A New Model for Basin Wide Water Use Efficiency

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IRRIGATION

In the field of irrigation, few concepts seem to inspire as much confusion and controversy as "efficiency". Most proponents of efficient water usage in irrigation fall into one of two camps. The first viewpoint is that of the user, or, in most cases, the farmer. In this viewpoint, efficient use of water means applying the minimum amount of water to a field in order to produce a crop. This viewpoint is important to the farmer because it is directly related to his or her costs to produce and ultimately his or her economic well being.

The second viewpoint is that of the river basin manager, who has the responsibility of assessing the total supply of water available to all the users within the normal drainage of a particular river or stream, and how to best manage the usage of that water. For the basin manager, certain types of inefficiency at the farm field level are not necessarily losses at the basin level, if those inefficient applications of water can be captured and used by others within the basin. The basin manager also needs to be concerned with the timing of availability of water, as well as the suitability of the water for uses that may be down stream. The complexity of the problem faced by the river basin manager has made finding a suitable model of irrigation efficiency difficult.

This paper compares the strengths and weaknesses of several commonly used measures of efficiency. The authors then introduce a qualitative concept that attempts to relate efficient practices at the field level to their impacts at the basin level. This new concept provides a way for the basin manager to assess the impacts of inefficient farm field irrigation practices on the basin's down stream users in terms of quantity, quality, and temporal degradation.

Efficiency, as a concept, has long been applied as a performance measure for machines, systems, and processes. As a concept, efficiency is simple and straightforward. The *American Heritage Dictionary* defines efficiency as – the ratio of the effective or useful output to the total input in any system.

$$\text{Efficiency} = \frac{\text{Effective or Useful Output}}{\text{Total Input}}$$

This basic concept has been applied in different ways by many water-use stakeholders to serve various needs and requirements. This is true for agricultural water use where a number of different efficiency measurements have been developed over the years. These measurements have become both more important and more scrutinized as growing larger quantities of food with less water to feed an ever-growing world population develops into a major global challenge. Many believe that improved water management at the basin and field level can lead to water savings and more productive use of finite water supplies.[1] Others, however, propose that traditional measures of irrigation efficiency fail to account for water reuse within a basin and that basin-wide irrigation efficiencies may be much higher than can be extrapolated from individual field irrigation efficiencies.[2] We will examine these two schools of thought in greater detail later in this paper. First, we offer below some common definitions of irrigation efficiency for the readers benefit:

Application Efficiency (E_a) – Ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied.[3]

Conveyance Efficiency (E_c) – Ratio of the water delivered, to the total water diverted or pumped into an open channel or pipeline at the upstream end.[4]

Irrigation Efficiency (E_i) – Ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied.[5]

Project Efficiency (E_p) - is calculated based on farm irrigation efficiency and both on- and off-farm conveyance efficiency, and is adjusted for drainage reuse within the service area. Project efficiency may not consider all runoff and deep percolation a loss since some of the water may be available for reuse within the project.[6]

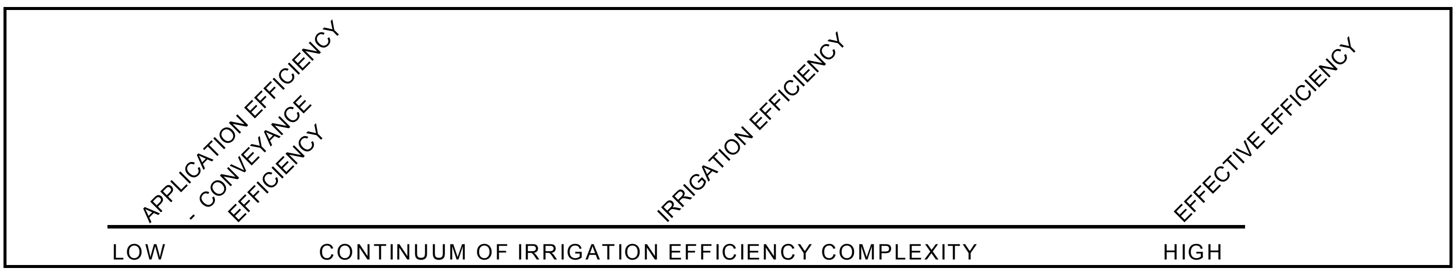
Effective Efficiency (Basin Efficiency) – is the beneficially used water divided by the amount of freshwater consumed during the process of conveying and applying the water.[7]

Water Use Efficiency – The mass of agricultural produce per unit of water consumed.[8]

There are numerous other efficiency measurements related to irrigation and different definitions for the terms defined above, however, we believe that the definitions listed above are reasonable and capture the general concept of each of the terms.

The irrigation efficiency measures listed above can be plotted along a continuum of measurement complexity as shown in Figure 1 below. As can be seen, Application and Conveyance Efficiency are straightforward measures that can be calculated by farmers and researchers with relative ease. In contrast, Effective Efficiency introduces a number of variables that add to the complexity of calculating and understanding this measure.

Figure 1



As stated in our introduction, in this paper we examine the efficiency measurements at each end of the continuum - Application Efficiency and Effective Efficiency. Farmers are typically interested in Application Efficiency both when considering irrigation equipment purchases and when calculating the effectiveness of those systems. Regional water managers and policy makers are more likely to have an interest in Effective Efficiency within the basin. Some tension and confusion can sometimes exist between these two groups and the efficiency measurements they use and espouse. We believe that neither measurement can be used without understanding its limitations; therefore, we will further examine these two efficiency approaches pointing out the limitations of each. In addition, a review and understanding of these measures is appropriate prior to the introduction of our qualitative concept.

Before we move on to further examine these efficiency measures, it is important to note that the actual efficiency of any physical irrigation system is influenced by many factors, including level of management, soil type, crop type, crop-growth stage, climatic factors, and water table considerations.[9] The physical “set-up” of an irrigation system may have theoretical efficiencies higher than those experienced in actual use because of the factors mentioned above.

Application Efficiency

Application Efficiency is the measure typically used in the agricultural community for comparing and contrasting brands, types, and methods of irrigation. Irrigators are interested in measuring, designing for, or estimating Application Efficiency because it takes more water to irrigate inefficiently than it does efficiently, and increased water use translates to higher costs and reduced profitability. Although Application Efficiency is not a perfect measure, it does serve as a common point of reference for irrigation stakeholders. As noted in an Advisory on the web site waterright.org, "The individual farmer should focus on individual, in-field irrigation efficiency because his/her crop development/yield and costs are dependent on this. Basin and project-wide estimates of irrigation efficiency may be useful in political discussions but do not address the individual farm."[10]

If we return to our general definition of efficiency, we see that an output is derived from an input and something is lost to achieve the output. For Application Efficiency, the output is water to the root zone and the input is water applied. The water lost in order to apply water to the root zone comes from evaporation, runoff, and deep percolation. For Application Efficiency, evaporation can occur during sprinkler application before the water reaches the soil or from surface water during flood irrigation. Evaporation can be almost completely mitigated with modern sprinkler designs. Runoff is water applied to the field that is not absorbed into the soil but runs to the end of the field where it cannot be used by the crop. Deep percolation is water applied to the field that seeps into the soil below the root zone and, therefore, is not accessible by the crop. Deep percolation typically occurs when excess water is applied during an irrigation event or when the uniformity of the application is low.

To better understand Application Efficiency we must examine some of the primary components of the definition. Our definition - ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied - can be examined by its component parts.

One component, the denominator of our formula, is irrigation water applied. The applied water is water leaving the nozzle of a pressurized system, or passing over the sill for border-strip systems.[11] It is the amount of water that exits the irrigation delivery system during an irrigation event.

Another component in the definition of Application Efficiency is the Crop Root Zone which is defined as follows:

> The soil depth from which a mature crop extracts most of the water needed for evapotranspiration. The crop root zone is equal to effective rooting depth and is expressed as a depth in inches or feet. This soil depth may be considered as the rooting depth of a subsequent crop, when accounting for soil moisture storage in efficiency calculations.[12]

Let's take a further look at why Application Efficiency is so widely known and used in agriculture. Farmers understand and use Application Efficiency estimates when making irrigation system purchasing decisions. Different irrigation methods offer vastly different Application Efficiencies. Drip and Mechanical Move irrigation systems can have Application Efficiencies beyond 90% while flood irrigation may be as low as 40% efficient. Farmers know that improved Application

Efficiencies reduce costs and, thus, are interested in the estimated Application Efficiencies of various irrigation methods when purchasing an irrigation system.

Most modern farmers have access to daily evapotranspiration estimates (the estimated crop water requirements) and, as a result, know how much water should be delivered to the root zone. As we now know, farmers typically understand the design application efficiencies of their irrigation equipment and use this information to control irrigation events. For example, a farmer using an irrigation system with an Application Efficiency of 50%, such as flood irrigation, will apply double the estimated need of the crop to meet the water needs of that crop (this is a simplified example and does not account for existing water in the root zone). Thus a key advantage of Application Efficiency is that it is used to measure the performance of a system in the field based on perceived needs of the crop, and, therefore, in comparison with other efficiency measures is much easier to quantify.[13]

Application Efficiency, while simple and widely known, is not without its shortcomings. It does not account for water Distribution Uniformity. Distribution Uniformity is a measure of how evenly water soaks into the ground across a field during an irrigation event.[14] A low uniformity means that water depth varies throughout the field being too little to meet crop water requirements in some places and too much in others which results in water loss through deep percolation. A high Application Efficiency does not ensure that an equal amount of water reaches all parts of a field. Low distribution uniformity can have significant negative impacts on crop yields or could lead to over-watering, which increases costs and could result in water logging and a reduction in yields.

A high Application Efficiency can be achieved without fulfilling the crop water requirement. Theoretically, Application Efficiencies can be high if very little water is applied with conditions being such that little water is lost to evaporation. This means that most of the water applied ends up in the root zone but that the amount of water applied is not enough to meet crop water requirements. Thus, under-watering could result in a high Application Efficiency but low crop yields because of a failure to meet crop water requirements.[15]

Another possible limitation of Application Efficiency is that the measure does not account for all beneficial uses of water such as deep percolation for soil salt leaching.[16] Some volume of water that percolates below the root zone may be beneficial as it takes with it, or leaches, unwanted salts from the soil. This leaching effect is considered beneficial because unwanted salts have a negative impact on crop growth and yields.

Application Efficiency can be over estimated when using simple measurement techniques. For sprinkler irrigation, when measuring Application Efficiency, researchers typically place containers throughout the field where the assumption is made that the average depth of water collected is equal to the average depth that would be stored in the root zone (assuming that the depth collected is not greater than the soil moisture deficit). This ignores the real possibility of evaporation prior to absorption into the soil.[17]

The Basin Model

In this paper we refer to the Basin Model or the Basin Model of Efficiency and use these terms interchangeably with Effective Efficiency as described by Keller, Keller, and Seckler.[18] The Basin Efficiency Model, when applied strictly to irrigation, estimates water used consumptively by crops relative to actual water applied throughout the basin. Consumptive use is primarily evapotranspiration (ET), which is water evaporated or transpired from plant foliage and adjacent soil during crop growth. In its most simple form, the model assumes that water not consumptively used by crops returns to the basin for reuse in the form of surface runoff, seepage, or infiltration.

To better understand the Basin Model we now take a closer look at an idealized version of the model, which is represented in Table 1 below. Our idealized basin begins with an initial diversion of water from some source such as a river, reservoir, or aquifer. This initial diversion is applied as irrigation water to a field.[19] In the example in Table 1 the initial diversion is a volume of $100m^3$. We assume that our basic field level irrigation efficiency is 40% which means that 40% of the diverted water is consumed through evapotranspiration. This leaves a remaining volume of water of $60m^3$ that flows out of the initial field through runoff or percolation and becomes available for use in a different location in the basin. The process continues with the amount of water not consumed by evapotranspiration ending up in usable form to be used again for irrigation. Eventually, the total volume of water consumed by the crops approaches the amount of the initial diversion. In our example, after just ten cycles, the amount of water consumed, presumably beneficially by crops, is over $99.9m^3$. This results in a Basin or Effective Efficiency of 99.9% (the logic for Table 1 was taken from Keller, Keller, and Seckler, 1996).[20]

TABLE 1

Initial Diversion	Return Inflow for Use	Irrigation Consumptive Use	Water Consumed	Outflows	Cumulative Consumption
$100m^3$	0	40%	$40m^3$	$60m^3$	$40m^3$
	$60m^3$	40%	$24m^3$	$36m^3$	$64m^3$
	$36m^3$	40%	$14.4m^3$	$21.6m^3$	$78.4m^3$
	$21.6m^3$	40%	$8.64m^3$	$12.96m^3$	$87.04m^3$
	$12.96m^3$	40%	$5.184m^3$	$7.776m^3$	$92.224m^3$
	$7.776m^3$	40%	$3.11m^3$	$4.666m^3$	$95.334m^3$
	$4.666m^3$	40%	$1.866m^3$	$2.8m^3$	$97.2m^3$
	$2.8m^3$	40%	$1.12m^3$	$1.68m^3$	$98.32m^3$
	$1.68m^3$	40%	$.672m^3$	$1.008m^3$	$99.328m^3$
	$1.008m^3$	40%	$.403m^3$	$.605m^3$	$99.933m^3$

The contrast between Basin Efficiency and Application Efficiency is now clear. In our example, each irrigation event has an Application Efficiency of about 40%, yet the overall efficiency in the basin approaches 100%. As stated above, the example provided in Table 1 was for an idealized Basin, that is, a theoretical model of a basin where all water applied to a field is either beneficially consumed by the crop or returned to the basin for reuse. In actual practice we know that this is far from reality. A number of different variables influence the amount of water available for reuse in the Basin Model. These variables include salts and pollution, evaporation other than crop evapotranspiration, rainfall, and sinks.[21] Sinks are destinations for water not available for reuse - a common sink for a river basin is a sea or ocean.[22] Any of the variables listed above may impact Basin Efficiency, for instance, a poorly designed irrigation system may result in relatively large amounts of non-beneficial evaporation. In this case, the overall Basin Efficiency is negatively impacted because non-beneficial evaporation is water lost that is unavailable for beneficial use in the basin. In addition, in actual practice, water is often used for leaching salts from soil and this water must also be accounted for in a Basin Model.[23] Adjusting for these variables will generally negatively impact Basin Efficiency.

The Basin Model of Efficiency may be a useful model for planners and politicians, but it, like Application Efficiency, is not without shortcomings. One variable that is not accounted for in the Basin Model is the timing of return flows. Imagine a scenario where water is diverted from a river and applied to a field using an irrigation system with an Application Efficiency of 50%. Let's also assume that 5% of the water evaporates during application and the remaining 45% is lost to this irrigation event through deep percolation. We'll call this deep percolated water W_1. Using the Basin Model we assume that W_1 is available for reuse. If, however, we add the element of time we can see that this is not always the case. In our example let's assume that it takes four months for W_1 to return to the river and during these intervening four months the irrigation season concludes. Further diversions from the river have ceased because crops are no longer being watered. In this simplified scenario, W_1 will not be used but will flow down the river and out of the basin. The actual Basin Efficiency will equal the Application Efficiency of 50%.

Let's return to our example only this time assume that the Application Efficiency is 85% and that 5% of the water is lost to evaporation during the water application. If our other assumptions are unchanged, W_1 in this case equals 10% of the water diverted and is eventually lost from the basin. Because of the higher Application Efficiency, less water will be diverted to put the same amount of water in the root zone. If the water saved at the field level, through higher Application Efficiency, is held upstream in a reservoir, it can be released as needed for irrigation or other water demands down the river.[24] Thus, in actuality reduced water consumption at the field level can be beneficial to water conservation in the entire basin.

What happens if W_1 flows to and is held in an underground aquifer rather than flowing back into a river? This scenario reveals other problems with the Basin Model. If the water in the aquifer is to be accessed for irrigation, additional water must be used to generate the power required to pump the water in the aquifer. The cost of this power is born by the farmer.

The examples above highlight another issue related to the Basin Efficiency Model - the accessibility of return flows. The Basin Model assumes that return flows can be reused through natural and/or engineering processes.[25] Basins are unique, each with distinctive geographical characteristics. So where does the excess water flow? That is a question that must be answered for each diversion, and each field in each basin. This is a highly complex problem that is certainly difficult to model with any degree of accuracy. The conceptually simple approach used in the Basin Model may be insufficient to accurately account for the complexities of individual basins.

Another deficiency of the Basin Model is that while it offers a method for considering the impact of salinity in the water, it is not clear how to account for pollution. The use of chemicals in agriculture has a negative impact on the quality of water infiltrating fields. The severity of this impact is conditional, but it certainly can make excess water unacceptable for reuse. The Basin Model does not provide a clear method to account for the impact of the various forms of pollution in water targeted for reuse.

We have examined some common irrigation efficiency measures for both the field and basin level. We learned that these are useful tools and in some ways complementary; however, we also have seen that both measures have limitations. Neither should be used alone without accounting for some of the deficiencies. Next we offer a new qualitative perspective on irrigation water flows within a basin. We believe that this perspective offers a new and, hopefully, lucid viewpoint for irrigators and other water-use stakeholders.

Thermodynamics, Energy, Entropy, and an Analogy to River Basins

What is Thermodynamics?

Thermodynamics is the study of physical systems and their patterns of energy change.[26] Systems in the thermodynamic sense can range anywhere from individual devices such as a block pulled up an incline, or an internal combustion engine, to extremely complex arrangements such as power plants or even entire planets. Systems can normally be characterized in one of three ways:

1. Isolated with no exchange of matter or energy with the surroundings.
2. Closed with energy exchange but no matter exchange with the surroundings.
3. Open with exchange of both matter and energy with the surroundings.[27]

For the purposes of this analogy, we will be thinking of a river basin as our “system” with water representing the equivalent to “energy” in thermodynamics. The analogy lacks an equivalent to mass transfer across the system boundary, and as a result we will be analyzing the equivalent of an “Open” thermodynamic system. If we imagine a theoretical river basin, water (energy) is flowing into the system in the form of precipitation. Water flows out of the basin through several methods including; evaporation, permanent sinks, and ocean outflow.

In most thermodynamic systems of interest, some of the energy of the system is converted into useful work. In our analogy, the “useful work” of the river basin consists of several items including; crop production through transpiration, water that sustains human life, water that produces industrial production and output, and water that is needed to sustain wildlife and the natural environment.

Excess withdraw of water within the basin can be thought of as the equivalent of “waste heat” generated in thermodynamic systems. Heat is usually a loss in the thermodynamic sense, although techniques exist to recover useful work from waste heat if it is of a useable quality (high temperature), and quantity. There are both theoretical and practical constraints on the use of waste heat. In the real world, cost and effectiveness of recovery heat exchangers, handling systems, and other equipment limit the amount of waste heat recovery possible. Our river basin acts in the same way, returning some of the excess withdraws of water to the system in a lower quality state. That water can still have, in some cases, additional “useful work” extracted from it if it meets the requirements of cleanliness, accessibility, and timeliness required by downstream users as has been pointed out by other authors[28]. As in thermodynamic systems, there are both theoretical and practical constraints in the handling of excess withdraws of water.

In thermodynamic systems, a key focus of analysis and design is to maximize the energy conversion efficiency. An efficient system turns more of the energy input into useful work than an inefficient system. In river basin management, the goal of most managers is to maximize the utilization of water within the basin to produce useful output also.

The First Law of Thermodynamics

The study of thermodynamics is governed by two important laws, both of which will be important to the water basin management analogy. The first law states that the energy of a system is neither created nor lost, but is instead conserved.

To understand this law, imagine an internal combustion engine as our system, complete with its driveshaft, its radiator, and exhaust system. Energy enters the system trapped in the chemical bonds of the fuel and air mixture as it is metered into the engine cylinders. The chemical energy is released as the fuel burns, pushing down the engine piston, and driving the driveshaft. This mechanical rotation is the useful work done by the system. If we measure the mechanical work produced by the engine and divide by the chemical energy that is fed into the cylinders, we would find that the ratio is roughly 32%[29]. Internal combustion engines require significant excess energy input to overcome losses and inefficiencies in their physical designs. Even independent of the losses and inefficiencies, the maximum theoretical efficiency of an ordinary automobile engine is 56%[30]. So where does the excess energy go? Most of it becomes heat generated either from the combustion of the fuel, or from friction in the mechanical system. Most of that heat is rejected to the atmosphere (the surroundings) through the radiator. There is also energy that exits through the exhaust gases. This energy is in the form of heat from the hot gases, and some left over chemical energy from incomplete or imperfect combustion. If our system includes a catalytic converter, much of the remaining chemical energy is converted to heat and also is transferred to the atmosphere. If it was economically feasible, the chemical energy in the exhaust gases could be extracted and burned again in the engine. In principle, the hot exhaust gases or the heat rejected by the radiator could be made to do additional mechanical work by flashing water to steam and turning a turbine. In the real world, however, such schemes that could theoretically increase the energy efficiency of the system are rarely economically justifiable. In the engineering of real world systems using thermodynamic principles, the ultimate task is to determine the degree of efficiency that maximizes the production of useful work and still is economically practical.

In extending the application of the first law to water systems, rather than considering an entire basin with all its complexity, let's draw the system boundary around a single irrigated agricultural field. Water enters the system via a well or canal (or via rainfall, periodically). The useful work of this system is transpiration of the intended crop that ultimately results in the production of some useful economic good (food or fiber). If we divide the evapotranspiration by the water applied, we are measuring the efficiency of irrigation, much like the measure of efficiency in our engine. Unlike most thermodynamic systems, our water system could achieve efficiency of nearly 100% as there are few, if any, theoretical limitations on the system's performance. In the real world, however, there are major and minor sources of loss in our irrigated field. The primary sources of loss include; direct evaporation, run-off, and deep percolation[31]. Much like the engine, these losses represent the "wasted" water in our application, and just as in the engine example, under the right circumstances some of this water can be harnessed for the generation of "useful work" in other applications. The clearest example of this is where run-off water from an irrigation field is collected in a ditch and then used to irrigate an adjacent field. These types of schemes are common in some river systems such as the lower Nile River in Egypt. In these applications, the vast majority of the water can be reused, and hence by including adjacent irrigation fields into the efficiency calculation, the overall application efficiency for the region or the basin is raised. At the other extreme is direct evaporation, which is almost never available for use within the system, atmospheric water vapor being too impractical to collect and utilize. The net basin-wide impact of re-use of waste water has been a subject of great discussion in recent years, as illustrated earlier in this paper. Unlike waste heat, whose utility is defined by its temperature difference compared to the surroundings, “wasted” or over-applied water can be characterized by three quantities; its quality, its accessibility, and its timeliness. Each of these quantities implies the water’s use in a particular process. For example, water that is clean enough for irrigation purposes, may have too much pollution for human consumption or for wildlife. This makes analyzing our basin system more difficult than a thermodynamic system. Fortunately the second law of thermodynamics offers some qualitative insights into how we should think about water management on a basin-wide basis.

The Second Law of Thermodynamics

Understanding the second law of thermodynamics is conceptually more difficult than the first law, and requires first the introduction of a concept called “entropy”. The textbook definition of entropy is something about which mechanical engineering students will spend several weeks developing a mathematical understanding. We will attempt a more conceptual understanding in this paper. Broadly considered, entropy is a measure of the degree of dispersion of energy[32]. For example, imagine a beaker of water that weighs one pound and is at a temperature 200 degrees Fahrenheit above the surrounding environment. This beaker of water would have a lower entropy than a one hundred pound barrel of water at a temperature of two degrees above the surroundings. The same amount of energy is present in each case, but in the latter example, the energy is more dispersed than in the former example. Entropy gives a comparative evaluation of the potential that the energy has to do useful work. The lower the entropy, the more concentrated the energy is, and hence the more likely we are to be able to economically extract useful work from the energy.

With this qualitative understanding of entropy, we are now ready to tackle the second law. The second law simply states that in a closed system that undergoes a process, entropy always increases as a result of the process. The second law is not an experimentally tested law, but is instead the product of extensive observations made of closed systems. The law applies to the entropy of the entire system, not the entropy of any individual parts. In our engine example, it is the process of combustion (and later mechanical friction) that causes the increase in entropy. While the useful work produced by the engine has no entropy, the heat energy from the engine has very high entropy and is of a large quantity. The resultant sum of all entropies of the system is increased by the process.

How can the Second Law Provide Insight into Basin Systems?

The Second Law qualitatively tells us that while energy is conserved, all energies are not created equal. From a practical standpoint, certain types of energy are of greater value than others. For example a small quantity of highly concentrated energy (steam, for example), is more valuable than a large quantity of highly dispersed energy (water near ambient temperature). This observation allows us to draw another analogy to the river basin. Water that is clean, easily accessible near the point of use, and available at the time when we need it, is very useful. Water that is polluted, difficult or expensive to access, or available only at the wrong time, is not very useful. In the theoretical example above, we could say that the former water has a high utility value and the latter a low utility value. To put it in the same terms as entropy (increases in value representing decreases in usefulness), we should probably call the quantity the water “degradation” value. Water “degradation” is at its lowest level when the water is clean, accessible, and timely. We can represent this with the following formula:

$$D = f(\text{quality, accessibility, timeliness})$$

While the concept of dispersion has been usefully developed into specific formulae for entropy values of various processes and states of energy in thermodynamics, such a framework does not readily exist within river basins. Nevertheless, we can qualitatively describe those quantities that represent quality, accessibility and timeliness to each of the primary stakeholders in river systems:

- Agricultural water users
    - Quality degradation occurs through the introduction of salts and some herbicides at various concentration levels.
    - Accessibility degradation occurs when the water is far from the farm field, deep underground, or at a flow level too small for practical irrigation.
    - Timeliness degradation occurs when the water is available outside of the peak demand periods (usually summer months in North America).
- Municipal water users (including human consumption)
    - Quality degradation occurs through the introduction of any one of many chemicals or elements, some in small trace amounts.
    - Accessibility degradation occurs when the water is far from the users, deep underground, or available at a flow level too small to allow effective distribution.
    - Timeliness degradation occurs when the water is available outside of the peak demand periods, which vary based on location and local practices.
- Industrial water users
    - Quality degradation occurs through the introduction of substances that cause scale, corrosion, or damage the quality of the ultimate product.
    - Accessibility degradation occurs when the water is far from factories, deep underground, or available at a flow level too small to fulfill process needs.
    - Timeliness degradation occurs when the water available does not meet temporal process needs.
- Environmental water users (wildlife and natural systems)
    - Quality degradation occurs through the introduction of salts, trace chemicals, and nutrients in sufficient quantity to cause algae blooms.
    - Accessibility degradation occurs when the water is not in the natural stream, river, or lake system.
    - Timeliness degradation occurs when the water is outside of the natural system during times of need, especially during seasonal low flow periods.

While there are significant differences in the needs of the various basin stakeholders, there are numerous similarities also. In some instances, the increase in degradation for a particular stakeholder may change rapidly only during certain parts of the quality, accessibility, or timeliness scale. One possible approach to dealing with the differences in the needs of various stakeholders is to develop a composite degradation quantity as shown below:

$$D_{Total} = D_{Ag} + D_{Muni} + D_{Ind} + D_{Env}$$

A more practical approach is to recognize that water degradation is occurring from the perspective of at least one of the basin's stakeholders when any one of the following situations occurs:

1. Water is removed from a river, lake, or stream in any quantity in excess of the amount needed to perform constructive output. The degradation increases as

the excess water is further from other points of use or moves significantly downstream, bypassing other potential users.
2. Water comes to rest in an underground aquifer. The deeper the aquifer and the lower the potential pumping rate, the more degradation has occurred.
3. Water returns to a usable point outside the season of peak demand for the basin.
4. Water becomes polluted by any one of a number of pollutants including salts, fertilizers, chemicals, or trace elements such as lead or mercury. The higher the concentration of any of these pollutants, the greater the degradation.

In practice, much like the situation for thermodynamic systems, the real physical environment is a significant factor in determining the amount of degradation. Characteristics such as the geology of the basin, the physical locations of the stakeholders and their relationships to one another, the connection between ground and surface water, the weather patterns, and numerous other factors all have a bearing on the water degradation experienced.

Using the Water Degradation (entropy) Concept for an Irrigated Field

Let's again imagine our irrigated farm field with a system boundary drawn around it. In this case, imagine that the field is irrigated by gravity flow irrigation. Further, let's assume that the water entering the field is pumped from a shallow aquifer and is relatively clean and plentiful and available with good flow even during the time of peak demand. We would say that the water degradation of the flow entering the field is very low. In the process of irrigation, water feeds the roots of the crop and eventually results in transpiration, which produces useful output (work). In addition, and common with most gravity irrigated fields, there is direct evaporation of water from the furrows, run-off that occurs (which includes fertilizers and other farm chemicals that are on the field), and deep percolation. Let's examine the impact of each of these points of exit in terms of water degradation.

Plant transpiration: This is the useful work of the system, analogous to the internal combustion engine's rotating shaft.

Direct evaporation: This water has the largest increase in degradation because it has essentially no future accessibility. In the Basin Model, direct evaporation is considered a loss to the system. In our model, it is simply water with a very high degradation.

Run-off: The degradation of run-off water is certainly higher than that of the incoming stream. The water is of lower quality due to the addition of pollutants. Usefulness of the run-off water depends on the downstream sensitivity of stakeholders to the specific pollutants, the concentration levels of those chemicals, and a dilution effect from combining with other flows. Accessibility is also lower for the run-off water, in that it will require in most cases some form of conveyance to be brought to the next point of use. If our system boundary was larger, then additional degradation considerations would occur in the form of evaporation and deep percolation of the run-off stream, as well as phreatorphytic vegetation consumption (consumption and transpiration of water by non-targeted plants).

Deep Percolation: The degradation of deep percolated water is the most dependent of any type of degradation on local geology and physical location. Deep percolated water is likely to suffer from degradation due to accessibility and timeliness. Where the water goes, and when and how it emerges again is difficult to generalize about. Some deep percolated water finds its way into virtual sinks that have a very high degradation value. Deep percolated water moves slowly in most cases. Its re-emergence during a peak demand time period cannot be counted on, and hence the water suffers degradation. Quality degradation can also become a factor when pollutants concentrate in aquifers. In a broader sense, water that comes to rest in an aquifer causes basin wide degradation because, as we pointed out earlier, it requires pumping power to lift it.

Applicability of the Degradation Model to Basin Management

Unfortunately, the water degradation model, as formulated in this paper, lacks the mathematical precision of the thermodynamic model. This means that calculating water degradation for various usage options and making direct comparisons is not possible. Nevertheless, the degradation model can provide a number of qualitative conclusions concerning basin management. The first of these is a restatement of the objectives of a basin management plan, which is described below:

1. Basin management plans should be developed to meet the needs of each of the four key stakeholders in the basin recognizing that:
    i. Stakeholder needs have varying water quality requirements.
    ii. Stakeholders have different temporal needs; special focus is needed on the peak demand period.
2. Basin management plans should attempt to minimize the overall water degradation of the basin.

There are numerous strategies that can be employed to meet the second of these two objectives within each of the stakeholder sectors. As the theme of this paper is to describe how agricultural irrigation should be managed in light of basin-wide constraints, let's focus our attention in this area. Water degradation in irrigated agriculture can be reduced by any and all of the following actions:

- Reduced direct evaporation due to more effective and efficient water application (in the classic "Application Efficiency" sense).
- Reduced run-off.
- Reduced deep percolation.
- Utilization of soil moisture or other data to improve decision-making and reduce over-application.
- Second order improvements such as:
    i. Reduced phreatophytic vegetation consumption.
    ii. Reduced farm chemical use.
    iii. Utilization of wastewater from industrial, municipal, or animal husbandry operations.

All of these actions will reduce water degradation ultimately allowing a larger quantity of "useful work" to be produced within the basin. On a more integrated basin-wide footing, the management strategy needs to focus on:

- Minimizing evaporation.
- Minimizing pollution.
- Keeping the maximum amount of water possible in reservoirs, rivers, and aquifers.
- Optimizing our storage and conveyance systems to meet peak demand time periods.
- Balancing the needs of all stakeholders.

Complications and Limitations of the Water Degradation Analogy

Unlike thermodynamic systems, where the entropy on a practical level can be referenced back to the potential for matter in a particular energy state to do useful work, with water the analysis is complicated by the implied question of – "Useful for whom?". In some of the theoretical work done on this subject by Keller, Keller and Seckler (IIMI, 1996) [33], the authors describe the theoretical limitation for reuse of irrigation water based on the salt concentration. In this exploration, the implicit downstream user is another agricultural irrigator, and the maximum allowable degradation is determined to be that point at which a specific crop can not be effectively grown using water of a particular salt concentration. Other downstream stakeholders, however, may have greater or lesser sensitivity to salt, or there may be other pollutants present from agricultural usage that they have greater sensitivity to than salt.

In any real world river basin, labeling return flows as useful implies that the question of "Useful for whom?" is known, can be quantified, and satisfies a real need from a temporal, quality, and proximity standpoint. Knowing the answers to these questions requires intimate knowledge of the geology of the basin, the stakeholders' needs and sensitivities, and the physical locations of major users. In short, evaluating real world river basins requires extremely sophisticated computer models. Unfortunately, as is frequently true with many real world phenomena, these models still require multiple simplifying assumptions in order to be workable. Despite its own limitations and lack of quantification, the water degradation analogy introduced in this paper represents a method of thinking about basin management that will find many day-to-day uses.

Summary

In this paper we have explored the limitations of classical models for looking at water conservation and water efficiency. When viewed at the project or basin level, it has been demonstrated that the Application Efficiency model may overestimate water savings generated by conversion from flood irrigation to modern technologies by ignoring the use of return flows within the river basin. The Basin Model makes a similar mistake by ignoring the impacts of accessibility, timeliness, and quality and assuming that only evaporative/consumptive losses within the basin are relevant to the question of water conservation. Real river basin systems follow neither of these theoretical models. Recent work by other researchers has recognized that both of these models are vast oversimplifications of complex real world systems that are highly dependent on specific physical characteristics. In this paper, the authors have proposed a framework of thinking about basin wide management, in analogy to thermodynamic systems, which can provide water policy makers, hydrologists, and individual users qualitative guidance on their water management decisions.

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