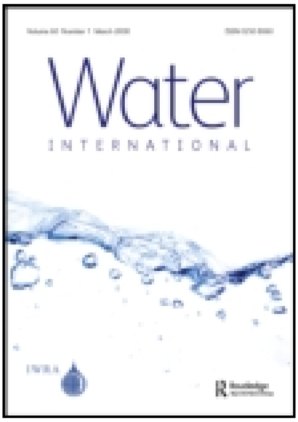

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Water-use efficiency and productivity: rethinking the basin approach

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This paper provides an analysis of three fundamental flaws in traditional water-efficiency discussions, as exemplified by a recent paper in *Water International* (Frederiksen and Allen 2011). In particular, we identify major components of inefficient water use typically ignored in theoretical discussions, address the concept of water productivity beyond simple efficiency, and identify important non-water "co-benefits" that are either ignored or discounted in most basin assessments, including improved water quality, increased production, greater reliability, decreased energy demands, and reduced or delayed infrastructure investments. While there are no silver bullets, water conservation and efficiency can play an important role in solving water management challenges.

Keywords: water-use efficiency; water productivity; basin efficiency; field efficiency; water conservation; co-benefits

Introduction

For at least two decades, water scientists and managers have explored and debated how to define, measure, and evaluate the efficiency and productivity of urban and agricultural water uses. The debate has been marred by several problems, including inconsistent and limited definitions of water use and efficiency, confusion about assumptions, and the inappropriate application of narrow, disciplinary tools to a complex, interdisciplinary topic (Seckler 1992, 1993, 1996, Dziegielewski 1999, Perry *et al.* 2009, Burt 2011).

In a recent example of an effort to apply faulty and outdated concepts, *Water International* (WI) published a paper purporting to provide a consistent basis for evaluating and comparing water uses (Frederiksen and Allen 2011). Instead, that paper repeats earlier work and perpetuates misunderstandings about how to define and measure water-use efficiency and productivity. Because the authors chose one of our studies as a case study in flawed water accounting and efficiency analysis, the editors of WI have offered us space for a detailed response. We provide that here.

But we wish to move well beyond a principled defence against a single misrepresentation of our work to a broader critique of the "basin approach" (Seckler 1992, 1996, Frederiksen and Perry 1995, Keller *et al.* 1995), which calls attention to the importance of evaluating return flows, measuring both basin and field efficiencies, and distinguishing between consumptive and non-consumptive savings. In brief, the basin approach posits that many basins in the world are approaching "closed" status, where all of the water that flows into them is used. The approach argues that in such basins all water is ultimately used

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beneficially or productively, even if there are small-scale or field inefficiencies: “In closed waterbasins, by definition, all of the usable drainage water is already being *beneficially* used; thus, water efficiency measures that only reduce drainage water create only ‘dry’ water savings” (Seckler 1996, emphasis added). “Dry” water savings are defined as reductions in non-consumptive water use (or water that was returned to the basin, such as through runoff, return flow, or groundwater percolation), while “wet” savings are reductions in consumptive water use (or water that leaves the basin or is no longer usable such as through plant transpiration, evaporation, or contamination). Thus, the basin approach discounts the need to pay attention to individual water uses and instead focuses on determining how much of the water that enters a basin is ultimately being recovered and used, as a measure of the overall “basin efficiency” (Frederiksen and Perry 1995).

The policy prescription that flows from this approach is that there are no significant “wet” water savings to be gained through efficiency measures in closed basins that would provide “new” water since all losses are assumed to be re-captured and re-used somewhere else downstream. The implication for many water-stressed regions is that there is no potential to reduce stress or increase resilience through improved water efficiency. The basin concept has been useful in helping to clarify some issues around the scale and scope of water efficiency, but it has three fundamental flaws, which are perpetuated in Frederiksen and Allen (2011):

1. The basin approach excludes or discounts a major component of inefficient water use: unproductive consumptive use.
2. The basin approach does not adequately assess the broader (and often important) measure of water *productivity* because it only values “new” water.
3. The basin approach fails to account for the many other non-water “co-benefits” of efficiency, including improved water quality, greater reliability, decreased energy demands and associated greenhouse gases, and reduced or delayed infrastructure investments.

Three fundamental flaws in the basin approach, as exemplified by Frederiksen and Allen’s (2011) proposed “Universal Water Uses Assessment Equation”

Early in their paper, Frederiksen and Allen (2011) propose the development and application of a “Universal Water Uses Assessment Equation” (Equation 1) for analysing water-use efficiency potential within a basin. As the authors put it: “The proposed WUA equation provides a common basis for evaluating water resource management options and their hydrologic impacts among users in the same class of use or among different classes, in different situations and at different levels of overall management.” The proposed equation, however, does not do what the authors claim, especially when applied to real-world water-use challenges. We present three major flaws in their equation and in the broader theory behind it below.

Flaw 1: Failure to differentiate between productive and unproductive consumptive use

Equation (1) in Frederiksen and Allen (2011) is a good example of how the basin approach fails to account for a major component of inefficient water use:

$$Q_W = Q_{CF} + Q_{RF} + Q_{NRF} \tag{1}$$

– where, in their terminology:

- Q_W is “the quantity of water extracted from aquifers, streams, lakes and associated storage” or a measure of total “withdrawals.”
- Q_{CF} is described as the “consumed water quantity” including “withdrawn water that is evaporated or transpired for an intended purpose and water incorporated into products.” According to the authors, Q_{CF} also includes “water not directly beneficial that is incidentally evaporated or transpired in the course of pursuing the purposes.”
- Q_{RF} is the “non-consumed recoverable water quantity,” or water is used but not “consumed” and that can be captured and reused.
- Q_{NRF} is the “non-consumed, non-recoverable water quantity” or water that is neither beneficially consumed nor available or suitable for further use.

Frederiksen and Allen (2011) argue that Equation (1) “close[s] the water balance and account[s] for all water withdrawn” (p. 268). As we show below, however, Equation (1) fails to adequately differentiate between different kinds of water use, which makes it inadequate for analysing water-use efficiency potential.

In particular, the first term, Q_{CF}, demonstrates a basic weakness in the traditional evaluations of water use by failing to differentiate between beneficial and non-beneficial consumptive uses. Frederiksen and Allen (2011) directly acknowledge this in their definition when they say Q_{CF} “would also include water *not directly beneficial* that is incidentally evaporated” (p. 268, emphasis added). Yet, the authors show their own failure to understand this distinction when they subsequently incorrectly describe Q_{CF} as “the portion of diverted water that is consumed productively” (p. 268). This statement is false: Q_{CF} lumps together water that is consumed *both* productively and unproductively, and Equation (1) fails to distinguish or separate the two. This leads Frederiksen and Allen to miss a potential source of “new” water.

Water use can be categorized as consumptive or non-consumptive. Consumptive use commonly refers to water that is unavailable for reuse in the basin from which it was extracted due to evaporation, incorporation into plant biomass, transfer to another basin, seepage to a saline sink, or contamination. Non-consumptive use, on the other hand, refers to water that is available for reuse within the basin from which it was extracted, for example return flows. This distinction is very clearly made in all of the Pacific Institute’s work (Gleick *et al.* 2003, Cooley *et al.* 2008, 2009, Cooley *et al.* 2010).

Less common, though equally important, water use can also be divided into productive and unproductive uses (what Heermann and Solomon [2007] refer to as “beneficial” and “non-beneficial” uses). Productive uses include those that contribute to societal goals, including traditional production of goods and services, but also things like evaporative losses that still contribute to crop health and applied water that leaches harmful salts from the root zone. Unproductive uses include uses that do not contribute to societal goals, such as transpiration from weeds and evaporation from soils, roads, reservoirs, and canals. Unproductive consumptive losses are among the most poorly measured and studied components of the overall water balance for certain important end uses, especially irrigation and outdoor landscaping. Such losses include evaporation from open water surfaces in flood irrigation or poorly designed and operated sprinkler systems, windblown losses from sprinklers, and excess surface wetting of urban hardscapes.

Correcting for this problem produces a first (but as we shall see below, still inadequate) improvement to the WUA equation of Frederiksen and Allen:

$$Q_W = Q_{CF(P)} + Q_{CF(UP)} + Q_{RF} + Q_{NRF} \tag{2}$$

where $Q_{CF(P)}$ refers to the productively consumed water component and $Q_{CF(UP)}$ refers to unproductive consumptive losses. Equation (2) now permits at least a minimal tracking of an additional factor of importance in efforts to improve water-use efficiency and offers an explicit way to track the value of water management practices that address reducing unproductive consumptive losses. Reducing these losses would create "new water" that can be reallocated to other basin users, left instream for environmental purposes, or transferred out of the basin.

A 2005 study, for example, found that unproductive soil evaporation was 75–85% lower with drip systems compared to flood irrigation during the early stages of cotton development (Luquet *et al.* 2005). Ignoring the potential to reduce such unproductive, consumptive losses may grossly underestimate potential water savings, even in regions that have already made efforts to improve efficiency. In California, nearly 60% of crops are still grown with flood irrigation, according to the most recent state survey (Orang *et al.* 2005). A variety of improved water management practices, including irrigation scheduling and deficit irrigation (on appropriate crops), have also been shown to reduce unproductive consumptive use (Kranz *et al.* 1992, Buchleiter *et al.* 1996, Dokter 1996, Shock 2006, Cooley *et al.* 2008, 2009, Christian-Smith *et al.* 2010). Even Seckler (1996) acknowledges the potential to reduce unproductive evaporative losses through a variety of efficiency measures:

> A study by the International Irrigation Management Institute (IIMI) [now the International Water Management Institute (IWMI)] of dry seeding rice in the Muda Irrigation Project in Malaysia showed water savings of 25 percent by eliminating pretransplanting flooding of rice fields. Some of this was probably 'paper' water savings of drainage water, but some of it was undoubtedly 'real' water savings of evaporative losses . . . . Field evaporation losses can also be reduced by drip and trickle irrigation systems, which apply water directly to the root zone of the crop in correspondence with Et_a [actual evapotranspiration].

Yet, none of these potential savings are acknowledged by Frederiksen and Allen (2011), who summarily dismiss their value, stating: "There may be other benefits from drip irrigation, however it is doubtful that there is a significant reduction in the consumptive use of water" (p. 279). They provide no citations or other corroboration for their "doubt."

This leads them to make another serious conceptual error. They argue that even when "new" water is produced by efficiency improvements, there is no real benefit because "most farmers will use any freed-up water within their operations by altering crops or expanding production rather than losing water allocations." Here, Frederiksen and Allen (2011) confuse the analysis of real reductions in water use with subjective policy decisions about how that saved water should be used. Decisions about allocations of saved water are policy choices; they are not scientific refutations of the potential for improving efficiency (or productivity). Some farmers do indeed use that saved water themselves to produce more food or fiber. In other cases, policies require that conserved water be transferred or committed elsewhere. For instance, the U.S. Farm Bill's Environmental Quality Incentives Program makes an explicit policy choice in stipulating that conserved water may not be used to irrigate new land (Section 2503, Public Law 110–246, 2008).

We address the error of assuming that finding "new" water is the only important goal of efficiency improvements below, but by wrongly assuming that all consumed water is consumed productively, Frederiksen and Allen's Equation (1) has no way to account for a set of efficiency strategies that reduce unproductive consumptive losses.

Flaw 2: Failure to account for improvements in water productivity

In the twentieth century, the primary objective of water policies was to simply make more "new" water available for human use through the construction of infrastructure to store, move, and distribute water. In this traditional paradigm, the best measure of success was total water delivered or used, or the Q_W of Equation (1). As a result, the basic theory behind traditional water-use efficiency assessments repeated by Frederiksen and Allen (2011) and elsewhere (see, for example, Seckler 1996, Hanak *et al.* 2009, 2011, Perry *et al.* 2009, Burt 2011, Cahill and Lund 2011), often assumes or implies that the only important value of water-use efficiency improvements is to produce "new" water. Indeed, we count at least 18 statements in Frederiksen and Allen (2011) alone that imply that the only true benefits of efficiency improvements result from freeing up "new" water, and they critique the work of the Pacific Institute and others on the basis that many proposed efficiency practices and policies do not do so. As noted in Flaw 1, above, there are substantial opportunities to produce "new" water through conservation and efficiency efforts. But equally important, "new" water is not, and should not be, the only measure or metric for evaluating the size and benefits of efficiency programs.

Total water use is now understood to be a poor indicator of the value or productivity of water, and a poor indicator of true efficiency. The "soft path" for water (Gleick 2002, 2009a, Wolff and Gleick 2002, Brooks *et al.* 2009) recognizes that the real purpose of water use is not evaluated or measured in terms of Q_W or total water volumes or "new" water produced, but by measures of the goods and services provided by that water use. As Gleick puts it:

> Soft-path planners believe that people want to satisfy demands for goods and services, such as food, fiber, and waste disposal, and may not care how much water is used – or even whether water is used at all – as long as these services are produced in convenient, cost-effective, and socially acceptable ways. *Thus, society's goal should be not the use of water, but improved social and individual well-being per unit water used* (2003, emphasis added).

This broader perspective is gaining traction in the water world, as shown by the growing effort to assess basin "productivity" rather than "efficiency." A recent special issue of *Water International* (Vol. 36, No. 1, 2011) was devoted to this topic and includes articles discussing water productivity in diverse river basins around the world (see for example the IWMI project on 10 river basins, in Cai *et al.* 2011). Frederiksen and Allen's WUA equation (2011), however, is incapable of assessing water productivity, and therefore the benefits of efficiency policies. We reject the argument that a reduction in Q_W and increases in "new" water are the only appropriate measures of efficiency. But then what might be a more useful approach? One of the simplest ways to think about this is to look at measures that incorporate broader water productivity metrics. A simple addition to Equation (2) might look something like this term for "productivity of water use":

$$P/Q_W = P/[Q_{CF(P)} + Q_{CF(UP)} + Q_{RF} + Q_{NRF}] \tag{3}$$

– where P represents any of several possible measures of the goods and services produced by a specific withdrawal of water, such as crop yield or revenue or households served.[1] In this form, Equation (3) can provide information about the goods and services produced per unit of water, or productivity. This can be measured as dollars of GDP per unit of water used ("economic productivity"), crop yield per unit of water used ("yield productivity"), or households served per unit of water.

One of the most important things to note about Equation 3 is that for any given application of water, P/Q_W becomes the metric to maximize. Now strategies that increase P without changing Q_W, or keep P constant but reduce Q_W, or increase P/Q_W without producing "new" water, all still make sense. Unless this additional factor P is explicitly included, strategies that increase P but do not reduce Q_W are mistakenly ignored, as they are by Frederiksen and Allen (2011).

Here is a striking real-world example. After rising rapidly in the first 75 years of the twentieth century, total water withdrawals in the United States have been essentially flat since the late 1970s, despite very substantial growth in the size of the US population and economy. Among the reasons suggested for this are improvements in water-use efficiency, structural changes in the industrial, energy, and irrigation sectors, and water-quality regulations (Gleick 2003, 2009b, Hutson *et al.* 2005, Kenny *et al.* 2009). Economic growth has continued, however, and the total economic productivity of water use has more than doubled. While total national water withdrawals have been approximately level since 1980, there have been dramatic increases in the economic productivity of water use (Figure 1). Before 1980, every 100 gallons of water withdrawal led to between \$3 and \$4 of economic activity. Now, every 100 gallons leads to between \$8 and \$9 of GDP, even adjusting for inflation. Similarly, Figure 2 shows another measure of water productivity, the tonnage of field and seed crops produced in California per acre-foot of water applied. Between 1989 and 2009, yield productivity for these crops increased from around 1.6 to nearly 2.5 tons per acre-foot, with no increase in total water withdrawal.

Using Fredricksen and Allen's Equation (1) does not capture this increased productivity. If the logic of the "basin approach" had been applied to US water policy, these massive economic productivity gains in US water use since 1980 would not have happened. As long

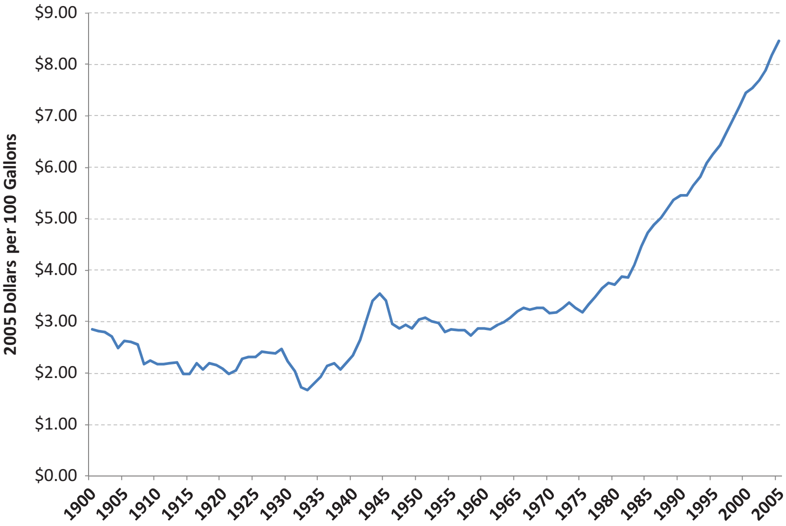

Figure 1. Economic productivity of water use in the United States, measured as 2005 dollars of GDP per 100 gallons of water withdrawn. While total national water withdrawals have been approximately level since 1980, water efficiency improvements have led to dramatic increases in the *economic productivity of water use*. Before 1980, every 100 gallons of water withdrawn led to between \$3 and \$4 of economic activity. Now, every 100 gallons produces between \$8 and \$9 of GDP. All numbers have been corrected for inflation.
Sources: GDP data from Johnston and Williamson 2007, Hutson *et al*. (2005), Kenny *et al*. (2009).

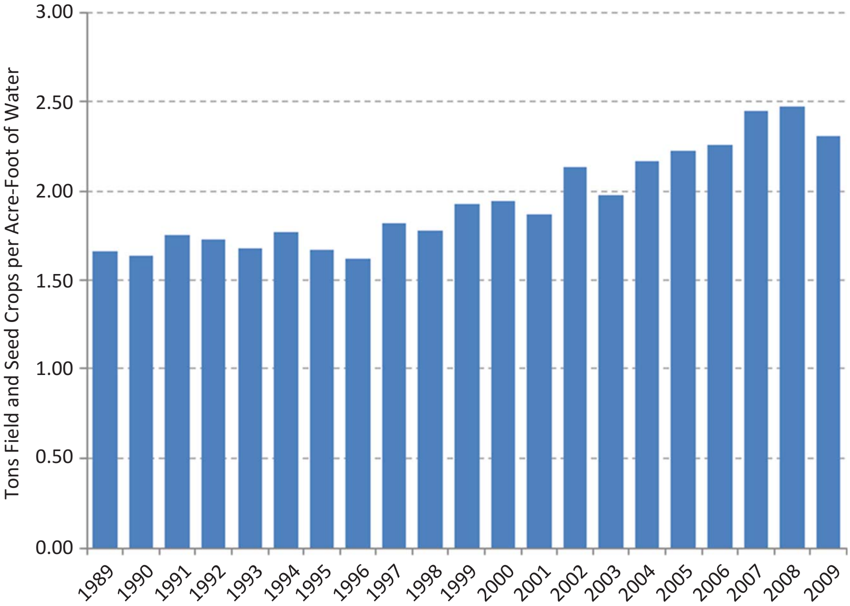

Figure 2. California crop productivity for field/seed crops (tons per acre-foot of water). Productivity has increased from around 1.7 to over 2.3 or more between the late 1980s and 2009 without a comparable increase in total water use for these crops.
Sources: USDA NASS CA Historical Data (1989–2008) and CA Agricultural Statistics Report (2009).

as Frederiksen and Allen and others continue to focus only on the narrow goal of freeing up "new" water and not on the broader issue of improving *water productivity*, they will continue to misunderstand and misrepresent the broader societal benefits of efficiency improvements.

Flaw 3: Failure to analyse co-benefits

A third major failure of the narrow basin approach is the inability of Frederiksen and Allen's Equation (1) to evaluate or assess any *non-water* benefit of water-use efficiency actions beyond simple quantity or even productivity. Such "co-benefits" can include improved water quality, reductions in water-related energy costs, elimination or delay of additional capital investments for new supply and conveyance facilities, improved instream ecological health, and improved crop quality (Evans *et al.* 1998, AWMC 2006, Shock 2006, Hanson *et al.* 2009, Christian-Smith *et al.* in press). Like increases in crop yields, discussed above, these co-benefits often accrue even when there is no "new" water produced from efficiency actions. These are not only real benefits, they are often highly valuable. Assessments that continue to insist that water-efficiency programs produce "new" water will underestimate the true economic, environmental, and social value of efficiency improvements.

Gleick *et al.* (2003) analysed a broad set of co-benefits associated with urban efficiency improvements and concluded that energy savings often far exceeded water savings in economic terms. This conclusion was supported by analyses by the California Energy Commission (2005), among others. Yet such co-benefits are routinely discounted and ignored in almost all discussions of the theory and tools developed to address inefficient water use. Frederiksen and Allen give this issue lip service when they hint that "some may have to modify the WUA equation" to address quality issues, but even here, their argument applies only to water quality as it affects quantity, not how it might affect human health, ecosystem flows and health, energy use, water prices, crop quality, or other quality-sensitive variables; Equation (1) is completely unsuited for this purpose.

As noted at the beginning of this article, the basin approach discounts the need to pay attention to individual water uses and instead focuses on determining how much of the water that enters a basin is ultimately being recovered and used, or the "basin efficiency" (Frederiksen and Perry 1995). Therefore, even if individual field efficiencies are low, basin efficiencies may still be high. As we have already shown, this assumption is only true if there is no potential to reduce unproductive consumptive losses, and field studies show that such losses are still common and often large. But the basin approach also completely ignores co-benefits, as shown in the following example taken directly from Burt (2011).

In a recent presentation to California's State Water Resources Control Board (SWRCB), Burt (2011) argued that there was limited potential to further improve agricultural water-use efficiency because, he claimed, most basins are highly efficient, even if individual fields are inefficient. He showed three identical fields in a basin, each with crop water demand equal to one unit. His example is shown in Figure 3, where three units of water are provided at the head of the basin to Field 1. Field 1 consumes one unit of water and the other two units run off as agricultural return flow (i.e., Field 1 has a field efficiency of 33%). Thus, Field 2 receives two units of water. Field 2 consumes one unit of water and the other runs off to Field 3 (Field 2 has a field efficiency of 50%). Finally, Field 3 receives one unit of water and consumes the full unit of water (i.e., Field 3 has a field efficiency of 100%). Interestingly, this example relies upon improved field efficiencies as you move away from the head of the system. Otherwise, Fields 2 and 3 would be unable to meet crop water demands. Conveniently, in Burt's example, Field 2 has the exact field efficiency to allow one unit of water to flow to Field 3, which in this example must have 100% field efficiency in order to fully meet its crop water demands. Burt (2011) argues that this shows that there is no real waste at the basin scale: even though Fields 1 and 2 have low individual field efficiencies, the overall basin efficiency is 100%. Burt also notes that if Field 1 or 2 were to improve efficiency then Field 3 would not receive its full water supply since it depends on the excess return flows. Simply put, he argues that any savings of non-consumptive uses that do not provide "new" water are valueless.

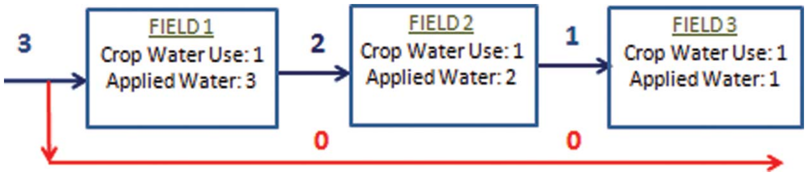

Figure 3. Inefficient field efficiencies, full basin efficiency, no co-benefits. The figure (redrawn from Burt 2011) shows three units of water coming into a basin with three identical fields. All three units of water are applied on Field 1, completely dewatering the river. Two units are excess irrigation and run off. Field 1, therefore, has a field efficiency of 33%. The two units of return flow are then applied on Field 2, with one running off to Field 3. Field 2, therefore, has a field efficiency of 50%. Field 3 uses the last unit of water, with a field efficiency of 100%. The overall "basin efficiency" is 100%. This example excludes any co-benefits of on-farm water efficiency improvements. These benefits are shown in Figure 4 and 5.

Unfortunately, it is put too simply. First, Burt's example ignores the potential for reducing unproductive consumptive losses (see our discussion in Flaw 1 above). But he also ignores important co-benefits. We can easily show the flaws in his argument using the identical example to show how field efficiency improvements can produce substantial co-benefits. In Figure 4, we again have three identical fields in a basin, each with crop water demand equal to one unit. Now, however, policies are put in place to improve the field efficiencies of Fields 1 and 2 to 100%, equal to the efficiency of Field 3 in Burt (2011). Again, three units are available at the head of the basin. Now, Field 1 takes only one unit, leaving two units in the river, thereby improving ecological flows. There is no excess runoff from Field 1. Field 2 also takes only one unit from the river, leaving one unit in the river. Field 3 takes and uses the final unit of water, depleting the water in the river.

In both cases (Figures 3 and 4), the "basin efficiency" is the same: 100%. In both cases, efficiency improvements do not produce "new" water (unless they also reduce unproductive evaporation, as noted in Flaw 1 above). But improvements in field efficiency (as shown in Figure 4) also can lead to major co-benefits, which include substantial water left instream for ecosystems, a reduction in energy demands for water pumping, and improvements in water quality. These are real, measurable co-benefits. Water is left instream for ecosystems in Figure 4, but not in Figure 3. Six units of water are pumped (with a cost in energy and equipment) onto fields in Figure 3 but only three units of water are pumped in Figure 4. Substantial water-quality contamination might be avoided by minimizing agricultural return flows.

But that's not all. Efficiency improvements have another critical co-benefit often ignored in these assessments: improved reliability of limited supply. Figure 5 demonstrates this benefit. Consider a basin with two farms (Figure 5A) with field efficiencies of only 50% – they each apply two units of water to satisfy one unit of water demand. When available inflow is three units, Farm 1 takes two units, leaving one in the stream. Farm 2 takes one unit of return flow and one unit from the stream to satisfy its demand, uses one unit and returns one unit to the stream. Figure 5B shows the same farms but under conditions of drought or constrained supply. With only two units available, Farm 1 takes both units, dewatering the stream. It uses one and returns one. Farm 2 needs two units for its inefficient systems, but only one unit is available. Farm 2 must now fallow half its land, thus reducing production.

Figure 5C shows the same drought scenario, but now with improved field efficiencies. Now Farm 1 takes and uses only one unit, leaving one unit in the stream. Farm 2 takes and

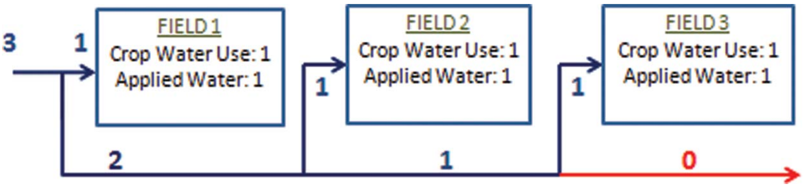

Figure 4. Efficient field efficiencies, full basin efficiency, substantial co-benefits. This example shows the benefits of improving field efficiency. It shows the same three Fields as Figure 3, and the same overall "basin efficiency" of 100%. But policies are implemented to improve field efficiency to 100% on all three fields. In this case, only one unit is applied to each field from the river, as needed, leaving instream flows. Less water also runs off the fields, with water quality improvements. Less water is pumped to each field, providing energy and infrastructure savings to each farmer. This example highlights some potential co-benefits of improving agricultural efficiencies even when no "new" water is created.

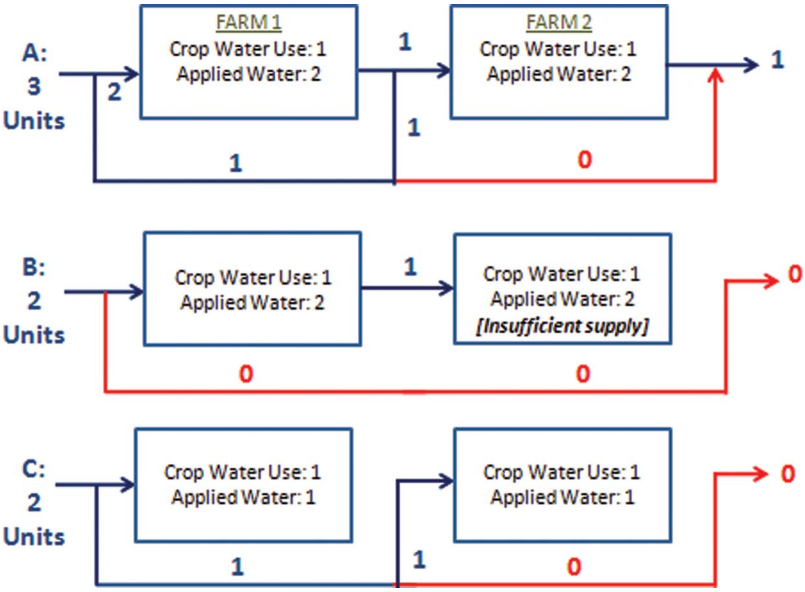

Figure 5. Efficiency improvements can also lead to improvements in water supply reliability, even during a drought, and even if no "new" water is generated. A: This figure shows two inefficient farms where two units are applied when only one is used productively. When three units of water are available, inflow leads to full production, but part of the river below Farm 2 is dewatered, and there are water-quality problems. B: In the event of a drought, only two units might be available. Now, with inefficient farms, two units of inflow leads to fallowing on Farm 2 because only one unit is available from the return flow from Farm 1. More of the river is dewatered. C: In the event of a drought, improvements in on-farm efficiency improve reliability and farm productivity. With efficient farms, two units of inflow permit full production at both farms, while also maintaining better instream flow and water-quality.

uses the remaining unit. While the stream is again dewatered (though only below Farm 2), Farm 2 is able to maintain full agricultural production. Thus, while the basin efficiency under drought is the same in both cases (100%), the improvements in field efficiency lead to improved water supply reliability, healthier streams, and continued agricultural production during a dry period.

The failure to consider these additional co-benefits of improving water-use efficiency highlights the danger of applying incomplete and inadequate theoretical approaches and metaphors to complex real-world problems. Over 20 years ago, Ostrom (1990) warned: "Relying on metaphors as the foundation for policy advice can lead to results substantially different from those presumed to be likely." Empirically, we see growing evidence of farms forced to fallow during drought periods (Draper 2009, Schneider 2009, Christian-Smith *et al.* 2010, 2011), increasing risks of non-point source pollution, including agricultural runoff, and new pressures to reduce energy requirements, including those associated with unnecessary or excessive water use. We note, for example, that non-point source pollution is the leading polluter of many U.S. waterways (USEPA 1996). These are the practical results of policies based on theories that isolate interconnected systems.

There are other disconnects between theory and the real world in Frederiksen and Allen (2011). For example, they imply that scientific irrigation scheduling practices have already been widely adopted, making any additional potential for improvements negligible. This conclusion is contradicted by field studies, for example the most recent Farm and Ranch

Irrigation Survey (USDA 2009), which finds that only 39% of farms in California are practicing some sort of scientific irrigation scheduling, a fact we also note in our agricultural efficiency studies (Cooley *et al.* 2008, 2009). They also claim that more robust irrigation scheduling will reduce crop yield. While this is, of course, possible, many field studies have documented increased crop yields or crop quality associated with irrigation scheduling practices (Christian-Smith *et al.* 2010, Ortega-Farías *et al*. 2004, Kranz 1992, Buchleiter *et al.* 1996, Dokter 1996, Eching *et al.* 1997, Eching 2002).

Frederiksen and Allen (2011) make one final argument against efficiency improvements that shows the illogical nature of their approach. They argue that inefficient irrigation is vitally important because excess irrigation "is a major contributor to aquifer recharge reducing the rate of overdraft in California's Central Valley" (p. 279). Here, we again find decision-making based on theory, rather than data. Not enough is known about groundwater recharge rates in many areas in the Central Valley, and there are portions of the valley that do not overlie accessible groundwater aquifers. While some excess irrigation certainly ends up back in aquifers, it is almost never 100%, and there are dislocations in timing and changes in water quality. In fact, the eight-county San Joaquin Valley has some of the most contaminated aquifers in the nation (Dubrovsky *et al.* 1998), and some recharge done with excessive applied water is leading to further contamination (Moore *et al.* 2011).[2] Secondly, their argument fails to consider that reducing unproductive demands can help reduce the withdrawal pressures on precisely those same overdrafted and contaminated aquifers.

Finally, their argument ignores the many active conjunctive-use projects throughout the world that have found that it is important to manage groundwater recharge for precisely the reasons described above. By reducing excess surface water withdrawals, that saved water can be used intentionally (not accidentally or incidentally) to recharge groundwater aquifers in the right places, at the right times. Such planned conjunctive use is a smarter and more sophisticated water management technique for managing groundwater overdraft, and it is being used more and more frequently.

Other misrepresentations of our work

Finally, we take issue with some additional specific misrepresentations by Frederiksen and Allen (2011) of the assumptions, findings, and conclusions of research from the Pacific Institute. Frederiksen and Allen (2011) imply that we ignore key characteristics of water use: (1) that impacts of efficiency programs on urban water use "are not universal but vary depending on location"; (2) that "recycling treated effluents to supply to recreational spaces are not adequately discussed"; (3) that we "ignore the fact that return flows are already part of the downstream water supply"; and (4) that all the water we identify through efficiency improvements is "new water." All of these claims are false.

(1) We have consistently noted that efficiency improvements depend on location and urged that "these kinds of estimates be done on local and regional levels as well, where uncertainties and data problems may be more readily resolved" (Gleick *et al.* 2003, p. 29).
(2) We were among the first to call for recycling and reuse of water as a way to reduce demand and expand supply, and we explicitly recommended that water agencies and policymakers "promote reclaimed and recycled water as a secure source for water supply" (Gleick *et al.* 2003, p. 16).

(3) As noted in this paper, we explicitly and regularly acknowledge the complex nature of water supply and the role of return flows – "In some cases, basin efficiency can exceed field efficiency. In these cases, conserving water does not necessarily increase the available water supply" (Cooley *et al.* 2009, p. 31) – but we also argue that *unproductive* or non-beneficial water loss should be reduced: "The multiple benefits associated with reducing overall applied water by reducing both consumptive and non-consumptive uses that are non-beneficial, strongly argue for a comprehensive approach that evaluates the potential for applied water reductions and creates policies to encourage water conservation and efficiency" (Cooley *et al.* 2009, p. 33).

(4) Again, as noted here, the arguments about the importance of "new" water as the only valid measure or goal of efficiency improvements are specious. Indeed, on the pages immediately following their criticism, Frederiksen and Allen reproduce an extensive section of our conclusions from Cooley *et al.* (2010) that clearly defines our terms and assumptions and contradicts their own criticisms. They also misrepresent the objectives of our efficiency analysis when they refer to "the proposed actions in the [Pacific Institute] Report for the irrigation sector *to free up water*" (p. 276, emphasis added). We do not state that it is a requirement for efficiency improvements to "free up water"; in fact, we argue the opposite, as we described above in Flaws 2 and 3.

Conclusions

Here we have attempted to move beyond the theoretical quagmire that has characterized the debate over water use and "basin efficiency" to a more comprehensive and useful approach, driven by proper water accounting and incorporation of the concepts of water "productivity" and "co-benefits." We have demonstrated in numerous analyses that common water conservation practices – including urban indoor and outdoor efficiency programs, precision irrigation systems, improvements in soil moisture monitoring and management, deficit irrigation, and other approaches – have enormous potential to conserve water in *some* basins and at *some* times, but we also have noted consistently in our research that we must have appropriate water-accounting procedures in place in order to identify the opportunities for water savings.

There is no "one-size-fits-all" solution to water management, despite efforts to find simplistic, "universal" answers. Water conservation and efficiency practices offer one set of tools to reduce pressures on scarce water supplies. Other options, such as increased storage, conjunctive use, water recycling, desalination, and other choices that seek to expand water supplies are also necessary in many regions. Every basin is different, and therefore the mix of demand-side and supply-side solutions will vary according to what is hydrologically, economically, socially, and politically possible. However, the faulty arguments that arise from narrow, disciplinary, twentieth-century theories about water uses no longer serve us. It is time to move away from a focus on practices that only produce "new" water or new supplies, on theories that ignore or underestimate co-benefits, and on narrow definitions of conservation and efficiency that misrepresent the potential for improvements in other measures of productivity and environmental sustainability. This requires an integrated basin-specific approach to sustainable water management that allows all solutions to water challenges to be analysed and compared in a systematic way.

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Notes

1. As one reviewer noted, it is possible to explore other changes in productivity associated with different components of this equation, such as:

   $P/Q_W = P_1/[Q_{CF(P)} + Q_{CF(P)}] + P2/[Q_{RF} + Q_{NRE}]$

   where $P = P_1 + P_2$. We leave this for another paper.
2. Twenty-four percent of domestic wells in tested in Eastern San Joaquin Valley during 1993-95 had nitrate concentrations above the legal limit of 10 mg/L nitrate-nitrogen (nitrate-N) (Dubrovsky *et al.* 1998). In 2006, the State Water Resources Control Board sampled 181 domestic wells in Tulare County and found that 40% had nitrate levels above the legal limit, in part precisely because of excess application of fertilizer combined with excess application of water and subsequent groundwater recharge with contaminated return flow (Moore *et al*. 2010).

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