see Figure 1. This gives rise to the water multiplier effect. However, during development Phases III and IV it is not unusual for exploitation to have exceeded sustainable yields or supplies in spite of conservation efforts. This is indicated in Figure 1 by the dash-dot-dash curve representing the **Net Withdrawals & Instream** Needs crossing the solid horizontal line, which represents the Average **Annual Renewable Supply.**

This imbalance between net withdrawals and supply can be maintained for some time by shorting instream flow needs or mining groundwater aquifers. However, in coastal areas mining groundwater aquifers usually results in salt-water intrusion. Considerable development can continue to occur in Phase IV without greatly increasing the imbalance. But in the long run, either demand must be reduced further (by abandoning some agricultural lands for example) or augmentation is necessary.

When a river basin becomes fully closed, expensive efforts such as costly **Water Transfers** from distant underutilized basins and **Freshwater Creation by Desalinization** become the only means for expanding the supply. These are the ***augmentation*** phases of water development (Figure 1, Phases V and VI).

The implication of the preceding discussion is that all river basins progress sequentially through the six development phases, from the undeveloped state to the fully developed, or closed, state. However, it is more common for a basin to progress through successive interim development cycles, corresponding to incremental development of water storage capacity. Typically, water storage is developed in relatively large increments while water demands grow gradually, along with general economic development. Each time new storage is added, the new developed supply suddenly becomes available and is initially abundant relative to the existing water demands. The developed water supply gradually becomes scarce as demand continues to grow while the developed supply remains fixed.

During this transition from abundance to scarcity, the basin tends to pass through the development phases described above with respect to the new water supply. Initially, new supply can be used in an exploitative manner, then conservation becomes necessary and eventually augmentation must be considered. At this juncture, when expensive water development opportunities become necessary to meet existing water demands with the current developed water supply, planners typically will re-evaluate major water storage options. The next increment of storage, which is likely to be much more expensive than the last and subject to stricter environmental reviews, may be developed at this point; if so, another development progression will begin.

We refer to these development sequences that correspond to incremental water storage development as interim (basin development) progressions. And, as each interim progression approaches its end, we say that the basin is approaching closure *relative to* the presently developed supply. In basins where enough storage can be constructed to develop the total water supply of the basin, we say that the basin is approaching *absolute closure* as it nears the end of its final development progression. The Nile River in Egypt provides a good example of a basin approaching absolute closure. With completion of the High Aswan Dam in the early 1970s, the full flow of the river came under regulation. This, in turn, allowed Egypt to intensify and expand irrigation to the point that nearly all of the Niles supply is consumed.

Although we do not deal with it in this paper, we acknowledge that the manner in which a basin proceeds through its development progression is profoundly influenced by its natural flow variability, geography as it pertains to cost of storage, and other factors. For example, one can imagine that basins with relatively constant flows (denoted by a small difference between the **Average Annual Renewable Supply** [solid horizontal line] and the **Supply During Minimum Flow** [dashed horizontal line] in Figure 1) will have lengthy exploitation phases compared to basins with highly variable flows. Similarly, basins with economical water storage development potential will have longer exploitation phases compared to basins where storage options are few and costly.

3. Water Supply Development and Treatment Costs

Following are some rough estimates of the general U.S. dollar costs per cubic meter ($/m3) of water associated with the different phases of water resource development (to convert to $/acre-foot, multiply $/cubic meter by 1,234):

The **cost of developing new water supplies** by capturing surface water flows and tapping groundwater reserves ranges from as low as $0.002 to perhaps as high as $0.10 per cubic meter. The lower costs are for construction, operation and maintenance of simple diversions and low-lift pumping. The higher costs are for developing complex storage and delivery systems and utilizing groundwater reserves and lifting water from deep aquifers.

The **cost of employing conservation practices** ranges from $0.03 to $0.25 per cubic meter of demand decrease depending on the difficulty and level of management and technology used. Water savings techniques that fall within the lower quarter of the range include: lining canals passing through very sandy areas, providing users with more flexible water deliveries, simple return flow systems, and regulating reservoirs to reduce main canal spills. Conservation savings at the higher end of the range include such practices as: lining canals that flow through relatively impervious soils, using sophisticated irrigation application technologies where more traditional techniques are already quite efficient, and piped distribution systems that deliver water on demand.

Treatment of sewage and industrial effluent so it can be used for irrigation without restrictions costs from $0.05 to $0.50 per cubic meter. The lower end of the range is for soil-application treatment and the high end is for high-tech mechanical and chemical treatment processes. Even treatment that is sufficient for unrestricted irrigation use may still be marginal for direct human consumption; however, it is certainly better than no treatment.

Desalinization of brackish water using reverse osmosis costs between $0.05 and 0.10 per cubic meter for the removal of 1000 ppm of dissolved solids.

> Typically desalinization ofseawater costs between \$1.00 and \$2.00 per cubic meter. However, very large-scale modern reverse osmosis facilities it may be practical to reduce seawater desalinization costs to as low as \$0.60 to \$0.75 per cubic meter.

The economic logic of the sequence of the water resource development phases is quite apparent in view of this wide range of water supply/conservation development costs. During the period when increasing the managed water supply is in the low cost stage, the collective good is well served by simply concentrating on the ***exploitation*** development Phases I and II, which is sometimes referred to as "developing supply". For closing water systems ***conservation*** through demand and salinity/pollution reduction (Phases III and IV) are the most cost-effective or only appropriate options. The importance of conservation increases as the opportunities for developing more supply become increasingly costly or there is no more supply to be developed in view of instream flow needs. Finally, the only development options remaining are the costly ***augmentation*** Phases V and VI, see Figure 1.

4. *Classical* and *Effective* Efficiencies

Irrigation efficiency is often used as a measure of system performance and the potential for water conservation savings. The assumption being that low efficiency values indicate there is considerable room for improvement and water conservation savings.

Real Water Savings. Early attempts in the western U.S.A. to stretch water supplies by increasing irrigation application and conveyance efficiencies were "unsuccessful in their objective and led to coinage of the term paper water". The implication of the term stems from the fact that the classical irrigation efficiency equations used in the paper calculations appeared to result in water savings. But in fact, when farmers improved their application efficiency, and extended the area irrigated using the apparent water savings, they increased their depletion at the expense of return flows relied upon by downstream users. In many cases the total area irrigated from the available supply remained about the same. Upstream users expanded their area irrigated while users downstream suffered. In other words, there was no real water savings.

As a result of these experiences state engineers (who are responsible for water rights allocations in their respective states) now refer to water rights in terms of allowed depletion instead of allowable diversion. Because of this line of reasoning, extensive efforts are made, especially where major water transfers are involved, to separate real water savings or wet water from "paper water" or "dry water".

Quantifying Real Water Savings. The first step in planning a conservation project with the objective of transferring the water saved requires focusing attention on strategies for quantifying real water savings. This can be done by first articulating the differences between the following two important irrigation efficiency concepts.

The conventional **classical irrigation efficiency,** EC, is equal to the ratio of the water beneficially used divided by the water supplied for a given use cycle. This is the irrigation efficiency needed for use in system design and for system operational and performance evaluations. But irrigation improvements that increase EC do not necessarily lead to real water savings. Much and sometimes nearly all of the water that is supplied for a given use cycle and not beneficially used is reused again downstream. Thus the sum of the diversions (and groundwater extractions) is usually much greater than the average renewable water supply of the basin as discussed earlier.

The conceptually new **effective irrigation efficiency,** Ee, is equal to the ratio of the volume of crop consumptive use of the applied irrigation water divided by the volume of water effectively used or consumed during a given use cycle. The amount of water effectively consumed accounts for the quantity and quality of both the supply and return flows associated with each irrigation use cycle. These quality implications include the buildup of salinity in the return flows associated with concentration due to evaporative depletion and any salt loading that may take place in each use cycle. This is the irrigation efficiency concept needed for making water resource planning and policy decisions because improvements that increase Ee lead to real water savings.

Descriptions, equations for, and the development of EC and Ee are presented by KELLER and KELLER (1995) and KELLER, KELLER, and EL-KADY (1995). These papers contain detailed examples of the computational procedures for calculating these efficiencies.

The most promising opportunities for real water conservation savings occur where the Ee values are low. Using data from Egypts Nile system where the typical on-farm classical irrigation efficiency, EC, is between 35 and 45%, the following effective efficiencies, Ee, were determined. For the entire or global system Ee is between 70 and 75% and for the Valley portion of the system Ee is between 90 and '95%. Thus there is little opportunity for real water conservation savings in the Valley because all of the return flows are reused. Since about one-third of the irrigated area is in the Valley and two-thirds is in the Delta, the Ee for the entire Delta must be in the range of 60 to 65% (based on the above Ee values). Most of the return flows from the Upper Delta are reused in the Lower Delta. Therefore, the potential conservation savings are greatest in the Lower Delta reaches. (See KELLER, 1992 and NWRC/Winrock Int. Team, 1996.)

Water Use Cycles. The reason for this difference between EC and Ee is because there are two types of situations in water basin systems: situations where there is potential for multiple use cycles; and those where only one use cycle is economically practical (see KELLER, DAVIDS, and KELLER, 1996). Multiple use cycle (multi-cycle) systems are systems where surface and subsurface spillage that is often thought of as a loss in one part can be economically reused in another part. For such multi-cycle systems, because of multiple reuse the input of water into the system (such as a river basin) can be much less than the total (aggregate) amount of water actually diverted for use within the system (see the dotted Total Withdrawals curve in Figure 1). This is referred to as the multiplier effect mentioned earlier. Single use cycle (uni-cycle) systems (or parts of a system) are systems where there is limited potential for reuse of the spillage because it becomes too saline or polluted for economic reuse, too expensive to recapture or relift, or there is no opportunity to use it before it reaches a salt sink.

In the Nile Valley the Nile River serves as both the main supply and drainage channel. Thus this is a multi-cycle system as there are multiple chances for reusing all return flows. The Lower Delta is a uni-cycle system since there is no easy way to capture and reuse the return flows. Where the return flows are not reused EC = Ee.

In the past, planners cited the low on-farm EC values and concluded there was considerable potential for conserving water on-farm that could be used to expand Egypts irrigated area well beyond the Nile Valley and Delta. But improving on-farm EC in much of the system will not result in the anticipated real water savings that would be necessary for fueling this expansion. The fallacy and yet persistence of this misleading thinking throughout the world has lead to the International Water Management Institutes promotion of "The New Era of Water Resource Management: From "Dry" to "Wet" Water Savings" (see SECKLER, 1996).

5. Conservation Planning

The major purpose of conservation planning is to develop a program for realizing real water savings that can be used to transfer water to other areas, which is referred to as horizontal expansion; or to increase the productivity of the existing area, which is referred to as vertical expansion.

The first conservation planning stage should be to develop a general understanding of water quantity and quality changes related to time and location as water flows through its basin toward its ultimate salt sink(s). The second stage is to divide the basin (or sub-basin) under study into sections according to the above two situations: those where multiple use cycle systems are practical; and those where only one use cycle is practical.

The **third** planning stage is to determine the state of development or closure of the various sections of the basin. A multi-cycle system is said to be "closing" as the actual degree of use and reuse approaches the limit of the water multiplier. The water multiplier is regulated not only by the quantity of evaporation and transpiration but also by the quality of the water related to each use cycle. Thus in closing water systems the interaction between efficiency and salinization/pollution are important considerations. As long as salinity/pollution is not limiting, there is opportunity to select the most cost effective mix of the following water conservation actions:
enhancing the reusability and reuse of residual waters, improving localized efficiency, or reducing evaporation and transpiration.

Uni-cycle systems (or uni-cycle portions of closing multi-cycle systems) are said to be closing as the degree of use (or amount of water diverted) approaches the water input into the system, i.e. the initial supply. Thus, for closing uni-cycle systems the emphasis of water conservation efforts must be focused on reducing evaporation or transpiration or improving localized water use efficiency, because the system's efficiency is the weighted average efficiency of the individual components of the system.

The **fourth** planning stage is to select water conservation options that are cost effective and appropriate for the type of system (multi- or uni-cycle) and degree of closure as outlined above. This planning stage involves choosing appropriate physical *Water Conservation Opportunities*. In closing water systems, consideration should also be given to the *Implications for Planning* that are listed in the following section while considering the above four planning stages and selecting appropriate water conservation opportunities.

The **ultimate** planning stage is when the system is essentially closed and the potential for further resource development, use, or reuse has been exhausted. However, the use of waste water treatment and desalinization or costly water transfers from distant freshwater sources can potentially reopen a previously closed system (see Phases IV, V, and VI in Figure 1). Thus the question of reopening the system becomes an economic (or a political) issue: What is the value of the freshwater relative to the cost of transfer, treatment, or desalinization?

Closure Management Zones. Due to the naturally conservative nature of water basins, salts are concentrated into the remaining water volume during successive use cycles. This typically results in increasing drainage water salinity in the downstream portion of the system to the point that, as the basin approaches absolute closure, the drainage water becomes unsuitable for direct use although it has remaining usability.

To exploit the maximum consumptive potential (usability) of the water within a basin while maintaining suitability of the supply, it is necessary to delineate an area in the lower portion of the basin that is sufficiently large so that the blend of fresh water and drainage water supplied to it will be suitable for use. This area is called the "closure management zone" and is defined by the target blended water quality and the relative supplies and salinities of the fresh and drainage waters. Within this area there can be only one water use cycle (i.e., no internal drainwater reuse) and the potential of the system to use the water is defined by the classical efficiency or the effective efficiency. This is because in the *Closure Management Zone* as defined herein, EC = Ee (see KELLER, DAVIDS, and KELLER, 1996).

Water Conservation Opportunities. There are four levels of Water Conservation Opportunities: macro, two mezzos, and micro. The macro level includes the entire basin or major subsets of the basin. The mezzo level includes the conveyance network (and associated drainage network) that distributes water from major points of diversion to the fields being irrigated. The mezzo level is divided into two parts:
the main mezzo level is the part managed by the irrigation authorities; and the user mezzo level is the part managed by the water users. Finally, the micro level is the field level.

The following strategy can be used to estimate the real water savings potential associated with any intervention (or project activity) that is being considered as a candidate for a proposed water conservation program (see KELLER, DAVIDS, and KELLER, 1996).

First the current effective volume of water being used, Ue, is estimated for the area that could potentially be affected by the project. This is referred to as the pre-conservation project effective use or simply the pre-project Ue. The second step is to estimate the projected Ue anticipated after the conservation project is implemented. This is referred to as the with-project Ue. Then, the anticipated volume of **real water savings,** Vc, that can be expected from implementing the conservation project is:

$$Vc = (\text{pre-project } Ue - \text{with-project } Ue)$$

One method for conserving water is to fallow and not irrigate a portion of the land. This may not improve the effective irrigation efficiency or increased the production per unit of water used or consumed. The following strategy can be used to determine if there is **increased production per unit of water effectively consumed.**

First the current effective irrigation efficiency, Ee, will be estimated for the area that could potentially be affected by the project. This is referred to as the pre-conservation project effective use or simply the pre-project Ee. The second step is to estimate the projected Ee that is anticipated after the conservation project is implemented. This is referred to as the with-project Ee. If the with-project Ee is greater than the pre-project Ee, there will probably be **increased production per unit of water effectively consumed.** For a conservation project to fully satisfy an increased production objective the with-project Ee should be significantly higher than the pre-project Ee.

6. Basin Closure

As mentioned earlier, a water resource system is "closed" when there is no usable water leaving the system other than that necessary to meet minimum instream and outflow requirements. From the agricultural standpoint, either all of the initial available water supply has been lost to beneficial evaporation and crop evapotran-spiration, ET, plus unavoidable non-beneficial evaporation and ET, or it has such high concentrations of salts and other pollutants that it is unusable. Conversely, an integrated water resource system is "open" when excess usable water does leave the system and there is non-beneficial evaporation and ET that can be avoided.

Figure 2 provides a synoptic view of water resources development relative to the degree of closure. The development phases in Figure 2 are the same as those presented in Figure 1. The degree of Closure in Figure 2, expressed as a percentage, corresponds directly to the demand ratio, Use/Net Withdrawal, delineating the various development phases in Figure 1.

As water development in a basin matures the degree of **Closure** approaches 100%. It should be noted, however, that a basin may approach closure and then be reopened by development of additional storage, conservation, or augmentation. Thus the curves in Figure 2 are idealized relative to the average annual renewable freshwater supply and reflect general trends.

In Figure 2 the y-axis indicates the annual effective (freshwater equivalent) supply and depletion. The origin of the axis is set at the total outflow requirement, which is that effective quantity of water necessary to meet environmental needs and protect downstream water rights. Thus the origin reflects the beginning of the developable water supply.

The water development and depletion curves in Figure 2 asymptotically approach the total available water supply. The total available effective water supply, which in the long term is the **Average Annual Renewable Effective Supply Less Outflow Requirement,** is depicted by the solid horizontal line in Figure 2. During the ***augmentation*** phase the total available effective water supply gradually increases as seen by the gently upward sloping trend of the **Augmented Developed Supply** (the right-hand end of the solid curved line).

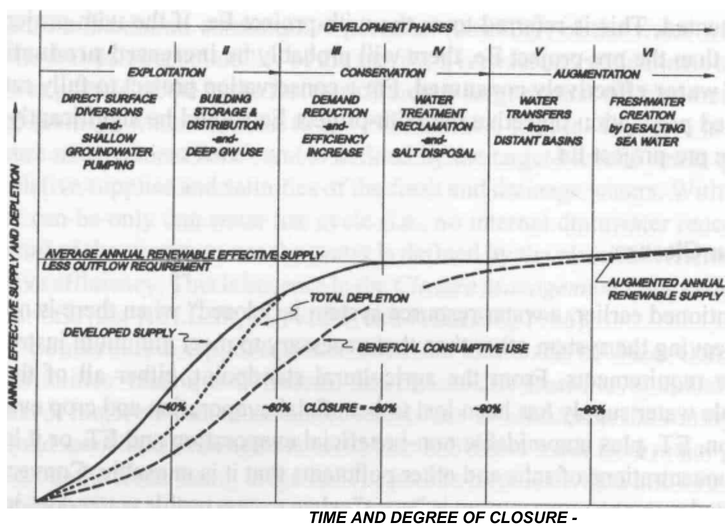

Figure 2:
Synoptic View of Water Resources Development Phases and the Percentage of Closure of a Water Basin

Total Depletion (the curved line with short dashes in Figure 2) consists of beneficial and non-beneficial consumptive use, losses to sinks, and water effectively lost to pollution. During the initial phase of exploitation, total depletion lags behind the **Developed Supply** (solid curved line). With the development of storage and deep groundwater, losses to sinks are reduced and the total depletion catches up to the developed supply at the end of the exploitation era.

The ***conservation*** era is inaugurated when conservation measures are required to increase beneficial consumptive use. Initially conservation results in an effective increase in the developed water supply, and correspondingly in beneficial use, through increased efficiency resulting from enhanced capture and use of water. Later (Phase IV in Figure 2), when the developed supply equals the total available effective supply, continued conservation results in an effective re-partitioning of the total depletion into more beneficial use and less non-beneficial use and loss.

Finally, during augmentation the total effective available water supply gradually increases and **Beneficial Consumptive Use** (curved line with long dashes in Figure 2) eventually reaches its theoretical maximum, i.e., equals the total effective supply. At this point, and to be cost effective, there are essentially no losses to sinks, non-beneficial consumptive use, or effective losses due to water pollution. For all practical purposes the basin is completely closed and the only way to continue increasing beneficial consumptive use is through continued ***augmentation.***

Most of the important policy questions in the water resources field depend on the degree of system closure, and a thorough understanding of the concepts and differences between efficiencies in the classical and effective sense.

7. Policy Implications of Closure

There are important policy implications for systems that are nearing closure such as is the case for most river and groundwater basins in the Western United States. ***First,*** in a closing system, all users obviously become increasingly interdependent. Each use cycle reduces the relative supply for someone downstream by reducing the quantity and/or quality of the water that is discharged. Management of the interdependence becomes a public function. Ultimately, a closing water system requires much more management than an open system. If adequate data are available about the nature and source of both surface and groundwater resources and the dynamics of the system, it is possible to establish realistic, reliable parameters for analyzing and projecting supply and demand patterns.

A difficult part of managing a closing system is developing mechanisms to entice all users to acknowledge their interdependence and to engage them in a negotiation process that binds them to the agreements reached (see KELLER, KELLER and SECKLER, 1996). Without some mechanism to allocate water reasonably among competing interests and to set, monitor and enforce discharge standards, downstream users are increasingly put at risk. It is usually difficult to develop institutional mechanisms to manage water systems fully, as system boundaries rarely coincide with other administrative boundaries, and the range of authority required for effective system management is seldom vested in a single administrative unit. The difficulty also can be compounded if competing interests are entrenched and powerful, or the river basin is shared between two or more countries or political jurisdictions.

Second, efficiency of water use in closing systems increasingly becomes a public issue, rather than a private issue, as users must become accountable to each other for the efficiency of use and the quality of discharges. Population growth and increased and diversified demand continually put stress on water supplies. The efficiency of use and/or misuse affects the amount of water needed for any purpose and thus affects the amount available for competing or downstream uses.

Third, if we take efficiency to mean the most productive output per unit of water, whether for agricultural production or habitat maintenance, then we can see that strategies to improve and manage efficiency differ from one part of the system to another and at different levels within the system. Such differences must be factored into the analysis, planning and management of water resources. For example, the drainage water and groundwater in much of the northern part the Imperial Irrigation District has salinity levels above 2000 ppm. Thus excess water applied in irrigation is lost to deep percolation and becomes saline drainage water that, in turn, becomes saline groundwater. From a system perspective, this drainage water is of limited value for reuse to supply irrigation and industrial needs. Increasing the effective efficiency of the system thus requires reducing percolation losses and drainage. In contrast, along most of the Sacramento River and the east side of the San Joaquin River, deep percolation returns to the rivers or recharges aquifers of good quality water that can be tapped as needed. In this case, basin wide system efficiency objectives can be met even where local classical irrigation efficiencies are low. In fact it may even be beneficial to over water crops or have high seepage losses from the distribution canals to recharge the aquifers.

Fourth, in closing water systems, increasing the effective efficiency of water use and reducing or reversing the degradation of water quality in a given water-use cycle affects all subsequent cycles. Thus the associated costs may have to be borne collectively or shared by those most affected.

Fifth, water management in closing systems requires increasingly efficient, effective management (conjunctive use) of both surface water and groundwater. This may include transporting and storing surface and groundwater in different quantities and qualities, mixing and blending water to improve quality, establishing groundwater recharge programs, regulating groundwater extraction, and perhaps alternating surface application and pumping on a seasonal or emergency drought cycle basis. Such programs present both technical and policy challenges and may require institutional realignments to be successful.

Sixth, managing closing water systems requires flexibility to be able to move water where and when it is needed to maximize the water multiplier and to increase its aggregate value. This "plumbing" issue, closely related to policy issues, is dependent upon the existence of adequate, appropriate institutional mechanisms and the necessary physical infrastructure.

Seventh, water demands change over time, reflecting changes in population and economic structure as well as the changing values of the population. Changes in demand can easily put new stress on water systems as the quantity, quality and location of water use changes. Consequently, in closing water systems, the key to effective management of water resources is the ability to allocate and reallocate water to accommodate changing demands and priorities. Whether the real location function is centralized or decentralized, it needs to be responsive and fluid, able to challenge and modify existing water rights and established water-use traditions. In the Californias Central Valley the principal opportunities and problems with regard to water are defined by two factors: the reallocation of water among beneficial uses. to achieve the highest overall benefit in a closing system and increasing the efficiency per unit of freshwater effectively used for any purpose, especially agriculture.

8. Summary and Conclusions

As river basins are developed to meet growing water demands, they tend to follow a general progression through three main development phases (each with 2 sub-phases), which generally correspond to increasingly costly sets of water development options. The main phases are **Exploitation, Conservation** and **Augmentation.** Because the relative costs of water development options vary from basin to basin, as do the amounts of water that society elects to reserve for ecological maintenance, each basin has its own unique develop progression. Basins approach closure as they progress through the development phases; absolute closure is reached when no usable water is leaving the system, other than that needed to meet instream flows and downstream water requirements.

In closing river systems, it is important to be able to identify and quantify real water savings that can be used to transfer water to other areas, or to increase productivity of the existing area. The concept of effective efficiency, which accounts for the quantity and qualify of both the supply water and the return flow from each irrigation use cycle, provides a basis for quantifying real water savings: real water savings will result wherever the effective efficiency of irrigation is increased. In conservation planning, the focus is often on the closure management zone or zones. These are areas, typically near the tailend of the river system, where salts are concentrated in the remaining water from successive upstream use cycles. By definition, only one use cycle is possible in closure management zones; thus, all reductions in irrigation losses result in real water savings.

There are several policy implications of river basin closure. Among these are that water management issues become much more technical and interrelated and water users are unavoidably thrust together in the development of solutions. Also, in fully closed river basins, the key to effective water management is the ability to allocate and reallocate water to accommodate changing societal values.

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