# 3 The Concept of Efficiency in Water-resources Management and Policy

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> All science depends on its concepts. These are the ideas which receive names. They determine the questions one asks, and the answers one gets. They are more fundamental than the theories which are stated in terms of them.
>
> (Sir G. Thompson)

> Let not even a small quantity of water that comes from the rain go to the sea without being made useful to man.
>
> (King Parakramabahu of Sri Lanka (AD 1153–1186))

## Introduction

Many areas of the world are experiencing increasingly severe water scarcity. Recent studies by the International Water Management Institute (IWMI) indicate that one-third of the population of developing countries lives in regions that have absolute water scarcity, in the sense that they do not have sufficient water resources to meet their agricultural, domestic, industrial and environmental needs in the year 2025 (Seckler *et al.*, 1998a,b). An additional 500 million people live in regions of severe economic scarcity; they have a sufficient amount of potential water resources to meet their 2025 needs, but will have to more than double the present utilization of these resources, through large, expensive and possibly environmentally destructive development projects to achieve reasonable amounts of water consumption.

One of the ways of alleviating water scarcity is by increasing the efficiency of water use. Many different ways of increasing water-use efficiency are proposed, ranging from water-saver flushing toilets and low-flow drip-irrigation systems to pricing water to encourage demand reduction and adaptation of water-saving technologies. Indeed, it is sometimes contended that the current efficiency of water use is so low, especially in irrigation, that most, if not all, of future water needs could be met by increased efficiency alone, without development of additional water supplies.

While the potential for saving water through increased efficiency is substantial, it is not as large as might be thought. The reason is that the most commonly used concepts of water-use efficiency systematically underestimate the true efficiency of existing systems by a very large amount. One of the cardinal

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features of water use is that, when water is used, not all of it is 'used up'. Most of the water remains in the hydrological system, where it is available for reuse or recycling. As water is recycled through the hydrological system, the efficiency of use increases. Thus, while every part of the system may be at low levels of water-use efficiency, the system as a whole can be at high levels of efficiency.

This 'water-efficiency paradox', as it may be called, constitutes the core of this discussion. It is shown how the older, 'classical' concept of efficiency ignored recycling and thus underestimated efficiency. The newer 'neoclassical' concepts represent attempts to integrate water recycling into the concept of water-use efficiency. These conceptual changes have important implications for water-resources management and policy. The classical concept of efficiency often leads to erroneous policies and management systems; the neoclassical concepts point in more effective directions for increasing water-use efficiency. As Willardson *et al.* (1994) rightly observe in the field of irrigation:

> Unless the ideas now associated with irrigation efficiency terms are modified, it will be extremely difficult to properly manage the shrinking supply of freshwater due to the misconceptions and misunderstandings of irrigation efficiency by the engineering, political, and news communities. Yet, much current irrigation literature contains many recommendations to increase irrigation efficiencies in order to create more available water. The economic damage and waste of limited resource management funds caused by such articles and misconceptions are very large.

Indeed, as explained below, these authors and others recommend purging the 'E' word from the literature on irrigation altogether! While we have a good deal of sympathy with this recommendation, we show that the same concept as 'efficiency' is absolutely necessary and, to paraphrase, a rose by any other name remains a rose all the same.

In this chapter, we trace the evolution of the concept of efficiency mainly in the field of irrigation. Irrigation is chosen as the focus because: (i) over 70% of the world's developed water supplies are diverted for irrigation and, therefore, it is especially important to get these concepts right in this field; and (ii) so far as we know, these concepts have been studied more intensely in the field of irrigation than in other areas of water resources. There is a vast and complex literature on the subject of irrigation efficiency. In our opinion, the best comprehensive account of this subject is that of Jensen (1980). In this chapter, we ignore most of the complications and refinement of the subject in order to focus on what we consider to be the central issues pertaining to water-resources policy and management.

## The Classical Concept of Irrigation Efficiency

Before the concept of irrigation efficiency was invented, engineers used the irrigation duty to design irrigation systems. The duty is the amount of water that needs to be diverted from a source and applied to the root zone of crops 'to bring the crop to maturity'. (Willardson *et al.*, 1994). The duty is expressed as, say, 0.5 m of depth of water applied per hectare per crop season, or so much per 10-day interval, etc. The irrigation duty is essential for designing the physical structure of water storage and conveyance systems. But there are two problems with irrigation duty. First, it is a rule of thumb, without a clear rationale. Secondly, because of this, it does not indicate whether one is irrigating more or less well. These problems gave rise to the concept of irrigation efficiency.

A major breakthrough was to refine the objective of irrigation in terms of meeting the actual evapotranspiration requirements of crops, or Eta. Once Eta was defined after generations of research, the door opened to the concept of efficiency. Israelsen (1932) is generally credited with rationalizing the duty of irrigation (Willardson *et al.*, 1994) by developing what Keller and Keller (1995) aptly call the 'classical' concept of irrigation efficiency. Israelsen's definition is a direct application of the basic concept of engineering efficiency to the field of irrigation: 'an output divided by an input, both of the same character' (Willardson *et al.*, 1994). Stated simply in contemporary terms, the primary output of irrigation is the amount of water needed to satisfy the crop water requirements (although there are many other uses of irrigation water (noted below)). The crop water requirements are defined here as the Eta requirements of the crop, minus effective precipitation (Pe), (the amount of water that enters the root zone of the crop). This is called net evapotranspiration (NET) (Keller *et al.*, 1996):

$$NET = Eta - Pe \qquad (3.1)$$

The input is defined as the amount of water withdrawn or diverted (DIV) from a specific surface-water or groundwater source to achieve NET. Thus classical irrigation efficiency (CE) can be defined as:

$$CE = NET/DIV \qquad (3.1a)$$

For example, at the field level, in terms of metres of depth per unit of area:

$Eta = 1.0$
$Pe = 0.2$
$NET = 0.8$
$DIV = 2.0$
$CE = 0.8/2.0 = 40\%$

Thus, while the duty may be 2.0 m of water, this implies only 40% irrigation efficiency: 60% of the water diverted is not necessary to meet the crop requirement. Put another way, the degree of inefficiency of irrigation in this case is the complement of CE: $(1 - CE = 1 - 0.4 =)$ 60%.

It is commonly said that the water that is not used to satisfy NET is 'wasted' or 'lost'. While this is true from the point of view of meeting the direct objective of satisfying NET, these phrases are a source of endless confusion in the field of water resources. As explained in detail below, only some of this water is truly lost from the hydrological system. Most of it is captured and recycled somewhere else in the system.

In irrigation, there are essentially three sources of classical inefficiency, or putative water 'losses':

- Evaporation from the surfaces of land, water and plants that do not contribute to crop Eta. This includes 'non-beneficial evapotranspiration' by weeds, phreatophytes and other non-beneficial grasses, trees and bushes. However, these uses of water may be of great value in terms of objectives other than irrigation.
- Drainage losses are surface and subsurface losses in the process of delivering the water from the point of diversion to the root zone of crops: leakage from the conveyance system, deep percolation below the root zone of crops and surface drainage from the fields.
- Spillage losses due to mismatches between water supply and demand. When there is more water supplied than demand – for example, irrigation water flowing in canals during heavy rain – the surplus water is spilled into drains.

As discussed further below, the only real water losses to the hydrological system, however, are those from evaporation and flows to 'sinks', such as saline seas. Drainage, spillage and other water flows are losses only in so far as they flow to sinks.

Three important points should be made about the classical concept of irrigation efficiency before proceeding:

**1.** CE is defined at different scales, in terms of differences between the point of water diversion and the ultimate destination of the water in the root zone of crops (or Eta) (Bos and Nugteren, 1974; Jensen, 1980).

- Application efficiency (Ae) is the ratio of water delivered to the root zone to water delivered to the field.
- Conveyance efficiency (Ec) is the ratio of water delivered to the field to water delivered into the canal from the source.
- Project efficiency (PE) is the overall efficiency of the system, which is also equal to classical efficiency (application efficiency × conveyance efficiency)

For example:

$Ae = 0.5$
$Ec = 0.8$
$PE = Ae \times Ec = 0.40$

Thus, CE decreases as the scale of the system increases.

**2.** As intimated in the discussion of 'non-beneficial evapotranspiration', the output is not as easy to define as may first appear. Even in the apparently simple case of satisfying Eta, the question of the amount of Eta to be satisfied arises. In cases of water shortage, for example, it may be optimal to practise deficit irrigation, providing less than full Eta to a particular crop area and suffering reduced yields, so that water can be supplied to a greater area (Perry and Narayanamurthy, 1998). Also, irrigation water has multiple uses; in addition to Eta, it is used for moistening land for cultivation and for weed control in paddy irrigation. Because of these optimization and multiple-use complications, some proponents of the concept of CE recommend calling it irrigation 'sagacity' instead (Burt *et al.*, 1997).

**3.** As noted before, CE ignores the possibility of recycling water 'losses' within the hydrological system. This is the subject of the second part of this discussion.

The concept of CE is used in two important ways. First, it is used as a tool in the design of irrigation and other water-delivery systems. In this example, NET divided by CE (0.8/0.4) is equal to the amount of water (2.0 m) that has to be diverted from the source to satisfy the objective at the destination. Thus, in designing water-delivery systems, engineers explicitly assume a value for CE to size the conveyance system. Secondly, CE is used as a criterion of engineering efficiency. It is generally assumed that the higher the CE the better.

The same concept of engineering efficiency is used in other water sectors. For example, if the objective is to deliver 1 $m^3$ of water $day^{-1}$ to a household, but 20% of the water is lost in transit because of leakages in the delivery system, the efficiency is 80%. Or, inside the household, if the tap is left on while brushing one's teeth, the (tap to tooth) efficiency may only be 10% because only 10% of the water is beneficially used to meet the objective in this application. The overall efficiency of the domestic water system in this case is only $(0.8 \times 0.1 =)$ 8.0%. However, as in irrigation, most of the 92% of the water that represents the inefficiency of household use is not lost to the system as a whole but is captured and recycled.

### Influence of classical efficiency

Notwithstanding the problems of the concept of CE it has had enormous influence both within the irrigation profession and in the wider fields of irrigation and water-resources policy and management.

Generations of irrigation engineers have devoted their lives to improving the efficiency of irrigation. Below are some characteristic CEs of various irrigation systems at the farm level (Merriam, 1980; Wolters and Bos, 1990).

**1.** Conventional gravity = 30–50% (the lower range is mainly in paddy irrigation, to flooded fields).
**2.** Level basin = 40–70% (the high value is achieved with laser-beam levelling).
**3.** Sprinkler = 60–75%.
**4.** Drip = 80–90%.

Since conventional-gravity systems probably comprise 80% or more of the total irrigation systems in the world, shifting from gravity to more efficient forms of irrigation could, theoretically, nearly double the average CE.

This line of thought leads to important effects of Israelsen's (1932) concept outside the irrigation profession. As the concept of irrigation efficiency spread into the realm of water-resources planning, management and policy analysis, it became a commonly accepted fact that irrigation is so inefficient that enormous amounts of water being 'lost' in irrigation could be 'saved' through improved technology and management, and these savings could be used to meet most of the future demands for water by all of the sectors. However, there is a fundamental error in this interpretation of CE, which has led to major mistakes in thinking about irrigation policy and management. Various attempts to solve this error led to the neoclassical revolution in the concept of irrigation efficiency.

## The Neoclassical Concept of Irrigation Efficiency

The neoclassical concept of irrigation efficiency developed as a consequence of the evolution of interest in irrigation from the point of view of water-delivery systems to the broader perspective of irrigation management and policy within the context of water resources as a whole, in the entire river basin. It soon became clear that from this perspective the concept of CE was erroneous and misleading. The reason is that the water 'losses' of CE are not necessarily 'real' water losses to the system as a whole – many of these losses are only paper losses – because they are captured and recycled elsewhere in the system. While this problem has probably been in the back of people's heads for a long time (as shown below, it is intimately related to King Parakramabahu's declaration used as an epigraph for this chapter), Wright (1964), Bagley (1965) and Jensen (1967) are the first published references we know that discuss this problem clearly and explicitly. The fact of water recycling set up a 'problem situation', as the philosopher Karl R. Popper (1962) describes it, which evolved through a process of articulation and refinement (or, in Popper's classic phrase, 'conjectures and refutations') to what we call the neoclassical concept of irrigation efficiency.

## Net efficiency

This problem was first formally addressed (so far as we know) by Jensen (1977), who proposed revising CE to 'net efficiency' (NE):

$$NE = CE + Er\,(1 - CE) \qquad (3.2)$$

where:

CE = classical efficiency (Equation 3.1);
1 − CE = classical inefficiency, i.e. the percentage of the diverted water that is not used to meet the Eta requirements of crops;
Er = the percentage of 1 − CE that is potentially available for recovery, reuse or recycling somewhere in the hydrological system.

Thus, as in the discussion of CE, if 40% of the diversion leaves the system in the form of evapotranspiration and 70% of the remainder is potentially available for reuse, then:

$$NE = 0.40 + 0.7(0.6) = 0.40 + 0.42 = 0.82 \qquad (3.2a)$$

Thus, with the same basic parameters, NE is more than twice as high as CE!

Jensen's NE clearly shows the trade-off possibilities between CE in the first term of the equation, and what may be called the 'recycling efficiency' in the second term. For example, assume that it is decided to shift from a surface-irrigation system with a CE of 40% to a sprinkler-irrigation system with a CE of 70% then, following Equation 3.2a, the NE of the sprinkler system is:

$$NE = 0.70 + 0.70(0.30) = 91\% \qquad (3.2b)$$

In the shift to sprinkler irrigation, CE increases by (0.70/0.40) − 1 = 75%, but NE increases by only (0.91/0.82) − 1 = 11%. While it might pay to invest in sprinkler irrigation to save water in the first case, it might not pay in the second case – even though the basic water situation is the same in the two cases.

By 1980, with the publication of the state-of-the-art work, *Design and Operation of Farm Irrigation Systems* (Jensen, 1980), NE (or 'effective irrigation efficiency', as it was also called) was the recommended practice. In this volume, Burman *et al.* (1980, p. 220) note that: 'Effective irrigation efficiency … of a farm, project, or river basin is necessary to estimate or evaluate the *net depletion of water within a river basin* or groundwater system' (writers' italics).

As this discussion proceeds, it will become clear how prescient the statement in italics turned out to be. We shall continue calling Jensen's formulation NE reserving effective efficiency for a later formulation of efficiency within the neoclassical framework discussed in the next section.

A particularly interesting consequence of these neoclassical concepts may be mentioned. It was noted before that CE decreases as the scale or boundary conditions of the system increase, because of increasing water losses. But, in NE or other neoclassical formulations, the opposite is the case: as the scale increases the efficiency generally increases, because of increased water recycling. For example, as discussed further below, studies of the Nile irrigation system in Egypt show that the average CE of irrigation is about 50% but a series of estimations of the neoclassical efficiency of irrigation in the system as a whole has resulted in the latest estimate of 87% (Abu-Zeid and Seckler, 1992; Keller, 1992; Molden *et al.*, 1998).

### Effective efficiency

Keller and Keller (1995) developed the concept of effective efficiency (EE), as they called it (see also Keller *et al.*, 1996):[2]

$$EE = NET / I - O(R) \qquad (3.3)$$

where, with the same illustrative quantities as in Equation 3.2:

I = inflows of water from the point of diversion = DIV (= 2.0 m)
NET = 0.8 m
Enb = non-beneficial evaporation = 0.1 m
O = outflows of water from the application = I − (NET + Enb) = 2.0 − 0.9 = 1.1 m
R = the percentage of reusable outflow = 70%
$EE = 0.8/\{2.0 - 1.1(0.7)\} = 0.8/(2.0 - 0.77) = 0.8/1.23 = 65\%$

The Kellers also incorporate a highly ingenious means of employing pollution (mainly salinity) effects in EE. In brief, they subtract from the outflow the amount of water it would require to dilute to an acceptable level any pollution picked up in the use of the water. This concept pushes the concept of purely physical water efficiency about as far as it is possible to go. Clearly the (negative) value of pollution in the outflow depends on where and how it is reused – for example, rice is more tolerant of salinity than most other crops. But this is a generic problem in the concept of physical efficiency, as noted below, and, within the confines of this concept, it is a major contribution to the theory.

While the NE and EE formulations naturally yield somewhat different values, their substance is clearly the same.

### Fractions

A third development in the concept of efficiency is the introduction of 'fractions' to replace concepts of efficiency. As noted before, Willardson *et al.* (1994) extended their critique of the misapplications of (classical) efficiency, quoted above, to the point where they advocated eliminating the word and the concept of efficiency altogether. Instead, they proposed using various fractions in water-resources analysis – especially the consumed fraction (CF) – the ratio of evaporation to the diversion in any given process, such as irrigation.

Since the fractions approach is not, by definition, an efficiency concept, only a few observations will be made about it here. The CF is meant to be used in the context of the water balance of the hydrological system, as discussed in the section on 'Basin Efficiency: the Rate of Beneficial Utilization of Water Resources,' and does not imply a judgement as to whether the water is beneficially consumed or not. For example, in irrigation, the water consumed by both evapotranspiration and Enb is included in CF. Thus, a large CF is no better or worse than a small CF. For this reason, the CF must be considered along with the value of the components of CF, to determine a desirable course of action. This problem is addressed by the use of the term process fraction – i.e. the fraction used by humans for municipal, industrial and agricultural purposes. While the process fraction separates the intended uses from the CF, it does not account for other beneficial uses, such as use by trees, forests and wetlands. CF includes process fraction, non-process fraction and non-beneficial fraction. The excellent discussion of specific water problems in the text of Willardson *et al.* (1994)

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[2] This is the same as the Er term used in net efficiency. While the R term was not explicitly used by Keller and Keller (1995) in the original equation for EE, it is clearly implied in the text.

necessarily relies on an implicit evaluation of the CF. The fractions approach has been used in Perry (1996) and Molden (1997) in the context of water productivity, as discussed in the section on 'Basin Efficiency: the Rate of Beneficial Utilization of Water Resources.'

## Concluding Observations on the Classical and Neoclassical Concepts of Efficiency

Four important observations should be made before closing the discussion of classical and neoclassical efficiency up to this point.

First, the neoclassical formulations of efficiency are clearly superior in that they include CE only as special cases, where in NE or EE, respectively, Er or R is equal to zero (or is negative). Some of the most important examples of these special cases are as follows:

- Where irrigation is in saline areas and the outflows are too saline to be recycled.
- Where irrigation, or other uses of water, occur next to saline seas, where excess outflows are discharged directly into the sea.
- Where severe mismatches between water supply and demand occur in terms of specific times and places. While the outflows are still in the system, they may be at the wrong place at the wrong time.
- Where, especially in desert areas, outflows go to shallow lakes, where the water is evaporated with little, if any, benefit.

In all of these cases, high CE is called for; but the neoclassical formulations cover these cases as well as all the other cases where the outflows are beneficially recycled.

Secondly, the equation used for CE has an important role to play in the design and management of water-delivery systems, while the neoclassical equations are irrelevant for this purpose. It is best not to use the word 'efficiency' to describe the classical equation, but rather to use another term, such as the 'delivery ratio', as Bos (1997) recommends.

Thirdly, in all the definitions of efficiency up to this point, precipitation only enters the analysis as effective precipitation (Pe). The difference between total precipitation (P) and Pe (P − Pe) – the amount of 'ineffective precipitation', as it were – is lost; it simply vanishes from the system, much like the water 'losses' in CE. This is unacceptable in terms of the water balance of the hydrological system as a whole. Also, as Falkenmark *et al.* (1989) observe, it is important not to neglect 'green water' in concentrating on 'blue water' (diversions). While irrigationists do consider green water, in the form of Pe, in the formulation of NET, it is true that P − Pe is ignored. But irrigationists could reply that hydrologists (excepting Falkenmark *et al.*, 1989) are even worse, because to them 'effective precipitation' is only runoff, and the green water – which does not enter river drainages, but does support most plant life – is treated as a loss! This problem is addressed in the next section.

Fourthly, both the classical and neoclassical formulations of efficiency attempt to stay within the domain of purely physical flows of water, avoiding assignments of values to the flows and quantities of water. But this is an ultimately futile and misleading attempt. Whenever words like efficiency are used, value judgements are necessarily part of the underlying concept and it is best to use them explicitly. At the very least, a distinction must be made between the beneficial and non-beneficial (zero or negatively valued) aspects of water flows. In classical efficiency, this is not a major problem because it is clear that NET is beneficial evaporation. But it becomes a serious problem in the neoclassical formulations, where the outflows can have zero or negative effects – for example, in terms of waterlogging and salinity. Thus it is not just a matter of distinguishing between the amounts of depletion and non-depletion of water in the neoclassical formulations, but a matter of the values of the depletions. For this reason, it would be better to define the Er and O(R) terms of NE and EE as Eb and Ob, where 'b' indicates the amount of beneficial use. This subject leads directly to the concept of the beneficial utilization of water resources discussed in the next section.

## Basin Efficiency: the Rate of Beneficial Utilization of Water Resources

The discussion in this part of the chapter remains solidly in the neoclassical tradition. Both the classical and neoclassical concepts of efficiency followed a 'bottom-up' approach, as it were, from the perspective, first, of the individual farmer, through the project level, to intimations of the basin level of analysis. Here, we make the concept of basin efficiency clear and explicit within the overall concept of the beneficial utilization of water resources within river basins. Thus this discussion rather abruptly switches perspective by following a 'top-down' approach. It begins at the level of the river basin as a whole and then, once that is established, extends the analysis down through sub-basin levels to the water sectors, projects and users. In other words, this discussion proceeds from the macro- through the meso- to the micro-level of analysis, rather than in the opposite direction. This change in perspective is important because the whole can be different from the sum of its parts, due to scale and composition effects, and it is important to conduct the analysis of the part within the context of the whole (Keller *et al.*, 1996).

### River basins and beneficial depletion[3]

In this discussion, river basins are defined as including the offshore, coastal zone of brackish water formed by the mixture of water from the land and the saline water of external or internal seas and saline aquifers. Also, some basins are interconnected, either by natural or human-made flows, and interbasin transfers between basins must be included in the analysis.

The first and single most important thing to understand about river basins is that, with the exception of usually small and temporary increases of water storage within a river basin, all of the water that annually enters the basin through precipitation, including snow melt or interbasin transfers into the basin, is eventually depleted from the basin. It is depleted either by evaporation, including evapotranspiration, or by discharges to sinks, mainly to inland or external seas and to saline aquifers. Thus, at the river-basin level:

$$P + T - CS = E + S \tag{3.4}$$

where:

P = total precipitation
T = interbasin transfers (into the basin is positive)
CS = changes in storage in the basin (increase in storage is positive)
E = total evaporation
S = flows to sinks

Since, with the exception of increased CS, all of the water in the basin is depleted, the ultimate question in addressing the utilization of water is not whether the water is depleted or not, but whether it is beneficially depleted or not. The total beneficial depletion (Db) of water in a river basin is:

$$Db = Eb + Sb \tag{3.4a}$$

where Sb = beneficial flows to sinks.

Eb occurs in such areas as evapotranspiration of valued plants and the perspiration and respiration of animals and in cooling facilities. Some discharges to sinks are also beneficial – for example, in maintaining coastal zones, river flows for navigation, fishing and, in the case of saline aquifers, preventing seawater intrusion. The important aspect of sinks is that, while the water may serve a valuable function in the sink, it is not available for other uses outside the sink.

Non-beneficial depletion through evaporation or discharges to sinks may have either a zero or a negative value. Discharges to seas may have a zero value in water-surplus periods, for example; while discharges to saline aquifers may cause water tables to rise, reducing crop productivity through waterlogging and salinity and polluting domestic water supplies.

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[3] For a technical discussion of the material in this section in the context of water accounting, see Molden and Sakthivadivel (1999).

Clearly, it is impossible to 'add up' the sum of the beneficial and non-beneficial uses of water without knowing their exact, positive and negative, values. This fact makes the concept of beneficial utilization an intrinsically qualitative, rather than a quantitative, concept. But it is interesting and important to know, for example, what proportion of the water is being beneficially utilized, even if one does not know the absolute value of beneficial utilization or its net beneficial utilization. For example, if around 87% of the water resources of Egypt are being beneficially utilized, one knows immediately that it will be difficult to increase beneficial use in one area without decreasing it in other areas somewhere else in the system. On the other hand, if only 50% of the water is being beneficially utilized, as is commonly thought of Egypt, then there is large scope for increased beneficial utilization.

## Available water supply

Not all of the annual precipitation that enters a basin is available for beneficial use within the basin. The available water supply (AWS) at the basin level is defined as:

$$\text{AWS} = (\text{P} + \text{T} - \text{CS}) - \text{N} \tag{3.5}$$

where, with P, T and CS as defined in Equation 3.4:

N = non-utilizable water supply, as in discharges of floodwater to sinks.

This term can be defined either as actual N, with existing storage and conveyance facilities, or potential N, with all technically and economically possible water-development facilities.

At the sub-basin level (sb), the AWS term needs to be adjusted by: (i) replacing T by diversions (DIV) from other areas within the basin to the particular area under consideration; and (ii) including committed outflows (C) to other areas from the area under consideration, such as legally or conventionally committed outflows from upper to lower riparian states, or between other subunits within a basin (Molden, 1997):

$$\text{AWS (sb)} = [(\text{P} + \text{DIV}) - \text{CS}] - (\text{N} + \text{C}) \tag{3.5a}$$

It could be objected that it is wrong to use total precipitation, including ineffective precipitation (P − Pe), in the definition of irrigation efficiency at the sub-basin level – that this is a 'free' good and that what we want to optimize is diversions, not AWS. But we believe that this traditional approach is mistaken. First, in irrigation, ineffective precipitation can be a partial substitute for diversions by investing in better land- and water-management techniques, such as bunding, field levelling and the like. In other areas, rainwater-collecting devices can serve domestic needs. Secondly, under conditions of water scarcity, there is no free good; water used in one place has an opportunity cost in terms of the value of its use in another place within the system. The concepts of efficiency and productivity need to reflect the values of all the uses and alternative uses within the system.

There is also an important distinction between the amount of AWS that is actually available at a given point in time, with existing water-storage and control facilities, and the amount of AWS that is potentially available in the future with additional facilities. As noted before, this distinction is reflected in the term for non-utilizable supply (N), which is a variable depending on the storage and control facilities up to the ultimate potential AWS at each level.

The basin efficiency (BE) of water resources can now be defined in terms of the ratio of the beneficial utilization of water to AWS at either the basin level or the sub-basin level:

$$\text{BE} = (\text{Eb} + \text{Sb})/\text{AWS} \tag{3.6}$$

BE can be considered in terms of actual AWS, or potential AWS, resulting in either BE (a) or BE (p). At the sub-basin level, the AWS term is replaced by AWS (sb) and the resulting equation is called sub-basin efficiency, BE (sb). Also, if one wished to avoid the nomenclature of efficiency, this equation could be described as the rate of beneficial utilization of water resources (RBU) at the basin and sub-basin levels of analysis.

## Types of river basins

River basins can be classified according to the amount of uncommitted discharges to sinks of potentially utilizable water in the dry, low-flow season. For short, we shall call this the discharges of usable water in the dry season.

- An open basin has outflows of usable water in the dry season. In open basins, more water storage could be developed in the dry season and beneficially depleted upstream without diminishing existing uses; in other words, the opportunity cost of additional dry-season depletion is zero.
- A closing basin has no discharges of usable water in the dry season. Therefore, any additional depletion in this season results in a decrease in existing uses. However, closing systems do have discharges of usable water in the wet season. Thus there is at least the possibility that the basin can be reopened through the development of upstream surface and subsurface water storage of wet-season flows for use in the dry season.
- A completely closed basin has no discharges of usable water even in the wet season. In this case, there is no scope for obtaining additional water supplies. Additional water needs can be met only through gains in water productivity – for example, by reducing non-beneficial evaporation or by reallocating water from lower-valued to higher-valued uses.

It is surprising how many closing or closed river basins there are, once one begins looking for them. For example, it is said that such large and important basins as the Indus, the Ganges and the Yellow River basins are closing by this definition, and that the Colorado and the Cauvery River basins are completely closed. Unfortunately, there are few reliable data on discharges of water to sinks for many of the large river basins of the world, much less on the quality of the water. The fact that most water-management agencies do not bother to collect data on what is surely the single most important factor in water management is evidence of the newness of the river-basin perspective, notwithstanding hundreds of years of intuitive understanding of its importance by people like King Parakramabahu.

## The productivity of water use

It is important to distinguish between the rate of beneficial utilization, or BE, and the productivity of water use. While the two are related, they are not the same thing. The same degree of beneficial utilization may have substantially different values in terms of the productivity of water. For example, the same amount of water depleted in the irrigation of cereal crops may have a much higher value in vegetable or fruit crops; and it will probably have a higher value in the domestic sectors than in the irrigation sector.

Also, water serves both as an input to the production of a final good, such as irrigation in crop production or wildlife habitats, and as a final good in itself, such as drinking water or the aesthetic value of a beautiful lake. In these and other cases, the value of water is attached to the amount of water diverted to the particular use – for example, the value of so much drinking water supplied to a household – irrespective of the amount of depletion. But it should also be recognized that, if only a small amount of the diversion is depleted, the potential for the outflow being beneficially recycled into other diversions is increased. Repeated reuse of water creates the water multiplier effect, where the sum of the diversions in a river basin can be several times larger than the inflow of water into the basin (Seckler, 1992; Keller *et al.*, 1996). Because of the multiplier effect, the productivity of the water inflow into the basin is often enhanced.

The productivity of water in a given use is defined in terms of the quantity and quality of water diverted or depleted in that use. Given this, there are several different ways of expressing productivity:

- Pure physical productivity is defined as the quantity of the product divided by the quantity of AWS, diverted water or depleted water, expressed as kg $m^{-3}$. For example, a slogan at IWMI, 'increasing crop per drop', expresses physical productivity.

- Combined physical and economic productivity is defined in terms of the net present value (NPV) of the product divided by the amount of water diverted or depleted. Thus, the quantity of the product is productivity times the amount of AWS or water depleted.
- Economic productivity is the NPV of the product divided by the NPV of the amount of AWS or water diverted or depleted, defined in terms of its value, or opportunity cost, in the highest alternative use.

In estimating the economic value of water, it is more important to understand both the extent and the limitations of what can be rationally accomplished. When water is an input to a final good that has a real market value or shadow price, the marginal value of water, like that of any other input, can be estimated as a derived demand for the input. Obviously, values can also be assigned when water is itself a marketed product, whether a final product, such as drinking water, or an input, such as irrigation water. But, when water or its products are not marketed or when they have non-market values, as in the case of basic needs or ecological imperatives, then it is an abuse of economics to assign real or shadow prices to it as an indicator of its value. All one can rationally do in these cases is to commit agreed-upon quantities of water to these purposes. One can then evaluate the opportunity costs of these commitments in terms of shadow prices in an optimization model. But these shadow prices are costs, not values or benefits. Truly, as Oscar Wilde might have said, 'economists know the cost of everything but the value of nothing'.[4]

## The Persistence of Classical Efficiency

It is a remarkable fact that, from the time of their development in 1932 to the present, the neoclassical concepts – whether of NE, BE or EE – have not been widely accepted in the general community of irrigation and water-resource practitioners (see, for example, Clyma and Shafique, 2001). CE prevails, notwithstanding the fact that NE is clearly and demonstrably a more valid concept, developed and recommended by many of the outstanding authorities in the field. For example, in the volume, *Design and Operation of Farm Irrigation Systems*, edited by Jensen (1980) and published by The American Society of Agricultural Engineers, the neoclassical view could not be more clearly articulated (especially in the chapter by Burman *et al.* (1980)). But most professionals remain wedded to the classical view – one, in fact, accused Keller and Keller (1995) of advocating 'sloppy irrigation'!

Indeed, in Jensen (1980, pp. 17–20), reference is made to a debate in 1976 in the USA, where the General Accounting Office published a report on the massive savings of water that could be achieved by increasing CE! The experts in the field used Jensen's NE and water-balance analysis to correct that error. But it is remarkable that now, over 20 years later, the same confusion not only endures but actually predominates in the field of irrigation and water-resources policy and management in the USA and throughout the world.

Because of its importance and interest as an example of the evolution of scientific ideas, we may pause briefly to speculate on the reasons for the persistence of CE. First, there is the matter of training. Most irrigation practitioners were trained before the neoclassical concepts appeared in the later 1970s and went directly into practice – quite properly applying CE to the design of irrigation systems. This imprinted CE in their minds, as it were. Secondly, quite naturally, their professional interests and positions were oriented around CE. Thirdly, a large industry of consulting and construction firms, consultants and donors has been created around the task of rehabilitating and 'modernizing' irrigation systems to increase their CE. Fourthly, CE serves the interest of other professions and groups as well.

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[4] For a discussion of these issues in the context of poverty, see Seckler (1966) and, for a brilliant general treatment of the subject, Little (1950).

Economists can use low CE as justification for pricing water and water markets; and environmentalists can use it in their battles against large dams, transbasin diversions and other water-development projects. For all of these reasons, the very idea that old 'sloppy' irrigation systems may already be performing at high degrees of efficiency because they are recycling is hard to accept.

On the other hand, the neoclassical approach has been fully understood and applied by farmers and other practitioners in water law and management in the western states of the USA – and perhaps on a more intuitive basis elsewhere. Western water law explicitly recognizes that one farmer's drainage can be another farmer's irrigation supply, and return flows are zealously protected. In Wyoming, water allotments and charges are made on the basis of the 'consumptive use' of the water (NET), not on the amount of water diverted or applied. Thus it is illegal to increase irrigated land and NET through more (classically) efficient technologies, even if the amount of water diverted is the same.

Indeed, Californians commonly distinguish between 'real' and 'paper' water savings, or what they amusingly refer to as 'wet' vs. 'dry' water savings – depending on whether or not gains in classical efficiency for one user are offset by reduced recycling supplies to another user. An elaborate legal and regulatory framework has been created around water use to apply and enforce these neoclassical concepts (see the interesting case of Colorado in Vissia (1997)). As Burman *et al*. (1980) rightly say, 'The reuse of return flow is one of the main foundations of Western water right management, and its importance is impossible to overestimate.'

## Externalities, Regulations and Water Pricing

In terms of economic theory, regulations are a rational response to the problem of externalities – or, as they are also known, aptly for discussion of water, 'spillover effects'. As explained in any standard textbook on economics, externalities occur when the welfare of second parties is affected by the behaviour of first parties without compensation. In the case of external benefits, second parties should compensate first parties for the benefits they receive; in the case of external costs, second parties should be compensated by first parties for the harm they suffer. Compensation is not only a matter of equity; it leads to greater efficiency by 'internalizing the externality'. If the first party has to pay for an external cost, he or she will try to produce less of it and, if paid for an external benefit, will produce more of it. Direct private compensation arrangements between first and second parties are usually impossible in practice. Governments have to intervene to 'internalize the externalities', through taxes, subsidies or regulations. Without government interventions, the market fails to achieve an efficient, much less an equitable, allocation of resources.

Of all the goods and services in the world, water is probably the most externality-ridden. The outflow arising from efficiency Equations 3.1 and 3.1a is an external effect. Typically, it is of the order of 50% in irrigation, and it can be as high as 90% or more in the case of the domestic and industrial sectors. This constitutes a colossal potential source of market failure in water resources.

Given this fact, it is rather amazing to find many economists advocating free-market allocations and pricing of water in the name of efficiency. With externalities, free markets lead to inefficient allocations of resources, as shown in any standard economics text. And, at a practical level, if the developed countries have found it necessary to create elaborate regulatory structures to prevent market failure in water resources, how do advocates of water markets and water pricing imagine that developing countries – with much fewer resources, many more low-volume and poor water users and weak institutional structures – will be able to do this? (See the discussion in Perry *et al*., 1997.)

Having said this, it should be noted that charging service fees to cover at least the operation and maintenance cost of water-delivery services and even perhaps part of the capital costs is a valid practice that should be implemented everywhere. Also, there are many cases where the outflows create external costs, such as in outflows of water polluted by salinity or other harmful wastes into the water supply. These external costs should be internalized to the polluter either by marginal cost prices or by regulations. And, where the outflows have zero or negative benefits, water prices can and should be used to attain higher efficiencies of water use in the classical sense. In sum, the question of water markets and pricing is not one of either-or but rather of why, where, when and how.

## Conclusion

The ultimate goal of water-resources policy and management is to increase the beneficial utilization of water. In the final analysis, there are six basic ways of achieving this goal (Seckler, 1996).

**1.** Where the AWS at the basin level is underutilized, as in the case of open or closing basins, develop the remaining AWS through additional and improved technical and institutional means.
**2.** Reduce non-beneficial evaporation and non-beneficial discharges to sinks.
**3.** Increase the amount of benefits per unit of beneficial evaporation[5] and beneficial discharges to sinks.
**4.** Reduce water pollution.[6]
**5.** Reduce waterlogging and flood damage.
**6.** Reallocate water from lower- to higher-valued uses.

There is a large array of technologies, policies and managerial systems that can be employed for achieving these objectives under specific conditions of time and place. But these systems are a subject beyond the scope of this chapter. We strongly believe that before you act you must think, that sound theory is a necessary (but not sufficient) condition to effective action and that, *per contra*, poor theory can lead to ineffective and even counterproductive actions. Many of the problems of water-resources management today are due to the implementation of false, erroneous or misapplied concepts of efficiency in water-resources policy and management. We hope that the discussion in this chapter will help to resolve that problem.

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[5] One of the ways of increasing productivity by this means is through ‘exogenous’ changes in technology, outside water management such as reducing the length of the growing season through plant breeding.

[6] Even a mild degree of pollution reduces the productivity of water – for example, saline water reduces crop yields and polluted drinking water adversely affects health – far short of salinity becoming so severe that it is discharged to sinks.

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