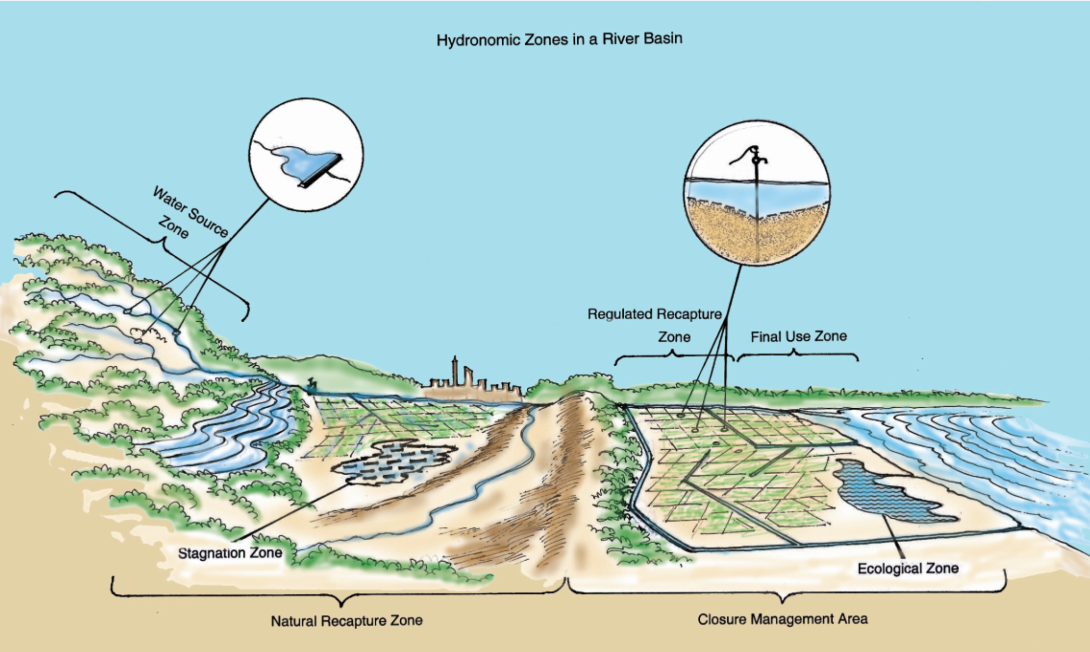
RESEARCH
REPORT

56

Hydronomic Zones for Developing Basin Water Conservation Strategies

David J. Molden, R.Sakthivadivel and Jack Keller



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Contents

Summary

In this report, the concept and procedures of hydronomic (*hydro* water + *nomus* management) zones are introduced. A set of six hydronomic zones are developed and defined based on key differences between reaches or areas of river basins. These are the: Water Source Zone, Natural Recapture Zone, Regulated Recapture Zone, Stagnation Zone, Final Use Zone, and Environmentally Sensitive Zone. The zones are defined based on similar hydrological, geological and topographical conditions and the fate of water outflow from the zone. In addition, two conditions are defined which influence how water is managed: whether or not there is appreciable salinity or pollution loading; and whether or not groundwater that can be used for utilization or storage is present. Generic strategies for irrigation for four water management areas, the Natural Recapture, Regulated Recapture, Final Use, and Stagnation Zones, are presented. The Water Source Zone and Environmentally Sensitive Zone are discussed in terms of their overall significance in basin water use and management.

Hydronomic zones allow us to define, characterize, and develop management strategies for areas with similar characteristics. The concept of zoning is demonstrated in four agricultural areas representing a wide variety of situations: the Kirindi Oya basin in Sri Lanka, Egypt's Nile basin, the Bhakra command area in Haryana, India and the Gediz basin in Turkey. We were readily able to apply the zones within each basin and suggest water management strategies for each zone. Hydronomic zones hold potential as a tool to help us better understand complex water interactions within river basins, to isolate similar areas within basins and to help us develop sets of water management strategies better tailored to different conditions within basins.

Hydronomic Zones for Developing basin water Conservation Strategies

David J. Molden, R. Sakthivadivel, and Jack Keller

Introduction

All terrestrial freshwater use takes place within a basin context. Within each basin, there are hydrological, topographical, and hydrogeological differences between areas or reaches, requiring different water management and conservation techniques. Unfortunately, too often this is not done and the same water management strategies are employed without consideration to characteristics of different parts of a basin.

Our objective is to provide a simple framework to visualize water use in a basin and enable formulation of effective, site-specific, water management strategies. This paper defines *hydronomic* (*hydro* water + *nomus* management) *zones*, describes conditions that may occur within zones, and presents generic water management strategies for the main zones. We hypothesize that a generic set of zones and strategies can be developed to characterize a variety of situations found in river basins. To test the hypothesis we applied these concepts to the Kirindi Oya basin in Sri Lanka, Egypt's Nile basin, the Bhakra irrigation system in Haryana, India, and the Gediz basin in Turkey.

Hydronomic Zones

Let us illustrate hydronomic zones with a simple example, washing hands. We turn on the tap, apply water and soap, then rinse off the soap. Some people may use the water quite frugally, while others may enjoy the process and spend several minutes savoring the water running over their hands. Given that water is an increasingly scarce resource, the question should arise whether or not the person is conserving water. The answer is found by considering what happens to the water *after* the hands are washed.

Some water remains on the hands, and is eventually evaporated, while the rest remains as a liquid, picks up some soapy material and passes into a drain. In many cases, the drainage water finds itself back to a river, is mixed with river water, and can be again diverted for another use. In other cases, the drainage water flows to the sea and cannot be reused, or it is not so easily drained and contributes to groundwater buildup and waterlogging. In the first case, from the point of view of water savings, we are not so concerned about using a high quantity of water since it is readily available for reuse. We may be concerned about the costs of delivery of water, and may wish to reduce the use of water to curtail costs of treatment and delivery. In the second case where water is not readily reused, we would be quite concerned about the amount of water applied to the hands.

Whether the water use is washing hands, industrial cleaning, or irrigation, it is useful to consider where the drainage water flows, and this is the essence of the concept of hydronomic zones. Hydronomic zones are defined primarily on the destiny of drainage outflows from water uses. Two basic conditions are presented in figures 1a and 1b:

1. Situations where outflow can be reused.

2. Situations where outflows cannot be reused because of location or quality of water.

Whether we are in condition 1 or 2 depends on our geographic location in the river basin. In its simplest form, we have two hydronomic zones. We will expand this concept further to six zones (figure 2), then include the possibilities of groundwater storage, and implications of pollution. When discussing real water savings opportunities, we will focus on irrigated agriculture, and outline irrigation strategies for the various zones.

Figures 1a and 1b represent two basic hydronomic zones. In figure 1a, as a result of a water use, part of the water is converted to evaporation or transpiration. The remaining flows departing the hydronomic zones are utilizable, and could be again put to use by a downstream user. In figure 1b, the outflows go to a sink, or become too polluted to be reused by downstream users.

FIGURE 1a.

Outflows recoverable.

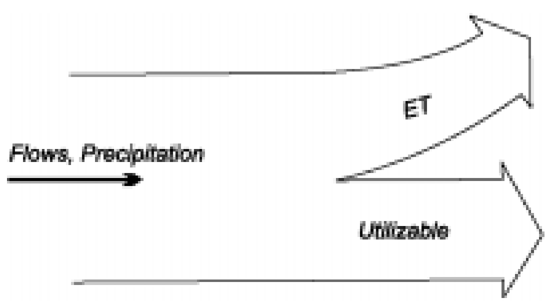


FIGURE 1b.

Outflows non-recoverable.

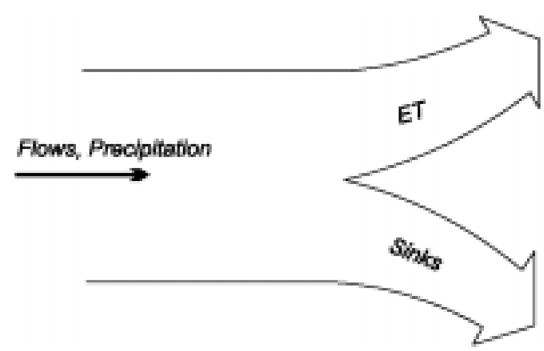
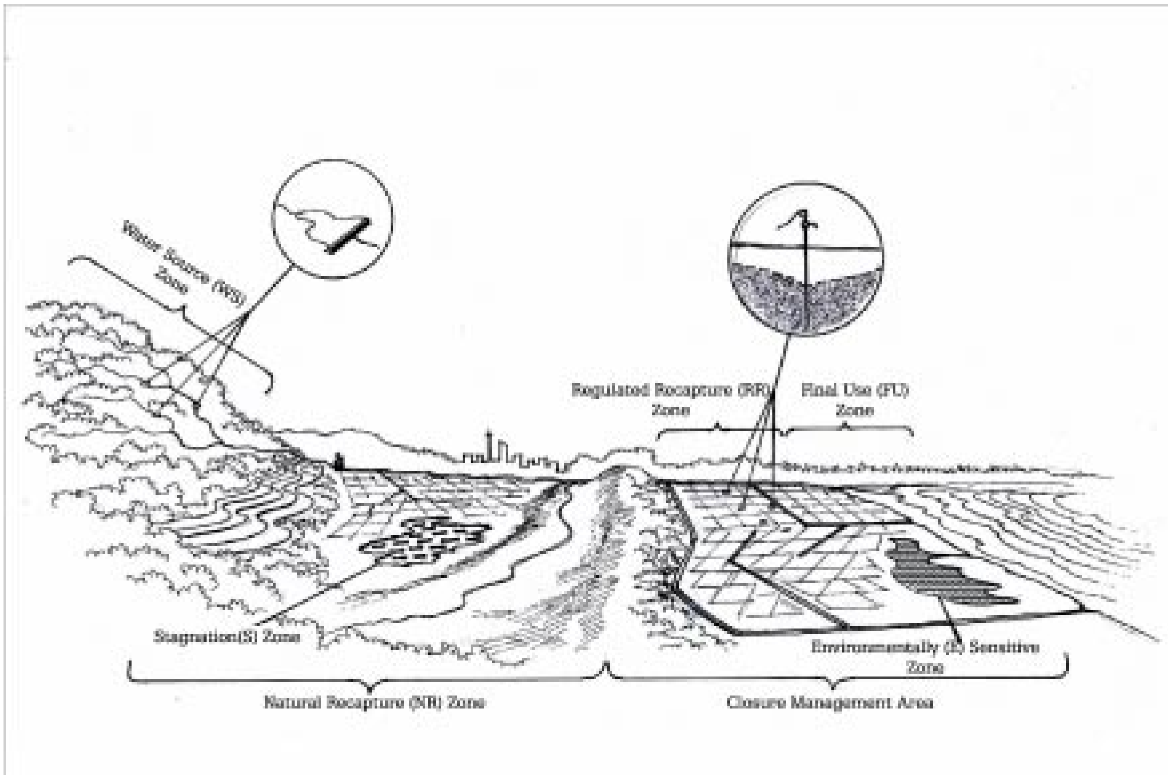


FIGURE 2.

Hydronomic zones in a river basin.



Description of Zones

The following description of the six hydronomic zones begins with *zones* where most water management and irrigation efforts are focused: the Natural Recapture, Regulated Recapture, Final Use, and Stagnation Zones. Then we describe the Water Source and Environmentally Sensitive Zones—zones that require careful consideration when considering a basin's *water management programs*. The concept of hydronomic zones evolved from a work originally performed in Egypt where the Nile was divided into Water Management Strategy Zones, and various strategies developed for each zone (WRSR 1996a; WRSR 1996b). The authors recognized that this concept had generic value, and with some expansion, could be applied and will be useful for most basins in the world.

Natural Recapture (NR) Zone. The Natural Recapture Zone is the reach or area of the basin where surface and subsurface drainage water become return flows that are naturally captured by river systems or channel networks. In this zone, rivers act as a conveyance channel for water and also serve as the main drain. The portion of water that is diverted but not depleted by evaporation in a given use cycle is naturally recaptured and available for reuse. There is little opportunity to manage the mixing and reuse of drainage water. For example, in the upland hills, valleys and alluvial benches along rivers and their tributaries, water is diverted for irrigation or other uses and the drainage or outflow returns to the same river. Throughout the Natural Recapture Zone the system is self-conserving because the drain and seepage flows naturally return to the water supply distribution system (without being pumped).

An example of the Natural Recapture Zone is the irrigation diversions in the hills of Nepal where the seepage and runoff flows back to the river system and are readily tapped downstream and reused. Another example is the Nile river valley in upper Egypt where outflows from irrigated service areas supplied with Nile water end up as seepage flows or in drainage canals that drain back into the river. Thus the Nile river serves as both the main supply and main drainage channel and the drain flows are naturally recaptured (without pumping). A third example is the Tambraparani system in Southern India (Brewer et al. 1997) where a series of diversion structures (anicuts) supply water to irrigation through contour canals. The drainage from irrigation application returns to the river, is captured by the anicuts, and used again a number of times through drainage, recapture, and reuse.

Regulated Recapture (RR) Zone. A Regulated Recapture Zone is any reach or area of the basin where the reuse of surface runoff, spills, drainage, seepage or deep percolation water can be regulated. Return flows are captured by a drainage network that is physically separate from the distribution network and water does not naturally return to the river. Therefore, physical linkages must be built and operated to facilitate the reuse of the portion of water that is diverted and not depleted by evaporation in a given use cycle. This situation is advantageous because the reuse can be managed for quality as well as quantity control. In some parts of the Regulated Recapture Zone gravity diversions on the drains can be employed to raise the water level sufficiently for irrigation reuse, while in other parts of the system pumps must be employed to lift the water from drains or from groundwater supplies.[1]

Typically, Regulated Recapture Zones are the irrigated areas in the upper reaches of river deltas adjacent to coastal plains. If the drainage and groundwater flows are not captured they will flow to the sea. Other Regulated Recapture Zones are found in areas where groundwater is extensively used such as the North China Plains, or the Punjab (in both India and Pakistan). In these cases, pumping groundwater is a means of recapturing percolation water. An example of the Regulated Recapture Zone is the upper three-quarters of the Egypt's Nile delta. There, the drains are separated from the canal distribution system. Wells are used in the uppermost reaches to *recapture and* supply water for use in municipal water supplies. Gravity diversions are used along the drains or river branches to re-divert water into irrigation canals in the middle reaches and large, medium and small scale pumping is necessary to lift water for reuse in the lower reaches. *Another example of Regulated Recapture Zones can be found in innumerable scattered tanks interspersed with surface irrigation systems of South India and Sri Lanka to capture surface runoff and drainage, and to supplement canal water supplies.*

Final Use (FU) Zone. A Final Use Zone is any reach or area of the basin where there is no further opportunity for downstream reuse. The water in the drains is of little or no value in productive uses. This zone is typically situated

[1]Where the drainage networks are permanently tied back to the canal distribution system there is no opportunity for regulating the reuse, that portion of the Regulated Recapture Zone in effect becomes part of the Natural Recapture Zone. In such cases the system is self-conserving because the drain and seepage flows naturally return to the water supply distribution system (without being pumped).

at the terminal end of the basin adjacent to its salt sink(s); its quality is too low for irrigating standard crops or there is no opportunity for reusing outflows from this zone. For example, even if return flows are of good quality, there may not be capacity to store water—or the quantity of water may be in excess of what can be depleted by the downstream area, and would thus flow to a sink. Final Use Zones may fall adjacent to Environmentally Sensitive Zones described below, in which case ecological requirements are a strong concern.

Final Use Zones fall at the end of basins such as the lower delta in Egypt, the lower portions of the Muda irrigation system in Malaysia, and the tail end of the Menemen basin in Turkey. Outflows may be required to remove pollutants or to maintain environments such as coastal lagoons, mangrove forests, or estuaries. Salt water intrusion is often an issue in the Final Use Zone. Final Use Zones may also be situated inland in open basins where there is no infrastructure capacity to reuse drainage water from the Final Use Zone. For example, areas that drain into the lower portions of the Yangtze river, or lower portions of the Ganges river are also Final Use Zones, because a reduction in drainage from the Final Use Zones (up to a certain extent) in these situations would not be of concern downstream.[2]

Where the Final Use Zone is adjacent to the Regulated Recapture Zone, there is often a tradeoff between having a more relaxed system allowing drainage and reuse or having a very tight system with little or no excess water, and limited opportunity for reuse. For example, one strategy to reduce drainage flows would be to have a narrow Final Use Zone, with intensive reuse upstream of the Final Use Zone, and very precise delivery and application techniques within the Final Use zone. *Another approach is to have a broad Final Use Zone with highly efficient water use but limited reuse upstream*. Thus, the size and shape of the Final Use Zone and Regulated Recapture Zone are a function of the infrastructure and management practices within these zones. The combination of these zones is referred to as the *Closure Management Area*. In closed basins, this is where there is the greatest opportunity for obtaining real water savings by recapturing or reducing canal operational spills and field application losses that would otherwise discharge into the basin's salt sink(s). It is within the Closure Management Area that we carefully examine the tradeoffs in terms of water quality, quantity and costs between precise irrigation practices and allowing more reuse.

Stagnation (S) Zones. A Stagnation Zone is any isolated area where the drainage capacity is insufficient for the removal of leached salts and excess water. Stagnation Zones are characterized by rising water tables, waterlogged and/or salinized areas. Stagnation Zones often occur in areas of saline groundwater, in areas where drainage water passes through soils naturally containing salts, in dead-end or depression areas, or in areas where surface drainage flows are mixed with saline or polluted surface drainage water. In this case surface or subsurface flows are not readily recoverable.

[2]In other words, present flows in these rivers are more than adequate to meet downstream requirements. A reduction or increase in drainage from the area would have little or no effect on downstream uses. However, if downstream uses increase such that downstream uses become adversely affected, the basin begins to close, and the Final Use Zone would have to be reclassified as a Regulated or Natural Recapture Zone.

Examples of Stagnation Zones occur throughout the Indus basin in Pakistan and in northwest India that have depressions or pockets of saline shallow groundwater. There are isolated areas along the fringes or outer irrigated edges of (and also within) Egypt's Nile valley and delta where drainage waters are quite saline and the soils are becoming salinized. In these areas where there is inadequate drainage, *excessive use of surface and reuse of drainage water* and groundwater results in waterlogging, salinization and decreasing yield due to secondary salinization.

Water Source (WS) Zone. In a Water Source Zone, excess precipitation provides runoff or groundwater recharge for downstream processes. It is the area of the catchment where most of the runoff or water supply originates. An isolated aquifer may also make up a Water Source Zone where mining of this water takes place, as in the Western Desert of Egypt. We have delineated this zone because this is of primary importance in the formulation of a water management program for a river basin. The runoff coefficient or water yield as a proportion of the precipitation on the basin and its sediment load are dependent on how the Water Source area is managed. Water harvesting and supplementary irrigation may take place in this zone.

Management strategies in the Water Source Zone can affect basin-wide water use. For example, in many basins, relatively small percentage increases in runoff can greatly affect the amount of water available for irrigation or other uses. Also in the Water Source Zone, there are opportunities to capture and use rainfall locally through water harvesting. When considering these options, basin-wide tradeoffs must be considered. For example, decreasing forestation to increase yield may increase sediment loading. On the other hand, practices to decrease sediment loading often also decrease water yield.

Environmentally Sensitive (E) Zone. An Environmentally Sensitive Zone is any area where there is a requirement of water for ecological or other environmentally sensitive purposes. For example, changes in quality or quantity of drainage flows from irrigation may adversely affect wetlands, thus wetlands are classified as Environmentally Sensitive Zones. Other examples include reaches of rivers that have minimum flow requirements, navigation requirements, or even special urban or industrial requirements. When developing hydronomic zones, it is very important to delineate these environmentally sensitive areas so that future programs will carefully consider their needs.

Formulating water management programs for Water Source and Environmentally Sensitive Zones requires special multidisciplinary efforts. We are describing the Water Source and Environmentally Sensitive Zones to ensure that they are sufficiently considered. At a future date IWMI (International Water Management Institute) will develop the methodology for formulating water management programs for the Water Source and Environmentally Sensitive Zones of river basins where irrigated agriculture is of importance.

Conditions within Zones

Two basic conditions within hydronomic zones should be considered when characterizing a basin: pollution and salinity, and existence of groundwater.

Pollution or salinity loading

Here we will consider two cases, pollution/salinity loading (p/s), and no appreciable pollution or salinity loading (np/s). An area loads the basin with pollution or salinity if an additional mass of pollution is added to the basin through the outflow from the area of interest. An example is the leaching of residual salts as a result of irrigation. Another example is a river reach where cities and industries pollute waterways and affect downstream uses.

Groundwater storage/utilization

Freshwater aquifers underlying irrigated areas support two important functions. One function is to temporarily store and convey water. This is common in irrigated areas where deep percolation enters the groundwater, is kept for some time, then pumped out at a different location. The second function is to provide long-term storage to balance deficits and surpluses of surface inflows and precipitation over seasonal, annual or even multi-year periods. The current or potential degree of dependence on and utilization of groundwater storage is an important consideration in formulating water management programs. In view of this we will consider three groundwater situations. No appreciable groundwater dependence (nGW), groundwater utilization focused on recapturing and distributing water (GWD), and groundwater utilization focused on water storage as well as recapturing and distributing water (GWS).

In GWS areas there is always the danger of over pumping and mining the aquifer. Where this is the case the long-term usage of the groundwater will be unsustainable, and the depth to the water table and consequent pumping lifts will become excessive and eventually the groundwater resource will be economically if not physically depleted. In coastal areas there is always the threat of saltwater intrusion from the sea, which is an insidious problem that may be undetected for a considerable time and eventually completely salinize the aquifer.

Formulating Water Conservation Strategies for Basins

The primary reason for separating basins into different hydronomic zones is because each zone has its own “best set of water-saving strategies.” Strategic research and design activities are needed to formulate packages of actions to implement in each of the zones. In this paper, we will focus on water savings in irrigated agriculture. Thus our focus will be on the Natural Recapture, Regulated Recapture, Final Use, and Stagnation Zones with special attention given to the Closure Management Area.

Typically, the Natural Recapture and Regulated Recapture Zones *not underlain with saline groundwater* are considered *Naturally Conserving Areas* when pollution in return flows is minimal. In these zones, water that is not depleted in a given use cycle will readily be available for reuse downstream. Because canal operation and field application losses are recaptured and available for reuse downstream, irrigation improvements in these zones will result in little real water savings. But, some improvements in these zones may be warranted on grounds of providing water-short areas with better access to water and increased production per unit of water consumed by crop evapotranspiration.

Formulating Strategies

Our procedure for formulating water management strategies for each of the hydronomic zones involves first considering whether the basin is *closing, closed* or *open*[3] (Seckler 1996; Keller et al. 1998). Then for each zone we consider the status of pollution/salt loading and groundwater storage/utilization.[4] While this may appear to result in a large matrix of water management strategy possibilities, it can be quickly narrowed down to a practical set of possibilities. First of all, determination of whether the basin is open or closed greatly reduces the number of possibilities. The Stagnation Zone stands alone because the package of strategies for Stagnation Zones are generally quite site specific.

Local and Basin Considerations

One common misperception is that increases in irrigation efficiency will lead to water savings at a basin scale to alleviate problems of water scarcity and competition (Seckler 1996). In some cases, increases in efficiency do lead to "real" water savings, where saved water can be transferred to an additional use. In other cases, this is not the case, and increases in efficiency do not lead to real water savings. Hydronomic zones help to clarify the issue of when efficiency increases lead to increased beneficial utilization, and when they do not.

At the scale of a particular service or use, like an irrigation system, city, or irrigated fields, expressions of local efficiency have been developed. Mathematical expressions of irrigation efficiency generally take the form of crop evapotranspiration (ET) less effective precipitation divided by diversions to irrigation, and is referred to as classical irrigation efficiency (CE) (Keller and Keller 1995):

$$CE = (ETa - Pe)/DIV$$

Where ETa is the actual crop evapotranspiration, Pe is the effective precipitation, and DIV is the diverted water from surface or groundwater.

Various versions or refinements of the general form of CE have been presented (Israelson 1932; Bos and Nugteren 1974; Burt et al. 1997). Classical Efficiency is higher when ETa increases or when diversions decrease. A disadvantage of this formulation is how rain is handled. Classical Efficiency formulations subtract out effective rainfall in the numerator, leaving the focus on water diversions.[5]

[3]In *open* basins, more water could be developed and beneficially depleted upstream without diminishing existing uses: in other words, the opportunity cost of additional depletion is zero. A *closing* basin has no more remaining available water flowing out of the basin during part of the year, typically a dry season. In a completely *closed* basin, all water is committed to environmental and process uses.

[4]For example: whether the area is pollution or salt loading (p/s) or not (np/s), or whether there is appreciable groundwater dependence for storage (GWS) or distribution (GWD) or not (nGw).

[5]In a different type of water accounting effort, Molden and Sakthivadivel (Molden 1997; Molden and Sakthivadivel 1998) developed terms called Process Fraction (PF) and Beneficial Utilization (BU). These terms relate intended or Beneficial Utilization to the water available for use within a field or irrigation system. These terms are similar to CE, but are especially useful in situations where rainfall on irrigated areas is an important supply for cities, industries, or environmental uses where irrigation efficiency does not apply. For simplicity we will use the Classical Efficiency formulation in the discussion, but the discussion would remain the same if Process Fraction or Beneficial Utilization were used.

If CE is 40 percent, is the other 60 percent a loss? This depends on what happens to the return flows (the flows that are diverted but not depleted by crop evapotranspiration). We know that in many instances return flows are available for other beneficial uses downstream and do not necessarily represent a loss. In general, there are 3 situations defined by hydronomic zones useful for deciding whether a high Classical Efficiency is warranted (table 1). The appendix (page 27) gives more specific means of increasing CE.

General Strategies by Zone

Consideration of water flow paths helps in formulating strategies for saving water. The zones tell us where water can be allowed to flow, and where water should not be allowed to flow. For example, in the Final Use Zone, drainage outflows in excess of environmental requirements should be restricted in closed and closing basins. Strategies to achieve real water savings are summarized in Box 1 giving consideration to flow paths and Classical Efficiency.

TABLE 1.

General guidelines for determining when it is appropriate to increase Classical Efficiency.

Situations calling for high Classical Efficiencies	Closed or closing basins in situations of: • Heavy pollution loading • Final use Zones • Stagnation Zones
Situations where tradeoffs between reuse and a high Classical Efficiency (CE) should be considered	In closed or closing basins in regulated recapture zones *Note*: Either high CE, or low CE with extensive reuse can result in the same amount of real water savings. Tradeoffs in these cases are analyzed in terms of benefits and costs in the use of water, and other social or environmental considerations.
Situations where high Classical Efficiency is *not* a major consideration	• Generally in open basins, except in pollution loading situations where downstream uses are adversely affected • In closed or closing basins in Natural Recapture Zones

BOX 1.

Matching irrigation strategies with zones and conditions within zones.

The procedure is to first map out zones within the basin, and then give consideration to these various options.

1. ***Natural Recapture (NR) Zone***
    a. Open basins with groundwater storage (GWS)
        i. For negligible pollution or salinity loading (np/s)
            1. increase irrigated area
            2. manage recharge to sustain the aquifer
            3. leave canals unlined and encourage irrigation deep percolation during wet seasons
            4. increase recharge opportunities
        ii. For pollution or salinity loading areas (p/s)
            1. eliminate point source pollution
            2. look for recharge areas that are non-pollution loading
            3. increase CE over salt loading areas
    b. Open basins with no appreciable groundwater (nGW).
        i. For negligible pollution or salinity loading (np/s)
            1. increase irrigated area and Beneficial Use
        ii. For pollution or salinity loading (p/s)
            1. clean up point source pollution
            2. continue to use dilution for mitigating pollution hazards
            3. increase CE over salt loading areas
    c. Closed basins with groundwater storage and distribution opportunities (GWS and GWD)
        i. For negligible pollution and salinity loading (np/s)
            1. utilize groundwater more effectively to open the basin for falling water tables, increase recharge with excess surface flow
            2. decrease non-beneficial depletion
            3. reallocate water from lower to higher valued use
        ii. For pollution and salinity loading areas (p/s)
            1. clean up point of source pollution
            2. utilize recharge areas that are non-pollution loading
            3. increase CE over salt loading areas
            4. reduce salt loading of groundwater aquifers

BOX 1. Continued.

2. ***Regulated Recapture (RR) Zone***

   The management strategies for this zone include those strategies for the Natural Recapture Zone, in addition to the following:

   a. For a zone with negligible pollution or salinity loading (np/s) in a closed basin
      i. decrease surface water supply to encourage reuse of drain water
      ii. optimize the use of drainage water.
   b. For a zone with pollution or salt loading (p/s) in an open basin
      i. manage by mixing fresh water with saline or polluted water
      ii. continue dilution and minimize pollution loading
      iii. if the source is very polluted, then shunt the polluted flow to sump or sink
   c. For a zone with pollution or salt loading (p/s) in a closed basin
      i. minimize pollution loading
      ii. if the source is very much polluted, then shunt the polluted flow to sump or sink

3. ***Final Use Zone***
   a. For negligible pollution or salt loading (np/s):
      i. decrease outflow to sinks up to amount required by environmental concerns
      ii. maximize CE allowing for environmental limits and limits set to prevent seawater intrusion
   b. For pollution or salt loading (p/s):
      i. maximize CE
      ii. shunt polluted drainage water to the sea

4. ***Stagnation Zone***
   a. For negligible pollution or salt loading (np/s):
      i. decrease diversions in to area, and increase CE
      ii. minimize percolation losses in areas of groundwater buildup
      iii. drain water out of Stagnation Zone
   b. For pollution or salt loading (p/s)
      i. avoid mixing fresh water and polluted water
      ii. drain salinized or polluted water, taking care in disposal

Case Studies

In this section, we present four case studies from various situations to demonstrate the use of hydronomic zones. For each case we provide a brief description of the basin plus a map showing the hydronomic zones. Then based on the zoning, we suggest various water management strategies that could improve water use in these basins.

Kirindi Oya Basin in Sri Lanka

The Kirindi Oya river basin in southern Sri Lanka flows from the medium range hills of Sri Lanka to the Indian Ocean (figure 3). Water resources in the area have supported vigorous agriculture since ancient times (Brohier 1934). The Yoda Wewa, Debera Wewa, Tissa Wewa, Weerawila, Pannagamuwa and Badagiriya tanks utilize Kirindi Oya water for irrigation and other uses (Bakker et al. 1999). This area is referred to here as the Old Area served by the old tanks. The Kirindi Oya Irrigation and Settlement Project provided irrigation upstream of this old area for new settlers with the addition of the Lunugamvehera reservoir, which began operation in 1985 (IIMI 1995). The additional lands irrigated by the project are referred to as the New Area.

The basin is considered closing because during parts of the year there are only very limited outflows to the Indian Ocean. During the wet seasons, there is utilizable outflow to the Indian Ocean through drains and the river in excess of environmental requirements. This outflow represents a real water savings opportunity. Except during wet periods, an increase in upstream depletive use would affect downstream uses of water. Occasionally, flood flows occur resulting in water spilling from the reservoir to the Kirindi Oya and to the sea. There is no appreciable salinity or pollution problem. While groundwater use is an important economic activity, the potential use of groundwater as a storage and regulating reservoir is not significant in terms of the volume of water.

The following zones are identified at Kirindi Oya:

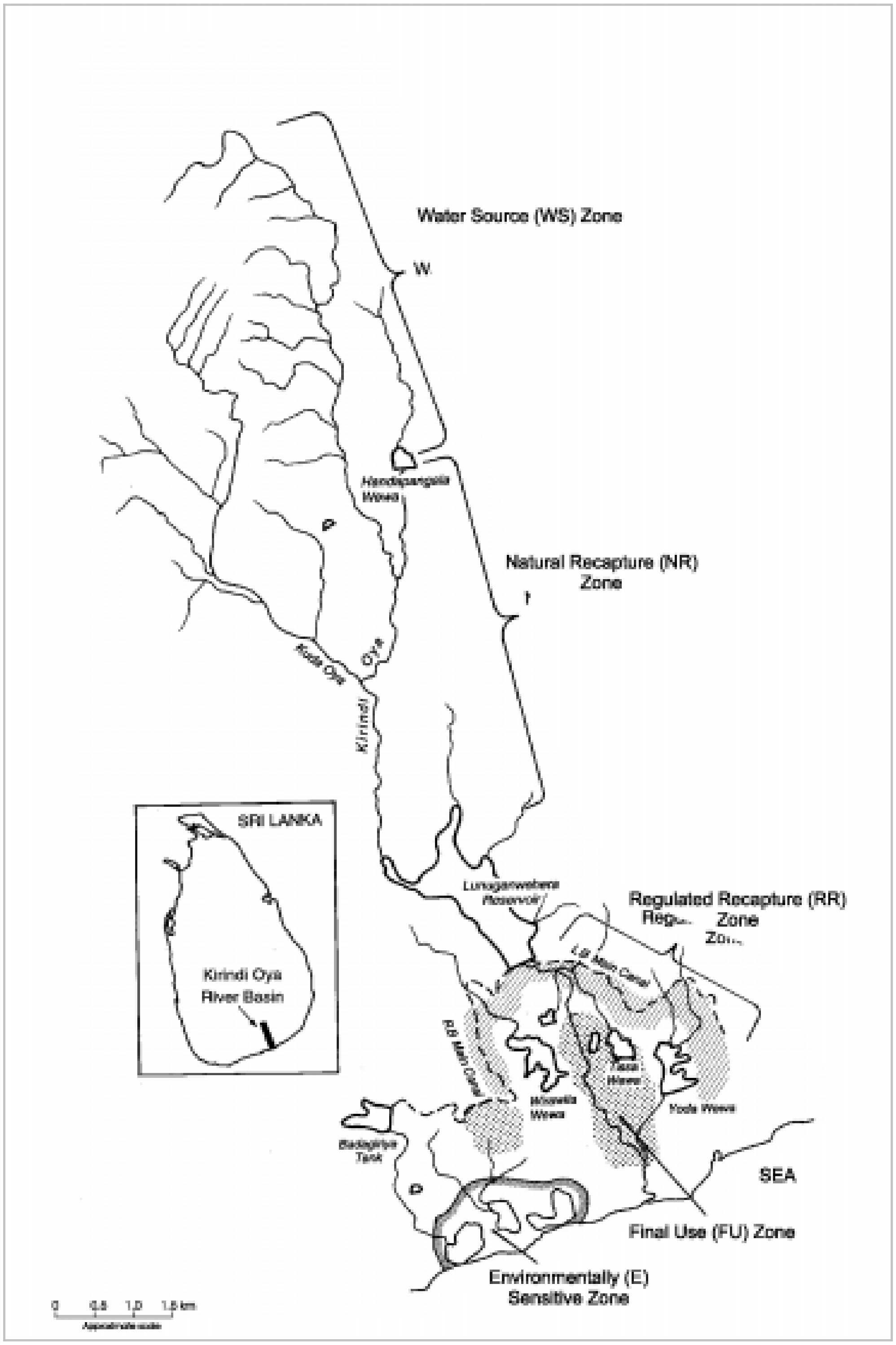
- **Water Source Zone (WS):** Beginning in the upstream area is the Water Source Zone. Upcountry plantations and forests occupy this area.

- **Natural Recapture Zone (NR):** Moving downstream is a Natural Recapture Zone, surrounded by Water Source areas. Here there are several small tanks serving irrigated farmers. Recently, many open wells and river lift pumps have been developed privately by farmers for vegetable growing. With increased population in the area, land use is rapidly changing. Any increase in evaporative depletion in this region results in a decrease in water availability downstream. Drainage outflows from various uses naturally find their way back to the Kirindi Oya where there is opportunity for reuse downstream. Eventually, they flow into the Lunugamvehera reservoir where they will be again diverted.

- **Regulated Recapture Zone (RR):** The Regulated Recapture Zone shown in figure 3 lies between the Lunugamvehera reservoir and the old tanks (reservoirs). Return flows are captured by drains and tanks separated from the river, and there are ample options for reuse. The old tanks serve as storage and regulating reservoirs, capturing upstream spills, storing them temporarily and providing a supply for downstream uses. Within the

FIGURE 3.

Kirindi Oya River Basin.



irrigated area are several trees, many that are economically important such as coconut trees, thriving on water indirectly supplied by irrigation via the shallow groundwater system (Renault et al. 2000).

- **Final Use Zone (FU):** Downstream of the old tanks, and adjacent to the sea, is the Final Use Zone. There is no opportunity for reuse of drainage outflows downstream of this area. There are patches of salinity, especially in the newly developed area where salts in formation have not been leached out. There is significant drainage outflow from this area, especially during the wet season, and apparently there is scope for real water savings in this zone.

- **Environmentally Sensitive Zone (E):** The lagoons incorporated in the Bundala national park, downstream of the Badagiriya tank, constitute an important ecological use of water and are sensitive to upstream, especially irrigation, water use. While some water is required to dilute the sea water for brackish water conditions, it is now thought that excess drainage flow induced by irrigation is artificially lowering salinity levels and adversely affecting the existing ecology (Matsuno et al. 1998).

Water Conservation Strategies

Many consider this a water-short area because during certain times of the year people do not receive sufficient water for agricultural and domestic needs. Water accounting studies in the area show that there is considerable *dry season* drainage outflow to the Indian Ocean that could be productively depleted by irrigation or other use (Renault et al. 2000; van Eijk et al. 1999). Present investigations (Matsuno et al. 1998) show that excess irrigation drainage changes the natural ecosystem in Bundala park by lowering salinity levels. It has been hypothesized that more upstream irrigation depletion would result in less drainage to the park, and thus be beneficial to this area.

There are certainly opportunities for real water savings below the Lunugamvehera reservoir to be found in the Final Use and Regulated Recapture Zones. Direct deliveries from the Lunugamvehera reservoir to tanks and farms in the Old Area (the Final Use Zone) could be substantially reduced or eliminated. Uses in the old area would then rely on “reuse” water from the old tanks.

Substantial savings could be found in the Closure Management Area consisting of the Regulated Recapture Zone and the Final Use Zone. Within the Regulated Recapture Zone, diversion and pumping facilities could be employed to recycle water. In fact, this is now being increasingly practiced at Kirindi Oya with positive results. By doing so, the Regulated Recapture Zone is growing while the Final Use Zone is shrinking. Classical Efficiency improvements in the Final Use Zone would reduce the water requirement and related drainage outflows. For example, when irrigating rice, alternating wet and dry irrigation (Guerra et al. 1998) would reduce application requirements and drainage outflows. Plus, more effective use of rain on farms, by increasing bund height in combination with a reduction in standing water levels on fields, could also reduce the need for deliveries to farms. Water saved by these practices could be stored in the reservoir for use in the dry season, or alternatively, more beneficial depletive use could be practiced upstream of the reservoir.

Changes that seem somewhat obvious are difficult to implement because they require significant changes in current perceptions and incentives. For example, downstream users in the Old Area perceive that they have a first right to water because they were the first to settle there. As a result, water is often delivered directly from the Lunugamvehera reservoir to this area first. This practice prohibits savings opportunities that could occur if water could first be delivered to the New Area, with downstream old tanks capturing return flows. Old Area farmers would have to be convinced that their needs would be met with new water savings practices to readily accept changing from their existing practices.

The Kirindi Oya case demonstrates how different water conservation strategies in different zones are required to overcome water scarcity and to maintain the natural ecosystem.

Egypt's Nile

Almost all economic activity in Egypt is situated around the river Nile, the main source of water for the country. Figure 4 shows the Nile river below the High Aswan dam. The Nile spreads out into the Nile delta, then water discharges through the river branches and drainage network into the Mediterranean Sea. Most water is diverted to agricultural uses, but domestic and industrial uses also rely on the same source of water (see WRSR 1996a; WRSR 1996b; Elarabawy et al. 1998; Molden et al. 1998 for more detailed descriptions of water use). Significant environmental requirements exist at the northern end of the delta where there are important lakes, lagoons, and coastal estuaries. The Nile is rapidly closing, and unless an additional supply of water is identified, additional water to meet growing agricultural, domestic and industrial needs must come from real water savings, primarily in agriculture.

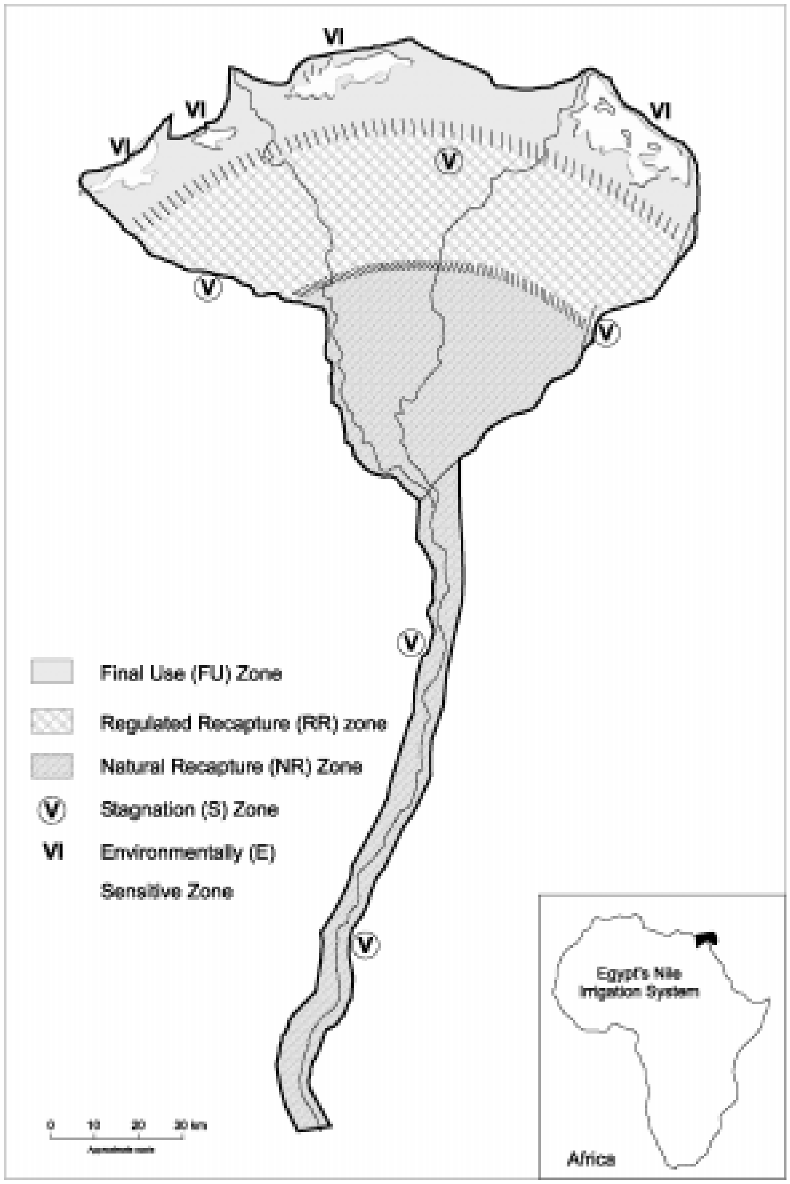
The Nile can be divided into five zones (figure 4).

- **Natural Recapture with Groundwater Distribution (NR with GWD):** The Natural Recapture Zone is situated in Upper Egypt. There is no appreciable salinity loading, but pollution loading, mostly from industrial and domestic uses exists. There are opportunities for groundwater pumping. Drainage water from all uses naturally drains back into the river Nile or enters a groundwater system connected to the river. Improvements in Classical Efficiency in this zone will not lead to real water savings, because drainage water is available for reuse downstream.

- **Regulated Recapture with Groundwater Storage and Regulation (RR with GWS):** The Regulated Recapture Zone is situated in the upper portion of the Nile delta. In this area there is no appreciable salinity loading, although effluent from cities and industries pollutes the water. There is ample opportunity for conjunctive management with groundwater storage and diversions, and there is intensive use of groundwater. This area is covered by an intensive drainage network, and there is substantial drainage reuse both through large drainage water reuse facilities and by individual or small groups of farmers operating small pumps. There is a tradeoff between drainage water reuse, groundwater use, and surface water use, and many farmers use several sources of water. Increases in Classical Efficiency will decrease drainage outflows to surface drains and groundwater, and thus decrease the opportunities for reuse. Cost considerations of various approaches is a more dominant consideration than real water savings.

Figure 4.

Nile River Basin.



- **Regulated Recapture with Groundwater Storage and Regulation and appreciable Pollution and Salinity Loading (RR with GWS and p/s).** Roughly in the middle of the Nile delta, there is increasing salinity. There are opportunities in the Regulated Recapture Zone for mixing fresh water and saline water for agriculture, but using saline drainage water alone would have to be done with great care to sustain productivity.

- **Final Use with Pollution and Salinity Loading (FU with p/s).** The Final Use Zone is located at the tail of the Nile delta system where drainage outflows are directed to the sea. There are important salinity and pollution considerations in the area including saline intrusion into groundwater (Amer and Sharif 1996). There are important environmental considerations at the Northern Lakes and the coastal estuaries. Classical Efficiency improvements accompanied by additional use elsewhere in the river system will result in real water savings.

- **Environmentally Sensitive (E) Zone.** At the tail end are the Northern Lakes and coastal estuaries of ecological and economic importance. Livelihoods of fishermen are dependent on good quality water, and the lakes serve important ecological functions. At present these are severely affected by pollution from upstream industrial, urban, and agricultural uses (Imam and Ibrahim 1996). Conservation plans need to consider the quality and quantity of environmental needs in these areas.

Water Conservation Strategies

Within the Natural Recapture Zone, increases in Classical Efficiency will not lead to basin scale real water savings. It will only lead to a change in water flow paths. Without Classical Efficiency improvements, water will be diverted from the Nile to irrigated fields, then drain back to the Nile. By reducing diversions from the Nile, water will remain in the river. Both options have associated economic and environmental tradeoffs for consideration, but both options are approximately equal with regard to the amount of water freed up for urban or further agricultural use. Within the Regulated Recapture Zone, there is ample recycling of water. Increases in Classical Efficiency may or may not have other social or economic benefits, but again, will not lead to real water savings because of the extent of reuse.

Most opportunities for real water savings lie with the Closure Management Area—the lower part of the Regulated Recapture Zone plus the Final Use Zone. There are several possible strategies for water savings within the Closure Management Area summarized in Keller et al. 1996a; Keller et al. 1996b; WRSR 1996a; WRSR 1996b. One option is to enlarge the Final Use Zone through Classical Efficiency improvements in the Final Use Zone. In this case, diversions to the area and drainage outflows would be minimized just to meet downstream ecological commitments. Another option would be to expand the Regulated Recapture Zone, taking advantage of the opportunities for recycling, and minimize the Final Use Zone. In this second option, the aim would also be to reduce drainage flows to a level where they are not in excess of environmental commitments. The selection of options would require detailed investigations of benefits and costs.

Bhakra Irrigation System

The Bhakra irrigation system in India is located along the divide between the Ganges and Indus water catchments. The Bhakra canal command in Haryana state serves more than 1.2 million hectares and contributes to about 40 percent of Haryana's wheat production and 6 percent of the national production, and is thus very important to India's national food security interests.

More than 98 percent of the command area is covered by alluvial plain lying between the Siwalik hills and Aravalli hills. Drainage is difficult because of the saucer shaped topography, and lack of surface and subsurface drains. Surface and subsurface drainage is absent in this system. The system is described in more detail in Sakthivadivel 1999; Bastiaanssen et al. 1999; Perry and Narayanamurthy 1998; Berkoff 1990; and Malhotra 1982. Groundwater is an important source of water, supplying irrigation water to more than half of the command area, through approximately 150,000 privately owned tubewells. About 65 percent of the command area is underlain with marginal and saline groundwater. Because groundwater quality varies with depth, these shallow tubewells tap mostly the upper unconfined aquifers, while some high capacity, deep augmentation tubewells were installed along Narwana, Bhakra, Ratia and Fatehbad canals to prevent waterlogging and supplement irrigation supplies.

The Bhakra canal irrigation system, introduced some 40 years ago, has changed the quality and use of groundwater in this area. Where groundwater quality is suitable for irrigation, there has been extensive groundwater use, resulting in falling water tables over a large area. In contrast, groundwater extraction has been less than recharge in the brackish/saline belt of the system. In these areas, the rate of water table rise has been noticed at 0.3–1.0 m per year.

Hydronomically, the entire Bhakra canal contains a Regulated Recapture Zone and Stagnation Zones pertaining to areas of groundwater extraction, and groundwater rise (figure 5).

- **Regulated Rrecapture Zone with Groundwater Storage and Distribution and Negligible Pollution or Salinity Loading (RR with GWS and np/s).** At Bhakra, much of the area comes under a Regulated Recapture Zone with groundwater pumping. Groundwater is recharged primarily by surface drainage flows from irrigation. Use of groundwater where salinity is not a major concern is widespread. The aquifer could also be used for water storage, but is now considered primarily as a source of water supply. In this zone, typically groundwater tables are declining at a high rate.

- **Regulated Recapture Zone with Groundwater Storage and Distribution and Pollution or Salinity Loading. (RR with GWS and p/s)** The Regulated Recapture Zone also contains areas where salinity is a major concern. There is a considerable area, especially in Sirsa and Hirsa service circles with deep saline groundwater at depths greater than 20 m. In these areas, surface water has to be used carefully in order to prevent build up of saline groundwater.

- **Stagnation Zones (S).** Stagnation Zones are those areas that are poorly drained, and hence waterlogging and salinity is a major problem. Water management practices and technologies in these areas that limit the buildup of groundwater assume great significance in sustaining the productivity of this system. If well managed, it is possible to convert these Stagnation Zones into Regulated Recapture Zones. On the other hand, it is also possible for the Stagnation Zones to enlarge the threat to the sustainability of the region.

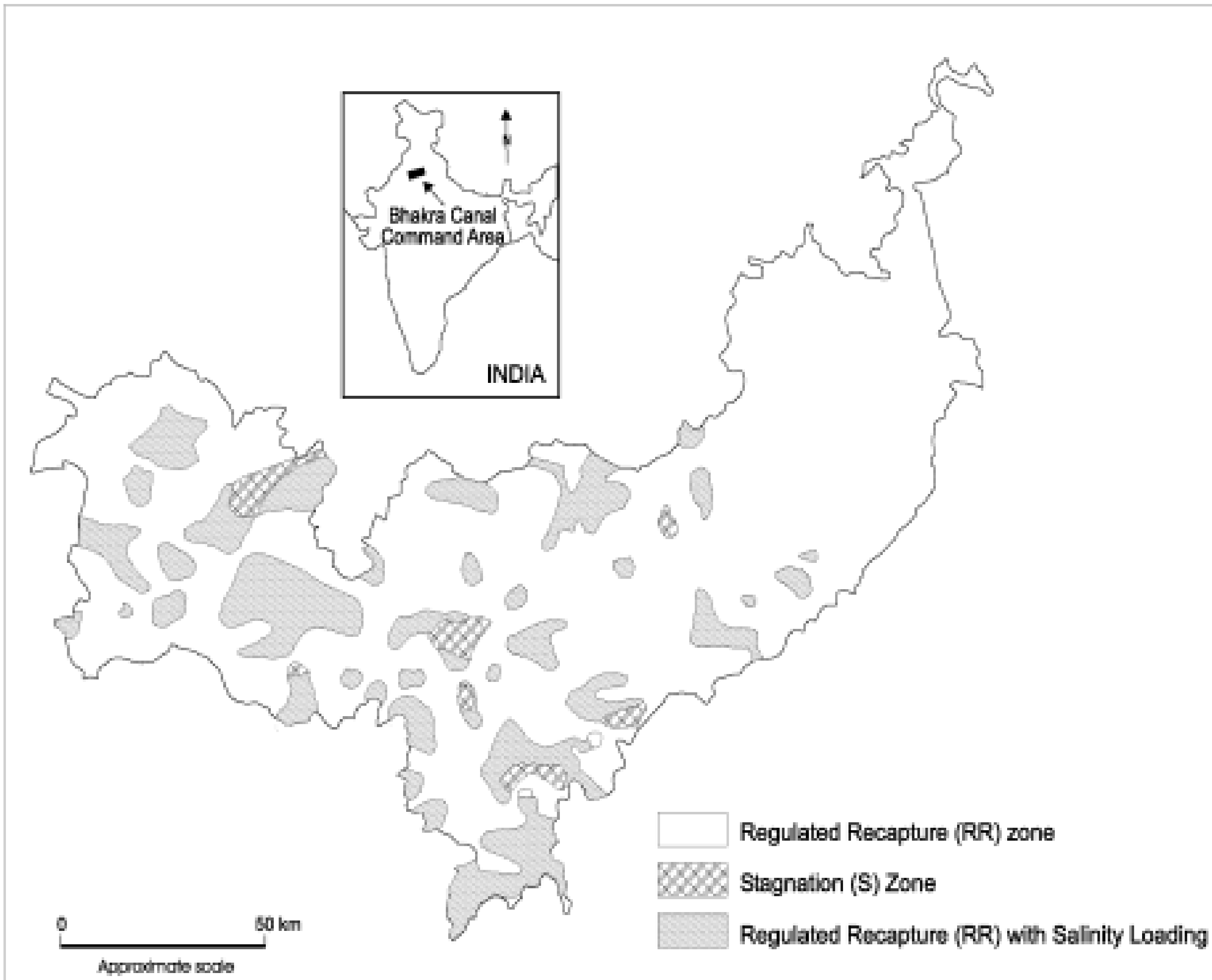
Water Management Strategies

Bhakra is basically a closed basin with all water allocated to various uses (Molden et al. 2000). There are opportunities and threats depending on the zone. Farmers are taking advantage of the opportunity provided by groundwater use resulting in productive and profitable agriculture. Unfortunately, it will be difficult to add substantially more supplies by water savings, although aggressive conservation measures can yield some water. The biggest opportunity lies in increasing the productivity of water in terms of increased agricultural output and increased economic benefit for every unit of water consumed.

The biggest challenge at Bhakra, in our view, is managing threats to sustainability. In

FIGURE 5.

Bhakra Canal Command Area.



the Regulated Recapture Zone with fresh groundwater, the biggest threat to sustainability is groundwater mining. Groundwater recharge by heavy monsoon rains is an option. Institutional solutions to regulate groundwater seem difficult to find, and difficult to implement. But an aggressive search for these solutions is warranted.

In the Regulated Rrecapture Zone with saline groundwater, the biggest concerns are managing salinity and preventing groundwater build up. An important approach is to minimize the mobilization of salts from deep aquifers, so as not to add more salts to reasonably good quality water. Water of marginal quality can be mixed with fresh water for irrigation, *if it is economical.*

There is a threat of growing areas of stagnation. In the Stagnation Zone, an important option is the addition of drainage. A second option is to limit the amount of canal water coming into this area, and improve the reliability of supply and farm management practices where deep percolation is limited.

Gediz Basin

The Gediz Basin in Western Turkey has a typical Mediterranean climate, hot, dry summers and cool winters (see IWMI and GDRS 2000 for a detailed description of the basin). The Gediz river has a length of about 275 km, drains an area of 17,700 km² and flows from east to west into the Aegean Sea just north of Izmir. Mean annual precipitation in the basin ranges from almost 800 mm in the 2,300 m high mountains to below 500 mm near the Aegean coast. Temperatures range from –24 °C at high elevations in winter to over 40 °C in the interior plains in summer. The natural vegetation of the basin is mainly shrubland, maki (bay, myrtle, scrub oak and juniper trees, among others) and coniferous forest with large outcrops of barren limestone mountain.

The Gediz basin is an important agricultural basin, with irrigation as a main water use. Gediz river water serves irrigation, municipal and industrial uses. A wetland of about 15,000 ha lies at the tail end of the Gediz river. The basin can be divided into four distinct zones: Water Source Zone (WS); a Natural Recapture Zone (NR), a Regulated Recapture Zone (RR); and an Environmentally Sensitive (E) Zone (figure 6).

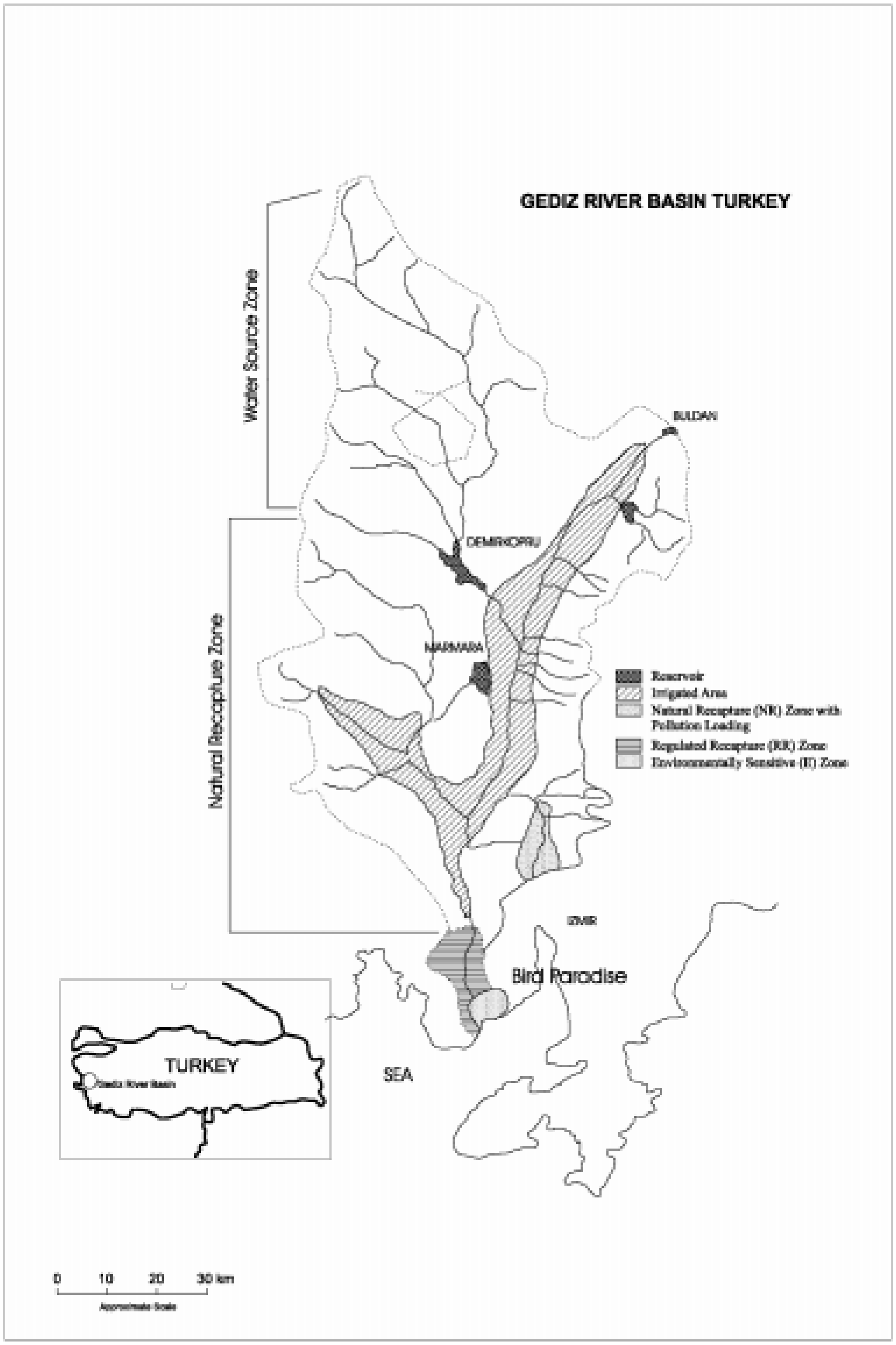
- **Water Source Zone (WS):** The Water Source Zone is situated upstream of the irrigated area in the Gediz basin. An analysis of the rainfall pattern in the basin indicates that the portion of the Gediz basin above the Demirköprü reservoir contributes most of the runoff to the basin because it has higher precipitation and lower evapotranspiration than the rest of the basin. The annual runoff cycle shows peaks in winter and spring, with flows decreasing over the summer and fall periods. The Demirköprü reservoir came into operation in the year 1970. Apart from the Demirköprü reservoir, and two smaller reservoirs on the Alasehir river, the major waterbody in the basin is Göl Marmara, a natural lake which is also fed by diversions from the Gediz and Kum rivers and used to store winter flows for the summer irrigation period.

  A comparison of the flow (maximum, minimum and mean) to the Demirköprü reservoir and flow at the outlet of Gediz basin indicates that much of the flow to the Gediz basin emanates upstream of the Demirköprü reservoir. There is very little contribution provided by the tributaries such as Alasehir (2,700 km²), Nif (1,100 km²) and Kum (3,200 km²) which are on the downstream side of the Demirköprü reservoir (IWMI and GDRS 2000).

- **Natural Recapture Zone with Groundwater Distribution (NR with GWD).** The whole of the Gediz valley situated between Demirköprü reservoir and Emiralem regulator is a Natural Recapture Zone interspersed with small Water Source Zones consisting of coniferous forest and maki cover. Agricultural land covers 62 percent of the valley, about half of which is irrigated. Irrigation water is diverted from the Demirköprü dam and Göl Marmara, a natural lake in the floor of the valley. Three diversion weirs or regulators were constructed on the Gediz downstream of Demirköprü and two additional dams built in the upper valley near Alasehir. The topography and drainage of the basin is such that all water re-entering the hydrologic cycle is directed back into the Gediz river, and water is reused at several locations.

FIGURE 6.

Gediz River Basin, Turkey.



Groundwater is an important source of water, increasing in importance after the drought of 1989–1994. Within the main valley there does not seem to be a problem with falling or rising groundwater from excess canal water. Many farmers use both canal water and groundwater, although somewhere between 30-40 percent of the total area appears to be irrigated solely by groundwater or pumping from drains and rivers.

- **Natural Recapture Zone with Groundwater Distribution and Pollution and Salinity Loading (NR with GWD and p/s).** The return flows from municipalities and villages are cause for concern because some of the water is polluted with human and other waste. The most rapidly urbanizing and industrializing area is in the upper Nif valley immediately east of Izmir. Many factories extract groundwater and then discharge polluted water back into the Gediz basin. The city of Manisa is also a rapidly expanding industrial area causing a lot of pollution in the Gediz basin. This condition of pollution loading affects uses within the area, and downstream uses of water.

- **Regulated Recapture Zone with Groundwater Distribution (RR with GWD):** The Meneman delta (below Emiralem regulator) is the closure area of the Gediz basin. This delta is fertile land supporting an irrigated area of roughly 23,000 ha. This is mostly cotton irrigated through right and left bank canal takeoff from Emiralem regulator. The upstream part of the delta is demarcated as a Regulated Recapture Zone because farmers use shallow groundwater, which is recharged primarily by irrigation, to augment supplies. The deep groundwater is saline, and is not used for agriculture. Most farmers growing vegetables and fruits feel they can no longer use canal water, and others complain of skin diseases and other problems as a direct result of contact with canal water. In this zone, drainage water takes either one of two paths. Water either drains to downstream wetlands or it re-enters the main river channel, where it is reused. There is very little drainage outflow in this area; thus no final use zone has been demarcated. Even the extreme tail-end farmers mix drain, canal and groundwater.

- **Environmentally Sensitive (E) Zone:** The Bird Paradise (14,900 ha) at the tail end of Gediz basin is one of nine wetlands in Turkey declared as a “Wetland of International Importance” under the convention of Ramsar by the Turkish Government, and is thus classified as an Environmentally Sensitive Zone. It is an important breeding or over-wintering area for many bird species such as flamingos, pelicans, herons and others. Protection of the Bird Paradise has become difficult as it is located at the end of the Gediz river and is therefore very sensitive to changes of land use or climate. In 1992, the water shortage in the Gediz river led to a drying up of significant areas of the wetland and the death of thousands of birds. Changes in upstream use in terms of quality and quantity affect this Environmentally Sensitive Zone.

Water Conservation Strategies

The Gediz basin is essentially closed, and there is only limited scope for real water savings. Most water savings opportunities have already been taken. The Regulated Recapture Zone has already extended through the Menemen plains reducing drainage outflows. Drip and sprinkler irrigation throughout the basin may yield some water savings by decreasing non-beneficial evaporation. These and other on-farm practices can result in increasing the productivity of water consumed by agriculture.

A constraint on improving the economic productivity of water is the pollution emanating from the pollution loading in a Natural Recapture Zone, which adversely affects downstream users by limiting crop choice and causing a health hazard. Basin management strategies need to address this issue to solve this major problem.

There are threats, besides pollution loading, that would decrease the overall productivity of water in the basin. Groundwater use has increased to levels that may not be sustainable, although this is not yet clear. Increased upstream use and degraded quality affect the downstream bird sanctuary.

Lessons from Case Studies

The layout of zones often follows a *path* as depicted in figure 2. Water Source areas are in the upstream, followed by a Natural Recapture Zone. Near the coast there is a Regulated Recapture Zone, and lastly, a Final Use Zone. But this pattern is not always the case as seen in the Bhakra example. This subbasin consists of Regulated Recapture Zones interspersed with Stagnation Zones. With more applications, more patterns will be found.

The zones are not a fixed physical feature of the landscape. They are dependent both on landscape characteristics, and on infrastructure and management practices. For example, *provision of drainage* can remove a Stagnation Zone. Thus, Stagnation Zones can grow or shrink. An interesting interplay is between the Regulated Recapture Zone and the Final Use Zone. Kirindi Oya has a fairly wide Final Use Zone relative to the total area. At the other extreme, we did not identify a clear Final Use Zone within Gediz. Farmers of Gediz practice some sort of reuse, either by pumping drainage water or groundwater, right up to the last piece of irrigated land next to the sea. They follow a sound conservation strategy of reducing the Final Use Zone, and increasing the Regulated Recapture Zone. *This leads us to conclude that the interfaces between zones are not permanent but vary with management approaches and degree of scarcity. In the case of Gediz, the Final Use Zone is completely eliminated and with still further stresses, the Regulated Recapture Zone may even move upstream to impinge on the Naturally Recaptured Zone.*

Excepting Bhakra, opportunities for saving water are most obvious in the downstream end of basin at the Closure Management Area consisting of the Regulated Recapture and Final Use Zones. The strategy is to reduce drainage outflows to an acceptable environmental limit. To do so requires a combination of reuse within the Regulated Recapture Zone, and high Classical Efficiency improvements in the Final Use Zone. In other areas, saving strategies are focused on reducing pollution loading, and reducing non-beneficial evaporation.

Hydronomic zones also lay out threats. Often times, the scope for water savings is small as in the case of Egypt's Nile, the Bhakra subbasin, and the Gediz basin. In these closed and closing basins, management efforts should be focused on these threats. Salt-loading at the lower end of the Nile and within Bhakra is a major threat. Groundwater overdraft exists at Bhakra and possibly within Gediz. There is considerable pollution loading in Egypt and the Gediz basin, posing a threat to the productivity of agriculture and other water uses.

Discussion

Understanding the dynamics of water use in a water basin at first seems a formidable task. Superimposed on the natural hydrologic system are human-made structures altering the course of *flow paths* for our use. People, influenced by culture, politics, and other diverse incentives, operate these structures, resulting in flows of water that are often different from original intentions. Over time population grows, and the needs of people change, resulting in an ever changing set of water relationships within a basin. Over time we are continually adjusting and looking for ways to manage water better. Given all these complexities, how do we conceptualize, form, and describe options for improvement within a basin?

Hydronomic zones and water accounting are methodologies that try to simplify complex relationships to help us understand the present situation of water use, the changes in how water is being used, and to visualize how changes may affect the performance in basin-wide water use. They are first approximation tools to help us quickly obtain an initial grasp of basin behavior. They allow the identification of issues that must be further probed. They provide contextual information about the basin, within which we can further study the complexities of water use.

Conceptualizing basin water use with the aid of hydronomic zones holds promise for several applications. For many water-related activities, it is not necessary to completely understand the dynamics and interactions within the entire basin. Conservation options and performance considerations are related to the zone rather than the entire basin. This has the potential to save considerable time and effort in basin analysis.

As a first approximation tool, hydronomic zones have limitations. They do not provide the resolution needed for more detailed performance assessment or design of solutions. They are only meant to give an overview and to help our initial thinking. The divisions between zones may not be so sharp, or even if there are sharp division lines between zones, they may be difficult to map out precisely. Thus, maps drawn with zones should be used as rough guidelines, rather than precise zoning tools. *With the development of basin water resources the locations of interfaces between zones can also shift.*

Detailed analyses are carried out many times in one part of a basin and focus on one aspect of water resource use. For example, studies are carried out to find out how to increase application or irrigation system efficiency, or how to reduce demand for water by increased pricing. When promising solutions are found, the reaction is to apply these to all locations in a basin. This is often done without consideration of whether solutions are appropriate to various parts of a basin, or how these solutions scale up to the basin. For example, the most common error is to assume that improvements in application efficiency of water will save enormous quantities of water. Technologies to increase application efficiency combined with increased water pricing, and a demand management response, are indeed likely to reduce applications of water to fields and deliveries of water within an irrigation system. These changes come at a cost, and are not necessarily easy to implement through existing institutions. Are they worth it? In Final Use Zones, or where pollution is a concern in closing and closed basins, there is likely to be large gains in benefits when transferable water savings are achieved, and more productive use of water is realized. In Regulated Recapture and Natural Recapture Zones, the result of demand management interventions may simply be to alter the course of water at an additional cost, with benefits remaining constant. The role of hydronomic zones would be to give an initial indication of where these demand management interventions are most appropriate, or to help prioritize areas where interventions would lead to the most benefits.

Hydronomic Zones can be useful in dealing with the problem of spatial scales. We are often most interested in working at one scale— for example, an irrigated field, or a domestic water supply system. Yet we hope that the actions we take at this scale, when replicated, will have broader consequence on basin water resources. When scaled-up, results are often not as anticipated because of reuse of drainage outflows or solutions that apply in one part of the basin are not appropriate for another part. Hydronomic Zones can at least help us to define solutions that are applicable to similar areas. This is much like the concept of agro-ecosystems, where solutions are found for particular agro-ecosystems so that they can be replicated in other areas within the agro-ecosystem.

There are many other tools that help in exploring options for improved water use, including economic and hydrologic simulation and optimization models. There seems to be synergy between these approaches. Models are capable of providing much more resolution and more accuracy in predicting what may happen under various scenarios. Various scenarios can be conceptualized with the aid of hydronomic zones and then further tested through modeling. Alternatively, solutions given by modeling results can be checked for logic using the concepts of hydronomic zones.

Hydronomic zones can play an important role in characterizing water basins. When making decisions that affect basin-wide water use, it is increasingly common to involve stakeholders in discussions. This zoning could be an effective tool in facilitating discussions between people from various backgrounds. It is important to describe key differences in the hydrology and use of water within basins and it is important to know how potential changes may affect users.

Summary and Conclusions

A set of hydronomic zones are defined to characterize the combination of hydrologic and water use settings within a basin. The zones are based primarily on considerations of outflow of water from the particular areas. Generic strategies for improving the productivity of water use were identified for each water management zone. Water Source and Environmentally Sensitive Zones were discussed in far less detail, and need to be addressed later through research. They are kept here as reference points in that they need to be recognized and considered when developing basin management strategies.

Zoning was applied to four basins or major parts of basins with diverse characteristics. We were able to somewhat rapidly sketch the zones within the basins and draw some statements about considerations within each zone, and possible water management strategies that must be considered by zone. These four cases provide examples, and demonstrate that the methodology can cover a wide variety of situations.

There are several potential uses of hydronomic zones:

- providing a quick overall characterization of how water is used in a basin, and providing an overview of special considerations
- dividing a river basin into areas where there are distinctly different water management considerations
- interpretation of water balance performance measures
- conceptualization of strategies to improve water management
- isolation of areas with like problems, so that the entire basin does not have to be considered in detail
- development of solutions for specific hydronomic zones, so that these solutions can be extended to like hydronomic zones in other areas
- providing information for use in stakeholder discussions for people from diverse backgrounds

Zoning and classification are common and useful practices in many fields, including agriculture and water resources. We feel that this type of zoning is a novel, yet useful approach, to help in conceptualizing how water is used in a basin, and to help in developing improved water management practices. Over time and with further examples, we expect that this method will evolve and find several applications.

Appendix

Conservation Measures to Increase Classical Efficiency or Process Fraction

In general the conservation measures that are addressed in formulating a water management plan are designed to increase the Available Water (AW), decrease non-beneficial evaporative depletions or increase the local or Mezzo Efficiencies: CE (Classical Efficiency) or PF (Process Fraction)[6]. In designing conservation measures through CE or PF, they can be organized in relation to the flow paths implicit in the terms of CE or PF applied within or throughout each hydronomic zone. To increase CE, either the numerator must be increased proportionally more than the denominator is increased or the denominator must be decreased proportionally more than the numerator is decreased.

The flow paths and means for decreasing (or increasing) them to improve or increase CE are as follows:

1. Evaporation (decrease)
   a. Deficit irrigation
      i. Reducing frequency
      ii. Reducing depth of irrigation
   b. Drip irrigation (to reduce surface area wetted)
   c. Sprinkle irrigate at night and/or during low wind periods
   d. Mulching

2. Crop transpiration (decrease or increase)
   a. Planting at a different date when the potential ET is less
   b. Using a shorter season variety
   c. Crop substitution with a crop having a lower ETa

3. Canal seepage/leakage (decrease)
   a. Lining
   b. Maintenance
   c. Rotation instead of continuos flow

4. Operational spillage (decrease)
   a. Canal interceptor systems
   b. Off-canal regulating reservoirs
   c. Better match between supply and demand
      i. Improved scheduling
      ii. Enhanced communications
      iii. Improved flow calibration and management
      iv. Canal automation

5. Deep percolation (decrease)
   a. Improved distribution uniformity
      i. Precision leveling
      ii. Shorter furrow or graded border lengths
      iii. Sprinkle or trickle irrigation on high infiltration rate soils
   b. Deficit irrigation
      i. Reduced irrigation frequency (increase soil water depletion between irrigations)
      ii. Reduced depth of irrigation
   c. Grow deeper rooted crops

6. Surface water runoff (decrease)
   a. Tailwater recovery systems for furrow and graded border irrigation
   b. Shorten furrow or graded border lengths
   c. Replace furrow and graded border irrigation with
      i. Level basin irrigation
      ii. Sprinkle irrigation
      iii. Trickle irrigation

[6]The amount of water depleted by agricultural, industrial or municipal processes divided by rain and other inflows to the domain. For agriculture at field level. This is - ETa/(Rain + Div).

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