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Impact of Irrigation Technologies on Water Use:

Clarifying Water Withdrawals and Consumptive Use

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Summary

When investing in new irrigation technologies, such as variable rate irrigation or putting sprinklers on drops, it is important to understand what the benefits are for both the producer and the watershed. The various components of the water cycle help explain how changes at the field scale impact water resources at the watershed scale. The topic of consumptive use of water is particularly important for making this connection; however, consumptive use tends to be a difficult concept to grasp. We address this need by providing a clear presentation of the topic of consumptive use in the context of crop production. Guidelines are given for determining whether a new irrigation technology, which reduces water withdrawals for irrigation, will also reduce consumptive use of water resulting in more water stored in the watershed and available to other water users or for use at a later date.

Introduction

In Nebraska and surrounding states, along with many other areas in the world, irrigation is the largest human-caused use of water. Optimal use of irrigation water is increasingly necessary to meet future water demands and to meet other economic, environmental, social, and political constraints.

Developments in irrigation technologies have led to more efficient irrigation application (Evett et al., 2020), meaning that a higher percentage of irrigation water is used by the plants with a lower percentage retained as increased soil moisture, return flow to the groundwater system, or lost to direct evaporation. Advanced technologies—such as variable-rate irrigation (VRI) and low-energy precision application (LEPA)—have reduced water withdrawals and/or diversions (from groundwater or surface water) for irrigation and may lead to a variety of benefits. These include decreasing groundwater pumping and pumping energy expenses, lowering the frequency/severity of yield loss due to over-irrigation, reducing irrigation runoff on slopes, and decreasing nitrate leaching. While increases in irrigation efficiency may reduce water usage, reduced water use may not necessarily translate to additional water being available for future or downstream use.

Next, we'll use the concept of 'consumptive use,' which we can apply to water withdrawals.

'Consumptive Use' Defined

Human intervention in the hydrologic cycle is often needed when water must be conserved to sustain a fresh water supply (surface water or groundwater), or to meet a downstream demand for fresh water. In this context, **the term 'consumptive use' is water used and not returned to the encompassing watershed**. In general, the largest consumptive use of water in a watershed is evapotranspiration (ET), the combined volume of water evaporated from the earth's surface and water transpired from crops or vegetation growth. If water were used for an industrial process for evaporative cooling, in which case the water is lost as water vapor, that would also be considered a consumptive use. However, a hydroelectric power plant that diverts stream water for generating electricity and returns that water to the same stream is not a consumptive use, because the water remains available to downstream users, except for the typically small direct evaporation component of the stream (Eisenhauer et al., 2021).

The next question is, how does the concept of 'consumptive use' connect to irrigation technology and irrigation application efficiency?

Misunderstandings about Conserving Water

A common misunderstanding regarding increasingly efficient irrigation technologies is that they uniformly "conserve" water with reduced pumping or diversion, resulting in more water available to future or downstream users. In an inefficient irrigation system, much of the "inefficiency" is due to the water that moves past the root zone, thereby increasing the amount of water held in the unsaturated layer between the root zone and the aquifer. Ultimately, this recharges either the same aquifer the water was pumped from, or a shallower "perched" aquifer, increasing groundwater storage (Figure 1). Fields lacking a containment structure may generate runoff that flows into a stream and is available for downstream users. Advancements in irrigation technology may reduce aquifer recharge by reducing inefficiencies, which previously led to deep percolation. At the watershed scale, the key concept is 'consumptive use,' water that is "consumed" (i.e., evapotranspiration or ET) and not returned to the water system for re-use by another water user. When examining the impacts of irrigation technology changes at the watershed scale, the best way to "conserve" water is to reduce consumptive use (Perry et al., 2009; Grafton et al., 2018). Reducing consumptive use of water is an important means of conserving water for other uses.

This misunderstanding is often applied to VRI technology. Stakeholders in Nebraska are rightly concerned about the declining groundwater levels and the subsequent impacts on streamflow. With proper management, VRI reduces pumping for irrigation, and it is often incorrectly assumed that a reduction in groundwater withdrawals will have a positive impact on groundwater levels and streamflow. Decision makers considering investing in new irrigation technologies (e.g., cost-share) must have a realistic assessment on the impact of water resources, considering both change in water use and overall change in consumptive use. Some of Nebraska's Natural Resources Districts (NRDs) implement allocations which limit the amount of water that can be pumped for irrigation, which may prevent producers from reaching full crop yields. Because of this, new technologies can be a tool for producers to maximize yields within an allocated amount of irrigation water. In this case, the new technologies reduce water losses, and consumptive use is likely increased (or at least not decreased) with a corresponding reduction in groundwater recharge, deep percolation, or runoff that would have otherwise returned (added water) to the water system.

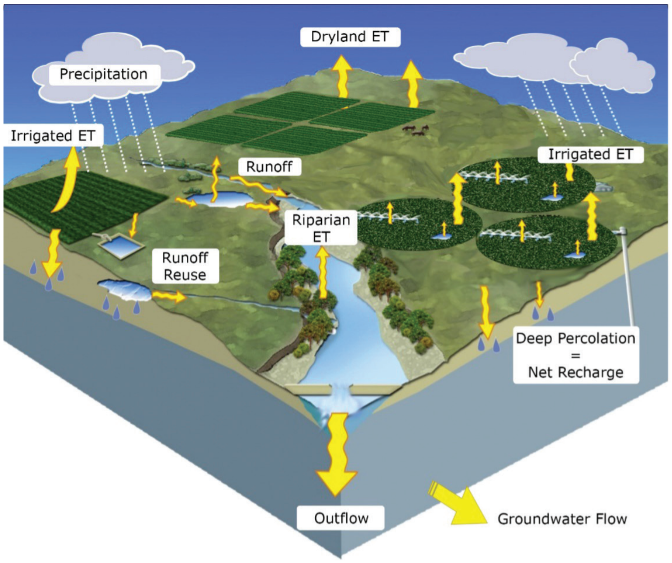

Fig. 1. Watershed-scale water balance (adapted from Eisenhauer et al., 2021). Some water "losses" are returned to the watershed. Over the long-term, the best way to increase the volume of water available to future and downstream users is to decrease consumptive use, which is primarily evapotranspiration (ET). Here, we use ET to include both ET from vegetated surfaces and direct evaporation from ponds and streams.

Applying the Concept of Consumptive Use

In many watersheds, it is desirable to maintain the current rate of consumptive use without increasing consumptive use. In some watersheds, it may be necessary to reduce consumptive use. Some studies have recommended reducing "non-beneficial consumptive use" (Perry et al., 2009), such as the ET of vegetation adjacent to an irrigation canal. This may or may not be practical; however, reducing consumptive use with no or minimal impact on crop yield is desirable.

For irrigated fields, **the 'consumptive use ratio' is the ratio of the change in consumptive use and the change in irrigation water applied** (Martin et al., 2010). The consumptive use ratio can be a useful metric to estimate potential consumptive use reductions for new irrigation technologies compared to conventional irrigation.

In terms of water law, the Nebraska Groundwater

Management and Protection Act defines both beneficial use and consumptive use as follows: Beneficial use means that use by which water may be put to use to the benefit of humans or other species; consumptive use means the amount of water that is consumed under appropriate and reasonably efficient practices to accomplish without waste the purposes for which the appropriation or other legally permitted use is lawfully made.

We'll now explore two scenarios that describe the impacts of irrigation technology on consumptive use in an irrigated field.

Scenario 1: New Technology for Irrigation Management

In this scenario, we focus on technology to determine timing and application depth of irrigation based on newer technologies, such as remote sensing data interpretation rather than more traditional approaches such as the hand-feel method for estimating soil water content.

We illustrate the concept of consumptive use with field data from Payero et al. (2008) for subsurface-drip-irrigated maize (corn) at the University of Nebraska–Lincoln's West Central Research, Extension and Education Center in North Platte, Nebraska. Using the data for seasonal evapotranspiration, seasonal depth of irrigation, and crop yield, we used two equations to estimate seasonal ET as a function of seasonal irrigation (Figure 2). Over-irrigated conditions are shown where additional irrigation does not increase yield.

We also defined **the "marginal consumptive use ratio" (*mCU*) as the change in consumptive use that would occur from a small change in seasonal irrigation** (i.e., the slope of ET-irrigation curve, Figure 2). In all cases, *mCU* begins at one (when seasonal irrigation is very small, on a scale of zero to one) indicating that all irrigation is used for ET. Eventually, as the applied irrigation depth increases, *mCU* becomes less than one, indicating that some of the additional irrigation (marginal irrigation) goes to consumptive use and some of the marginal irrigation goes to non-consumptive losses (runoff, deep percolation, etc.). When the applied depth becomes greater than the depth of irrigation required to attain a full yield, none of the marginal irrigation goes to ET (*mCU* = 0). In this range, any changes in irrigation that result in a reduction in application will not result in a reduction in consumptive use. This illustrates our framework for evaluating the impact of new irrigation technologies on consumptive use.

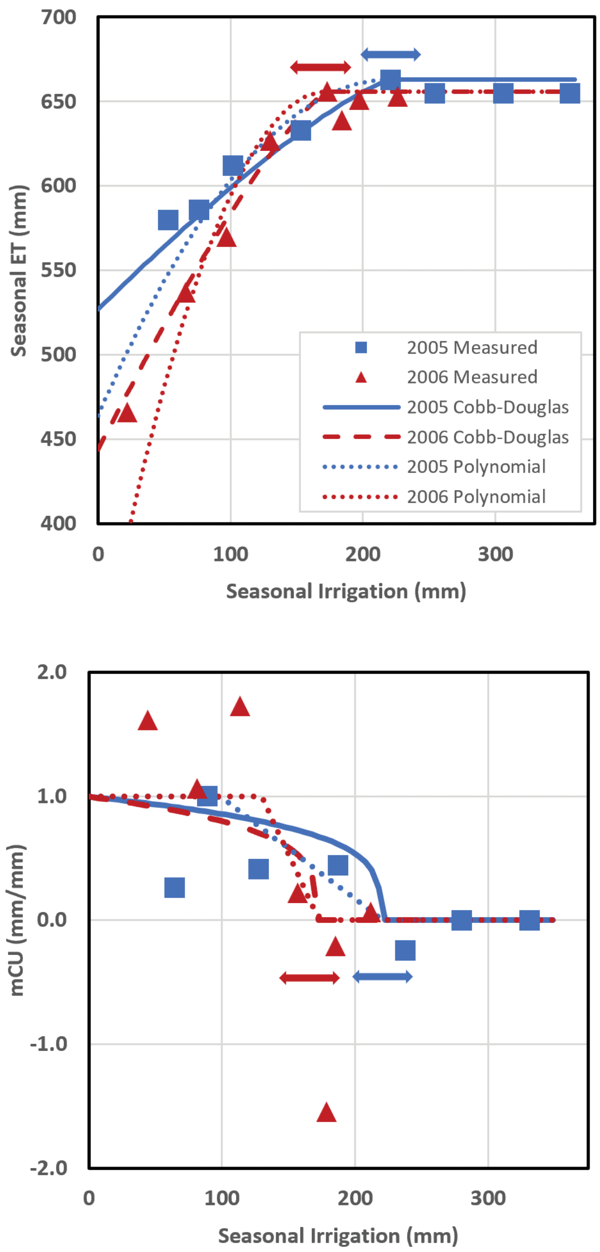

Fig. 2. Plots showing ET and *mCU* for a given water application method (figure adapted from Wilkening et al., 2021, and Payero et al., 2008). The block arrows illustrate a management range for full irrigation, correlating to the point of both the crop's full yield and plateau of seasonal ET. It is observed through the *mCU* that CU reductions are more likely in deficit-irrigation conditions.

For the purposes of practical irrigation management, we consider the full-irrigation depth to be within the range illustrated with the block arrows in Figure 2. More irrigation than this would be considered the over-irrigation range, while irrigation below the full-irrigation range would be considered in the deficit-irrigation range.

As an example, suppose the field in Figure 2 had a conventional center-pivot irrigation system with poorly managed irrigation scheduling, resulting in seasonal irrigation of 300 mm (~12 in). Suppose technology was used for irrigation scheduling which reduced seasonal irrigation to 250 mm (~10 in [still in the over-irrigation range in Figure 2]). Between 250 mm and 300 mm the *mCU* is zero, indicating that there would be no reduction in consumptive use from this technology. If the irrigation were already well managed, and technology was used to reduce seasonal irrigation from 250 mm to 200 mm (~8 in) in 2005 (Figure 2), then the *mCU* ranges from 0.0 to 0.5, indicating that there would be a small reduction in consumptive use.

Now, suppose that a field with a well-managed conventional center pivot was converted to a well-managed VRI system. For this comparison, data from field research at Mead, Nebraska, and Brule, Nebraska, resulted in *mCU* ranging from 0.13 to 0.99 for corn and soybean, with an average of 0.43 (Bhatti et al., 2020; Wilkening et al., 2021). This indicates that a 25 mm (1 in) reduction in water withdrawal would result in an 11 mm (0.43 in) reduction in consumptive use. On the other hand, if a poorly managed conventional irrigation system was converted to a VRI system, the *mCU* would be expected to be approximately zero (in the over-irrigation range in Figure 2), without a reduction in consumptive use.

In summary, this approach helps predict the potential benefits for adopting new technologies for irrigation management. Any reduction in water withdrawal has some positive results, including energy conservation and reduced water quality degradation (e.g., reduced nitrate leaching from reduced deep percolation). However, reductions in consumptive use are harder to predict. If the new technology is expected to reduce seasonal irrigation in the over-irrigation range (*mCU* = 0), then no reduction in consumptive use would be expected. A reduction in seasonal irrigation in the full-irrigation range (*mCU* around 0.2 to 0.5) may result in some reduction in consumptive use, which may or may not result in a small reduction in crop yield (while reduced ET usually results in yield loss, a small reduction in ET can occur without yield loss, Bhatti et al., 2022). If technology is used to reduce seasonal irrigation in the deficit-irrigation range (*mCU* > 0.4), then a large reduction in consumptive use is expected (with 40% to 100% of the reduction in water withdrawal coming from reduction in ET). This is particularly important to decision makers for determining when to provide cost-share and what the benefits would be.

Scenario 2: New Technology for Water Application Method

While the number of irrigated acres in Nebraska grows, adding 934,000 irrigated acres between 2002 and 2007 (Johnson et al., 2011), many older systems are also being updated and upgraded to more efficient application methods. As these upgrades continue to trickle across systems throughout the state, it is important to consider the impact they have on water resources, not just producing yield.

Scenario 2 includes changing the water application method. These are primarily system conversions (e.g., surface to sprinkler irrigation), which may result in a large change in application efficiency (Eisenhauer et al., 2021), but it could also be applicable to system upgrades such as switching from sprinklers on top of the pivot lateral to sprinklers on drops, or performing significant maintenance during a system checkup to improve application uniformity (Heeren et al., 2020). As a result of these changes, an irrigation manager is generally able to use less water for an irrigation event, because it is not necessary to compensate for low efficiency by applying additional water.

With the changes in water application method, consumptive use can be affected. Water mass balances (Figure 3) illustrate that the main component of water leaving a field-scale irrigation system is through ET, which is the main component of consumptive use in irrigation. In the illustrated systems, crop transpiration remains the main driver of ET; however, evaporation can be significant and the water application method may impact evaporation.

As an example, in a furrow-irrigated system significant water is lost as runoff (to return flows) and deep percolation (Figure 3); however, water evaporation from a furrow-irrigation system is minor. Consider a furrow-irrigated field with an unusual shape (therefore unable to accommodate a center pivot) that is converted to a subsurface drip irrigation system. The conversion would increase irrigation application efficiency, substantially reducing water losses for runoff and deep percolation. However, the consumptive use of the system would likely not change, as the total amount of ET would remain the same. The "losses" from furrow irrigation were not truly losses in the sense that the water was returned to the watershed.

If a center pivot with sprinklers on top (Figure 3) was converted to sprinklers on drops, or to subsurface drip irrigation, then the reduction in droplet evaporation losses would result in reduced consumptive use (particularly for semiarid locations with a low dew point). Irrigation allows for productive crops across numerous climatic and environmental conditions; however, these local conditions can have an impact on system performance. In Nebraska, climatic conditions differ greatly across the state, ranging from a subhumid climate receiving upwards of 75 cm (30 in) of annual precipitation to semiarid conditions receiving less than 50 cm (20 in) of annual precipitation (Irmak and Sharma, 2014). These conditions affect irrigation system efficiencies such as droplet evaporation rates, infiltration rates of irrigation water into the soil, and the amount of

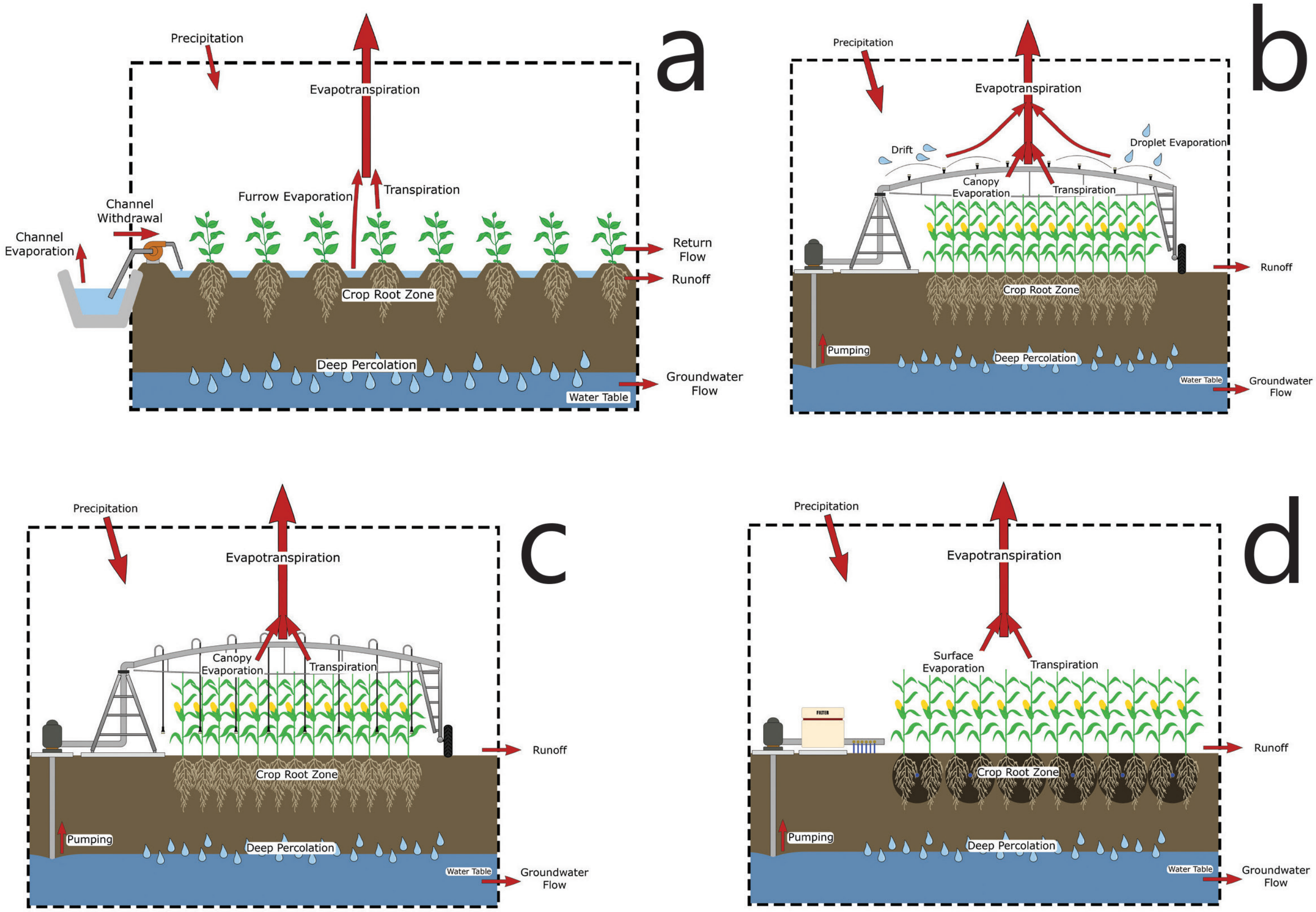

Fig. 3. Illustration of potential water flows, constrained to a field-level system, for furrow irrigation (3a), center-pivot irrigation with sprinklers on top (3b), center-pivot irrigation with sprinklers on drops (3c), and subsurface drip irrigation (3d). The aquifer (sand/gravel saturated with water) is shaded blue. (Figure adapted from Wilkening et al., 2021.)

deep percolation occurring. In locations where the dew point is high, rates of droplet evaporation are relatively small (Eisenhauer et al., 2021).

Although some losses are unavoidable, careful selection of system components can mitigate larger water losses, which is typically a benefit for water quality. In terms of consumptive use, using new technology for the water application method may or may not result in a change in ET. To the extent that a change in the water application method reduces evaporative losses (soil surface evaporation, droplet evaporation), consumptive use can be reduced without reducing yield. This provides insight into why technologies such as low-energy precision application and mobile drip irrigation have had more adoption in the more arid regions of the Great Plains, such as the Texas Panhandle; specifically, there are large potential reductions in droplet evaporation losses (due to the low dew point), and declining groundwater levels result in reduced well production rates (requiring reductions in consumptive use). The approach presented here for considering water losses (depending on water application method) can be helpful to both producers and decision makers when choosing whether to invest in a different water application method.

Conclusions

The concept of consumptive use, while difficult to grasp, is quite helpful in making the connection between field-scale irrigation management and watershed-scale water management. Watershed managers are often tasked with maintaining watershed consumptive use at a given rate, and are sometimes required to find ways to reduce consumptive use in the watershed. Our approach is focused on maintaining yield while looking for ways to reduce consumptive use. While technologies that reduce water withdrawals consistently help water quality and reduce energy costs, the impact on consumptive use is less clear.

We present approaches for two scenarios to help assess whether a given technology in a given situation will result in a reduction in consumptive use. For technologies that improve irrigation management, reduction in consumptive use depends on whether the reduction in seasonal irrigation is expected to be in the over-irrigation, full-irrigation, or deficit-irrigation range. For technologies that change the method of water application, reductions in consumptive use would be primarily expected in situations where droplet evaporation is reduced (especially in semiarid and arid climates).

For any irrigation technology being considered, a realistic expectation of benefits will result in more informed decisions. Considering consumptive uses within management practices can clarify expectations for decreased pumping and longer-term impacts on conserving water for future generations.

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