Irrigation System Efficiencies for Washington State:

Literature Review and Discussion of Irrigation Application Efficiency and Water Loss Destinations and How They Affect Long Term Water Availability

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Introduction

Managing water resources requires estimates of how much water is required and an understanding of where that water ultimately ends up. Irrigation accounts for the vast majority of water diversions in Washington State. Irrigation water use is especially relevant in the drier areas of the state where there are greater water shortages.

Some irrigation systems are inherently more efficient than others are. How efficiency is defined here is relevant. It is also relevant where the "lost water" goes since this water is sometimes recoverable and sometimes is not recoverable. This publication attempts to quantify the irrigation system efficiencies of various irrigation systems and where the "lost water" likely ends up.

Defining Irrigation Application Efficiency

Due to the conservation of mass, water can only change form or location. In an effort to make a comparison between systems and provide useful indices for improvement, we will use irrigation application efficiency (*Ea*, or efficiency of application) as the unit for comparing different irrigation systems (Kranz, 2020). It is defined as:

$$Ea = \frac{Avg.depth\ of\ irrigation\ water\ contributing\ to\ target}{Avg.depth\ of\ irrigation\ water\ applied} \qquad \text{Eq. 1}$$

Contributing to target in this case refers to increasing the soil water stored in the root zone (vadose zone) of the irrigated crop. This metric is useful because it allows for a comparison between the different irrigation systems regardless of the various final destinations of the "lost" water, whether it be deep percolation, wind drift and evaporation, or to field runoff (Figure). *Ea* can be measured directly using the change in soil water content in the root zone from before and after an irrigation. This is the depth of water stored in the root zone divided by the depth of water that would have been applied if all the water that flowed onto the field was stored in the root zone, as calculated from the flow rate, application time, and field area. There are calculators on http://irrigation.wsu.edu to help with calculating this denominator of this equation. *Ea* is typically determined or measured using different methods for different irrigation systems.

There are other definitions of efficiency including irrigation efficiency (*Ei*), which is water used beneficially divided by the water that is pumped or stored in the root zone (Burt et al, 1997). This accounts for irrigation scheduling and water use for an entire growing season. Water use efficiency (*WUE*) is also used and is the crop yield divided by the water that is pumped. This term includes all of the above aspects, but also includes the effects of deficit irrigation, water stress timing, etc. Other definitions account for water conveyance losses and are meant for basin-wide estimates of efficiency.

For the terms of this paper, we will focus on irrigation application efficiency, which focuses on the performance of the irrigation system at the field-scale. The various forms of water loss, or water that is inefficiently used at this field scale, are discussed below.

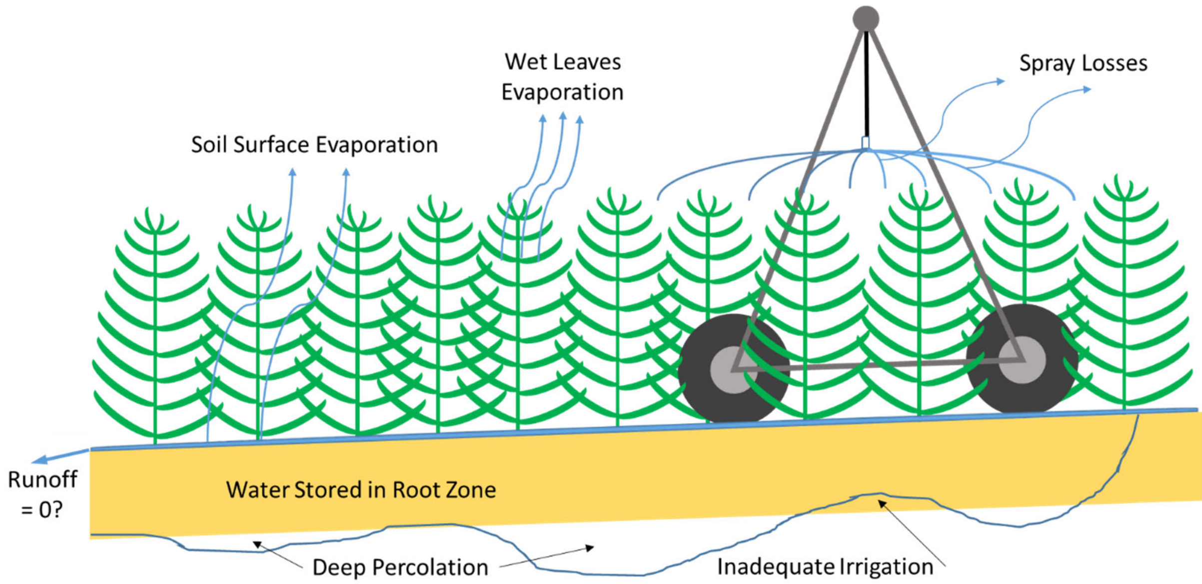


Figure 1. Water losses during irrigation include runoff, deep percolation, spray losses, and evaporation from a wet canopy and wet soil surface. The primary water losses from sprinkler irrigation are wind drift and evaporation (spray) losses and deep percolation due to non-uniform irrigation or imperfect irrigation scheduling.

Deep Percolation

Deep percolation, sometimes referred to as leaching, occurs when more water infiltrates into the soil than can be held long term in the root zone (the soil water content exceeds field capacity). This excess water moves through the soil profile and out past the bottom of the crop's root zone such that this water can no longer be accessed by the crop. Although this water is no longer useable for growing the crop, it continues moving on down through the soil and eventually into the groundwater. This groundwater may eventually be pumped up from wells for re-use. This water can also come out in river bottoms or in springs, becoming surface water again, and thereafter eventually flow out in rivers to the ocean.

In some areas of Washington, depending on the below-ground hydrogeology, deep percolation water will eventually be available for later use from wells. However, the water quality of deep percolation water losses can be severely degraded by its movement through the soil (primarily from nutrient additions or salinity), subsoil, and the underlying aquifer depending on the local soil and geology. This water quality degradation can limit its usefulness for other purposes including irrigation. The timing, quantity, and location of the eventual water recovery from deep percolation water losses is very difficult to monitor or predict. And although this can be thought of as recoverable, or "return flow", this water use is always lost to the farmer and the field crops.

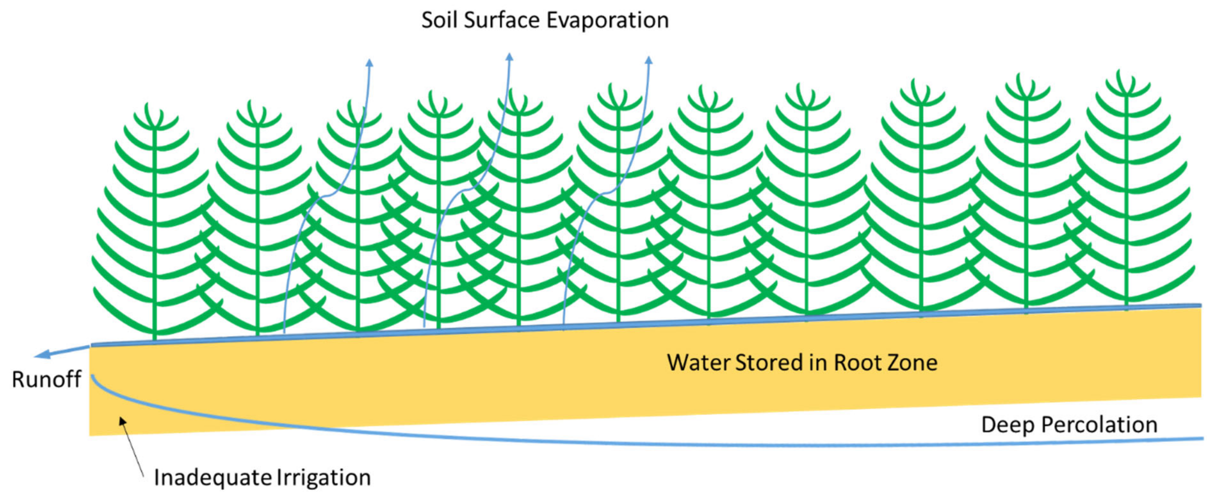


Figure 1. The primary water losses from surface irrigation are deep percolation and runoff.

Deep percolation is a very significant source of water loss in most irrigation systems, but it is especially prevalent in surface irrigation systems (Figure 1). Since water losses to deep percolation are not visible, most water managers (on-farm and state-wide) don't think about these very significant water losses. In irrigation, deep percolation primarily results from:

- Imperfect Irrigation System Uniformity – If an irrigation system or method cannot perfectly and uniformly apply the same amount (depth) of water to all areas of a field, then many areas must be over-irrigated (and cause water losses to deep percolation) in order to adequately irrigate the areas with lower application depths. No irrigation system is perfectly uniform and so a certain amount of deep percolation losses are expected if most areas of the field are adequately irrigated. Surface irrigation in particular forces water losses to deep percolation since it takes time for water to move across a field and thus the top part of the field has water infiltrating for many hours before the bottom of the field can receive any water (Figure 2).
- Irrigation Mismanagement – Irrigating too soon or too much such that all of the water that is applied cannot be held in the root zone will also result in this excess water "deep percolating" out of the crop's root zone.

Irrigation Uniformity and It's Relationship to Efficiency

Uniformity of surface irrigation systems is often estimated using soil infiltration rate curves and saturated time. Uniformity in sprinkler irrigation methods is most often tested with catch cans (Figure3). In drip irrigation systems uniformity is estimated using the variation in measurements of individual emitter flow rates.

Figure 3. A uniformity evaluation of a center pivot using catch cans.

A common index for quantifying irrigation uniformity is ‘distribution uniformity of the low quarter (DU, or DU_{lq})’. It is calculated as:

$$DU = \frac{AvgLowQuarter}{Avg} \qquad \text{Eq. 2}$$

where DU is a decimal that can be converted into a percent by multiplying by 100, and *AvgLowQuarter* is the average of the lowest ¼ of the measured application depths, and *Avg* is the overall average measured application depth (Figure 4).

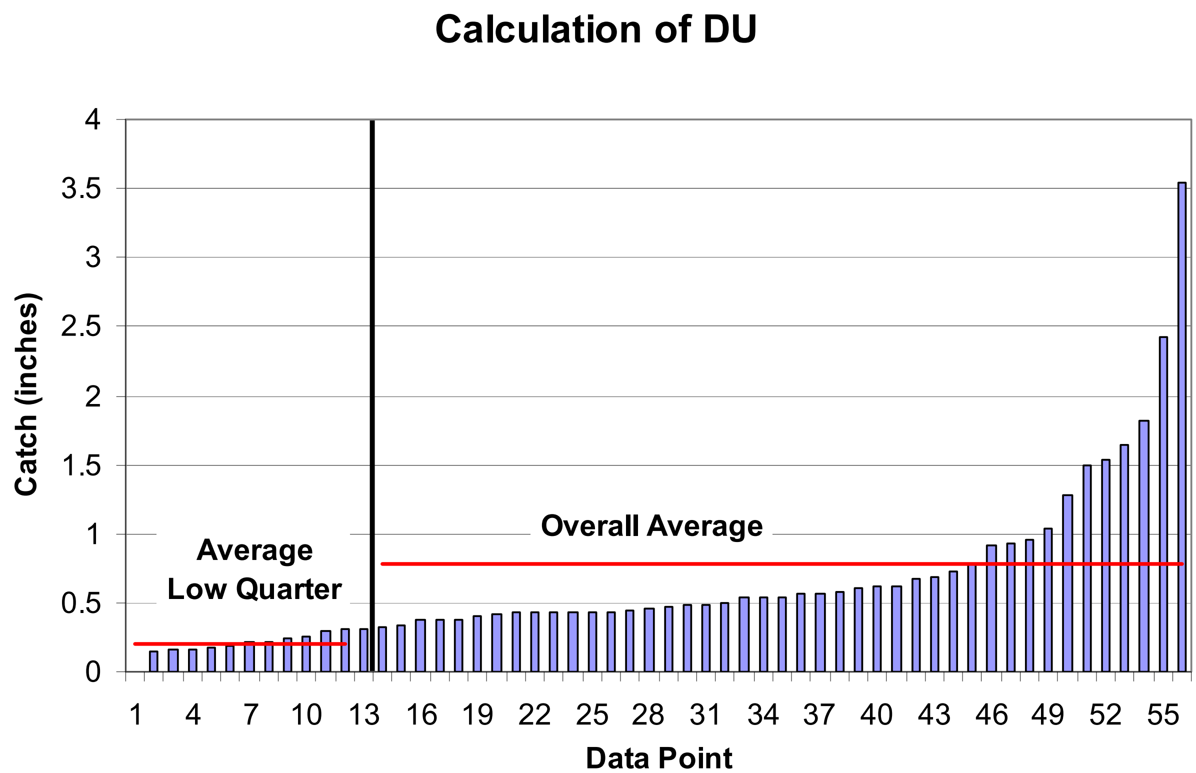


Figure 4. The application depths of an irrigation system uniformity test. The measured application depths (in catch cans in this case) are sorted, and the average of the low quarter is divided by the overall average. To adequately irrigate all areas of the field, additional water must be applied everywhere to adequately irrigate the low quarter.

Another commonly used uniformity index is the coefficient of uniformity (CU). This is one minus the mean absolute deviation of the individual observations divided by the mean of the observations. Written mathematically it is:

$$CU = 1 - \frac{\sum|individual\ obs. - mean\ obs.|}{\sum individual\ obs.} \qquad \text{Eq. 3}$$

where CU is a decimal that can be multiplied by 100 to get a %. The relationship between DU and CU is approximately:

$$CU = 1 - 0.63(1 - DU), \text{ or} \qquad \text{Eq. 4}$$
$$DU = 1 - 1.59(1 - CU). \qquad \text{Eq. 5}$$

Because of the limited wetted soil area for each emitter, drip irrigation system uniformity is a function of the variation in the individual emitter flow rates. It is often called emission uniformity (EU) but it is calculated the same as DU or as CU as shown above.

Most growers want to adequately irrigate all areas of the field and will thus over-irrigate some areas to adequately irrigate all areas. Indeed, most economic analyses show that this is the most economical way to irrigate. To adequately irrigate the low quarter (Figure 4), the necessary net application depth must be divided by the DU_{lq} of that irrigation system to increase the total gross application depth. If growers thus increase their application depths to account for poor uniformity then DU_{lq} is roughly equivalent to the way irrigation efficiency is used. If both are accounted for, the resultant equation is:

$$I_{gross} = \frac{I_{net}}{E_a \times DU_{lq}} \qquad \text{Eq. 6}$$

For example, if the DU_{lq} is 0.5 (pretty bad!) and the grower attempts to adequately irrigate the low quarter with one inch of water, then they would need to apply twice as much water (2 inches) to ensure that the low quarter got fully irrigated! CU is used similarly (by including it in the denominator of the gross application depth calculation) despite its difference in the method of calculation from DU_{lq}.

Irrigation application efficiency (Ea) and uniformity (DU) can be combined into the irrigation application efficiency of the low quarter Ea_{lq}. This is essentially E_a x DU_{lq}.

Improved management and maintenance to limit leaks and ensure good uniformity can greatly decrease water losses to deep percolation. Howard Neibling (Neibling)(University of Idaho) did a full evaluation of 30 hand-line and wheel systems and found a mean of 12% water losses to leaks on Thunderbird wheel-lines, 16% on standard wheel-lines, and mean of 36% losses on hand-line systems. On a typical 40-acre field, and with typical application depths, this amounts to 10 to 40 acre-ft of water on that field alone. Most of this water eventually goes to deep percolation. Obviously, these water losses are not trivial! (Figure)

Figure 5. A leaking wheel-line connection. The leak flow rate was over 180% of the flow rate of the sprinkler flow rate above it. Water losses from leaks go primarily to deep percolation when the field is otherwise adequately irrigated.

Runoff

Unlike the other largest losses (evaporation and deep percolation), irrigation water runoff from fields is very visible and thus most growers, irrigation districts, and law makers are aware of runoff and work to manage it. Although runoff water quality is often degraded, it is often collected in ponds or drainage ditches and is re-used downstream either for irrigation or for wildlife habitat.

Evaporation or Consumptive Use

Evaporation is when liquid water is converted to water vapor. All evaporation losses can be considered as total and permanent water losses to Washington State (consumptive use) since it is unlikely that this water vapor will have the chance to re-condense as rainfall and fall within the state. Reducing these types of water losses will have a significant impact on future total water availability for the state. In irrigation, the primary sources of evaporation water losses are:

- Sprinkler discharge (spray) losses to wind drift and evaporation,
- Evaporation from a wet canopy,
- Evaporation from a wet soil surface, and
- Plant transpiration.

Each of these are described and discussed below.

Sprinkler Discharge (Spray) Losses to Wind Drift and Evaporation

These water losses to wind drift and evaporation take place between the time the water leaves the sprinkler nozzle until the time the remaining water hits the soil. These losses are usually measured using catch cans placed at the soil surface. The depth of water that should be collected if all water that left the nozzle made it to the soil surface is compared with the actual depth of water caught. Because most of these losses leave the fields as water vapor, they are not visible and thus, like deep percolation, have the "out of sight, out of mind"-issue with capturing water managers' attention and are often not considered. However, these water losses are highly significant!

Many different catch-can tests from a wide variety of different scientists show that wind drift and evaporation losses range from close to zero to as high as 40-50% depending on the sprinkler type, height, pressure, and most importantly, the weather. Typical water losses are 35-40% for traveling big guns and pivot end guns, 25-30% for impact sprinklers on hand-lines or wheel lines, 15-20% for typical center pivot mid-elevation spray-application sprinklers, and < 5% for low elevation spray application (LESA) or low energy precision application (LEPA) sprinklers on center pivots (Alam, 1997; Association, 2010; Blaine Hanson, 2004; Brouwer et al., 1989; Charles M. Burt, 1995; C. M. Burt et al., 2000; Irmak et al., 2011; B. Kranz, 2020; T. R. Peters & McMoran., 2009. ; Rogers & Lamm, 1997; Sarwar et al., 2019; Solomon, 1988a, 1988b; Stetson & Mecham, 2011)

Evaporation from Wet Canopy

Water evaporation losses from a wetted canopy are usually a fairly consistent amount. This is because this depends primarily on how much water can be held on a wetted canopy, and thus depends primarily on the canopy size and the percentage of the canopy that is wetted. Some researchers have found that this water loss is about 0.05 inches after each irrigation. These losses are largely avoided in surface, drip (Figure 66), LEPA, or mobile drip irrigation (MDI) systems because these do not wet the crop canopy. Because these losses occur after every wetting of the canopy, they can be minimized by irrigating less frequently (requires greater depths of water applied per irrigation). However, irrigation frequency reductions are of course limited by the soil's infiltration rates, and the soil's water holding capacity.

There is a reasonable argument, however, that water evaporating from a wetted canopy cools that canopy and thus directly suppresses crop water transpiration because it robs the canopy of the energy required to otherwise transpire water from the crop, and thus the water losses may be compensated for by reductions in crop transpiration.

Crop canopy evaporation is also often considered into a crop coefficient that is used to model crop water use from weather data. This is similar to soil surface evaporation.

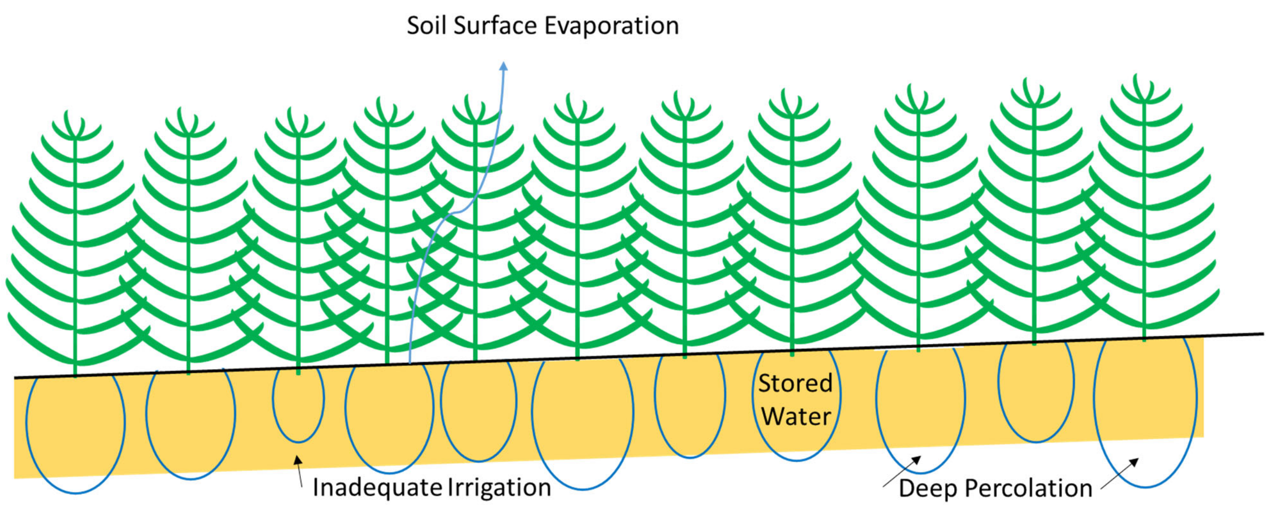


Figure 6. The water losses from drip irrigation are small. Soil surface evaporation is limited due to less soil surface being wetted. The primary water losses from drip irrigation are due to the differences in emitter flow rates which result in deep percolation if all plants are adequately irrigated.

Evaporation from a Wet Soil Surface

These losses are also usually about 0.05 inches after each irrigation. This can only be avoided by not completely wetting the entire soil surface, which is only possible with drip irrigation (especially subsurface drip irrigation or SDI), furrow irrigation (especially when irrigating every-other furrow), and with LEPA or MDI on center pivots. Soil surface evaporation can be separated out using dual crop coefficients, a basal or transpiration coefficient (K_{cb}), and an evaporation coefficient (K_e). However, like wet canopy evaporation, soil surface evaporation is included in the estimates for a combined crop coefficient, which is used in this paper.

Transpiration

Transpiration is water that is absorbed by the crop roots, travels through the plant stem and is transpired out of the leaves. Transpiration has been shown to be very linearly correlated with crop yield (Doorenbos & Kassam, 1979). Therefore, transpiration is the objective of irrigation, and it is usually not desirable to reduce or minimize transpiration. Of course, transpiration leaves the field as water vapor, and is thus truly "consumptive use", and as such is not considered recoverable in Washington State.

Consumptive Water Use Timing

Consumptive use is water that is essentially converted to water vapor (evaporation or transpiration). Once water is converted to water vapor, that water can be considered entirely lost to the drainage basin, and likely to the state of Washington. There are minor influences that this water vapor can have, such as slightly decreasing the air temperature and increasing the humidity which may suppress crop evapotranspiration (ET) downwind. However, one research paper showed that this resulted in only a 1% difference compared to the 20% differences in the wind-drift and evaporation losses of a MESA system compared to a LESA system. Thus, this suppression of ET downwind is minor related to the amount of water consumed by humidifying and lowering the temperature of the air (Molaei et al., 2023).

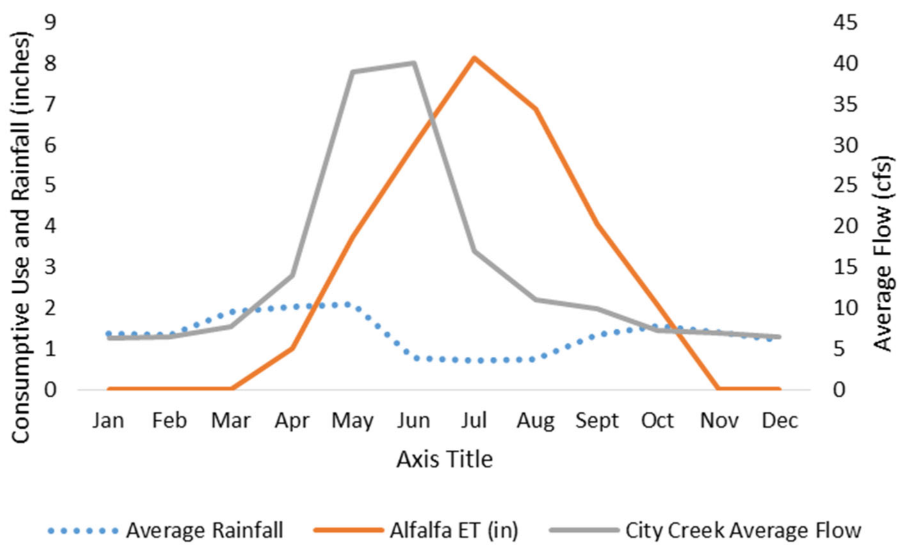


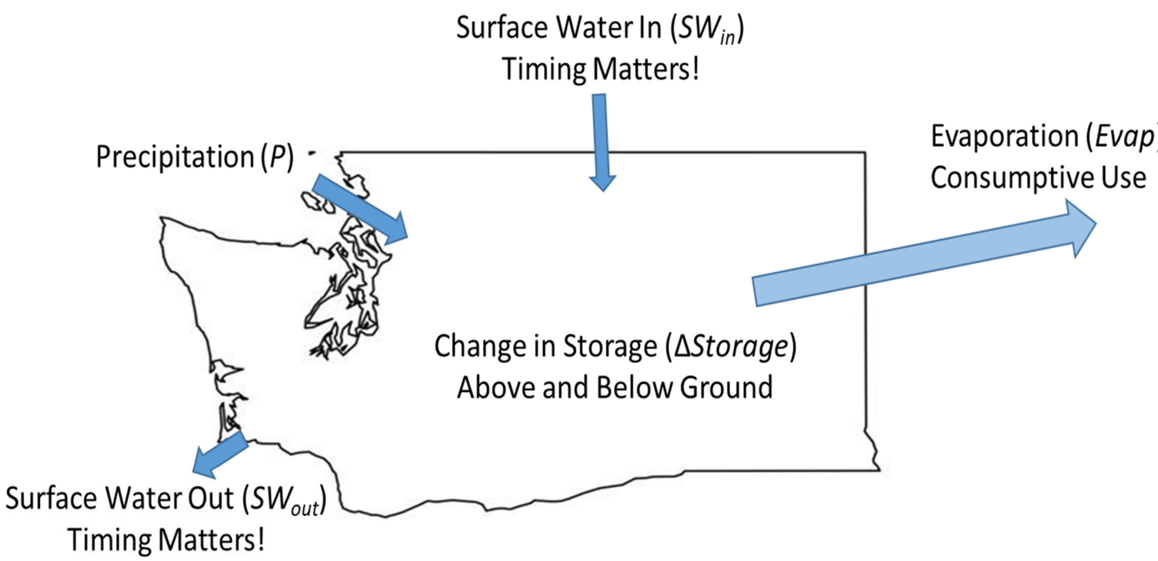
Figure 7. Example of the average consumptive use (ET), and rainfall compared to the stream flow rate in Salt Lake City, Utah's City Creek showing a typical disconnect between supply and demand for irrigation water.

The mountain snow melt in Washington peaks in May and June. However, the consumptive use of water for irrigation peaks in July and August (Figure 7). This disconnect between the timing of the supply and crop water requirements makes groundwater and reservoirs vital in the state to store this spring runoff for summer use. Climate change is predicted to cause the runoff to come earlier and the crop water needs to be greater. This would exacerbate this disconnect between water supply and water requirement timing which will likely necessitate either additional water storage, greater water conservation, or irrigated acreage reductions in the future.

The disconnect between the timing of water supply and demand should be kept in mind when evaluating irrigation and tillage technologies for water conservation. Some technologies conserve water mostly in the spring and fall when there are lower water needs and greater supplies (such as improved irrigation scheduling and deficit irrigation), while other technologies improve the water availability/productivity throughout the whole season, but especially during the hot part of the summer when the supplies are most limited, and the needs are the greatest (such as LEPA/LESA, MDI, and drip irrigation). This is because wind drift and evaporation losses are higher when evaporative demand is also high. A separate report describes various technologies and the expected water savings from these (Peters, 2024).

The Big Picture

When deciding which irrigation systems to promote, it is important to think of how they affect the water balance to the drainage basin or to the state as a whole. The major methods of water movement into and out of the state with the state-wide water balance is demonstrated in Figure 8 (below). We have no control over precipitation, and only limited control in the surface waters entering and leaving the state. However, Washingtonians can affect the change in surface and groundwater storage in the state by taking advantage of water from times when the demand is lower, such as in the winter, and they can try to limit evaporation (consumptive use) losses.



$$P + SW_{in} = \Delta Storage + SW_{out} + Evap$$

Figure 8. Considering the long-term water balance to Washington as a whole; the things we have the most control over with irrigation and tillage are the change in storage and the evaporation losses.

Irrigation system efficiency and estimates of how the final destination of the water losses affects the overall water balance in the state of Washington are shown in Irrigation Application Efficiency Estimates for Washington State Table . This information was compiled from a wide variety of publications (Alam, 1997; Association, 2010; Blaine Hanson, 2004; Brouwer et al., 1989; Charles M. Burt, 1995; C. M. Burt et al., 2000; Hanson, 1994; Irmak et al., 2011; Kisekka et al., 2016; B. Kranz, 2020; S.-H. Sadeghi et al., 2015; S. H. Sadeghi et al., 2017; Solomon, 1988a, 1988b; Stetson & Mecham, 2011; Steve R. Melvin & Martin, 2018). Based on this research and similar research reports, attempts were made to allocate the fraction of the water losses that end up as deep percolation, wind drift and evaporation, or field runoff.

Irrigation Application Efficiency Estimates for Washington State

Table 1. Irrigation system efficiency* comparisons and estimates of the affects to the overall water balance in the state of Washington.

Type	Irrigation System	Irrigation App. Efficiency *Ealq* (%)	Primary Destination of Water Losses	Irrigation Efficiency Range (%)	Fraction of Losses to DP (%)	Fraction of Losses to WDE (%)	Fraction of Losses to RO (%)	Total Consumptive Use (%)	Return Flow (%)
Sprinkle	Pivot/Linear MESA	79	WDE	75-90	27	73	0	94	6
	Pivot/Linear LEPA	91	WDE	80-97	100	0	0	91	9
	Pivot/Linear LESA	92	WDE	80-97	62	38	0	95	5
	Pivot/Linear (Top of Pipe)	56	WDE	50-70	9	91	0	96	4
	Hand move	68	WDE	60-85	16	84	0	95	5
	Wheel Line	68	WDE	60-85	16	84	0	95	5
	Microsprinkler	75	WDE	80-90	27	73	0	93	7
	Undertree Orchard	77	WDE	75-93	30	70	0	93	7
	Solid Set Sprinklers	67	WDE	70-85	26	74	0	91	9
	Big Gun - Traveler	59	WDE	50-70	16	84	0	93	7
Surface	Furrow	62	DP, RO	30-90	50	5	45	64	36
	Graded Furrow	73	DP, RO	30-90	50	5	45	74	26
	Furrow w/ Surge	75	DP, RO	60-90	50	5	45	76	24
	Furrow w/ tailwater reuse	80	DP, RO	60-90	100	0	0	80	20
	Basin	75	DP, RO	40-95	100	0	0	75	25
	Border	65	DP, RO	40-90	50	5	45	67	33
	Contour Border	73	DP, RO	55-90	50	5	45	74	26
	Corrugation	50	DP, RO	40-75	50	5	45	52	48
	Wild Flood	35	DP, RO	25-85	50	5	45	38	62
Drip	Subsurface drip	92	DP	65-98	100	0	0	92	8
	Surface Drip	89	DP	65-96	100	0	0	89	11
	Mobile Drip Irrigation	97	DP	65-99	100	0	0	97	3

* Irrigation application efficiency of the low quarter (Ea_{lq}) is defined as the water stored in the root zone divided by the water flowing onto the field. DP is deep percolation, WDE is wind drift and evaporation, and RO is runoff. A calculator to estimate water savings and the destination of those water savings based on this table is at http://irrigation.wsu.edu/Content/ConversionCalculator.html. Definition of terms, calculation methods, data sources, and explanation of assumptions follows.

Definition of Terms in Table 1

Table 1 Columns

Irrigation Application Efficiency of the Low Quarter (Ea_{lq}): Water that is stored in the soil for evaporation or transpiration (evapotranspiration or ET) by the crop divided, by the overall water that flows onto the field (Equation 1) x 100. The water that is not stored in the root zone for later ET by the crop includes water lost to deep percolation, wind drift and evaporation (primarily from sprinklers), and field runoff. This is reasonably adjusted for uniformity (see details about the edits for sprinkler surface and drip below) for typical season-long non-uniformity issues.

Primary Destination of Water Losses: No system is 100% efficient. The water losses from different systems go primarily to various destinations including wind drift and evaporation (WDE), deep percolation (DP), and runoff (RO).

Irrigation Efficiency Range: Irrigation application efficiency ranges considerably depending on a wide variety of factors, fields, system characteristics, operating conditions, weather, maintenance, timing, and irrigator. The named ranges are what is typical.

Deep Percolation (DP): When more water is applied than the soil can hold in the crop's root zone, the excess water drains through the soil and out past the reach of the crop's roots and enters the groundwater. Much of this water can be eventually recovered, albeit often with changed water quality, by pumping the groundwater from wells.

Wind Drift and Evaporation (WDE): Sprinklers lose large amounts of water to wind drift and evaporation. Although this humidifies and cools the air and thus can decrease crop water demand down-wind, these changes in water demand have been shown in research to be minimal. Thus, nearly all this water leaves the basin as water vapor and can be considered to be forever losses.

Runoff (RO): Irrigation water runs off of a field when water is applied faster than it can be absorbed by the soil or used by the crops. Much of this water is often captured and used downstream.

Percent Losses to DP: Percent *of the losses* ($100 – Ea_{lq}$) that go to deep percolation (DP). Calculated as losses to DP / total irrigation water flowing onto the field x 100. Deep percolation losses stay in the basin and are thus sometimes referred to as “return flows”.

Percent Losses to WDE: Percent *of the losses* ($100 – Ea_{lq}$) that go to wind drift and evaporation (WDE). Calculated as: losses to WDE / total irrigation water flowing onto the field x 100. Wind drift and evaporation losses leave the basin and are thus part of “consumptive use”.

Percent Losses to RO: Percent *of the losses* ($100 – Ea_{lq}$) that go to field runoff (RO). Calculated as: losses that go to field runoff / total irrigation water flowing onto the field x 100. Run off losses stay in the basin and are thus sometimes referred to as “return flows”.

Total Consumptive Use (%): The percentage of the total gross irrigation water required that is consumptive use (evaporation and transpiration). Calculated as the $Ea_{lq} + [(100 – Ea_{lq}) \times (WDE + 0.1 \times RO) / 100]$. Or it can be calculated as 100 – Return Flow %. This assumes that all of the irrigation water requirements and all wind drift and evaporation losses, and 10% of field runoff (additional evaporation from tailwater ditches and weed growth) is consumptive use (converted to water vapor).

Return Flow (%): The percentage of the total gross irrigation water required that is return flow. Calculated as $(100 - Ea_{lq}) \times [(DP + 0.9 \times RO) / 100]$ or as 100 – total consumptive use %. This assumes that all deep percolation and 90% of runoff losses are eventually recoverable (return flow).

Irrigation Systems

Center Pivot/Linear MESA: Mid-elevation spray application. A center pivot or linear move irrigation system with sprinklers mounted at a mid-elevation of about 5-12 ft from the soil surface. This is currently the most common sprinkler configuration on center pivots.
Center Pivot/Linear LEPA: Low-energy precision application. A center pivot or linear move irrigation system with emitters mounted close together and close to the soil surface such that water dribbles directly onto the soil surface. These systems are very efficient but can require additional tillage and planting management for uniform irrigation and avoid surface runoff.
Center Pivot/Linear LESA: Low-elevation spray application. A center pivot or linear move irrigation system with sprinklers mounted close together and close to the soil surface (6-24 inches) but with spray emitter device on each sprinkler. These systems are very efficient, but can sometimes exacerbate runoff problems due to the sprinkler's reduced wetted radius.
Pivot/Linear Top of the Pipe: A center pivot or linear move irrigation system with high pressure impact or rotator sprinklers mounted on the top of the pipe. Although the application rate is slower, these systems lose a tremendous amount of water to wind drift and evaporation and inefficient.
Hand Move: Sprinkler irrigation systems with larger wetted radii (10-40 ft) where there is usually one sprinkler per span of pipe, and the pipe is disconnected and moved by hand throughout the season.
Wheel Line: Sprinkler irrigation systems with larger wetted radii (10-40 ft) where there is usually one sprinkler per span of pipe, but the pipes have a wheel mounted such that the entire line can be moved simultaneously with a mover at the center of the line.
Microsprinkler: Emit water at lower pressures and low flow rates and have smaller wetted radii (3-10 ft). Most often used in orchards or vineyards.
Under-tree orchard: Sprinklers (often impact or rotating type sprinklers) that operate below the canopy in orchards.
Solids Set Sprinklers: Sprinkler irrigation systems with larger wetted radii (10-40 ft) where the sprinklers are not moved throughout the irrigation season.
Big Gun – Traveler: A large, usually singular sprinkler with a large nozzle size and operates at high pressure such that it has a large wetted radius. These are usually attached to a hose that reels the sprinkler in slowly to irrigate a strip.
Furrow: A surface irrigation method, common in cultivated row crops, where water flows accross the field in furrows or rills that are tilled into the soil, usually between every crop row, or every-other crop row.
Graded Furrow: A surface irrigation method where water flows through furrows or rills where the land has been graded to make the water flow more evenly across the soil surface to increase the infiltration uniformity.
Furrow w/ Surge: Furrow irrigation where the water is controlled such that it applies water in pulses. This wetting and settling affects the infiltration rate of the previously wetted soils such that it results in improved irrigation uniformity, and thus efficiency. It usually requires an automated valve and gated pipe to work effectively.
Furrow w/ Tailwater Reuse: Furrow irrigation where the runoff water is collected in a small pond or basin and pumped back up to the top of the field for re-use. This limits runoff.
Basin: A surface irrigation method used in very level fields where irrigation flows onto the field and fills it up like a bathtub. Runoff is restricted.
Border: A surface irrigation method where water flows evenly (ideally) accross a field as restricted by borders on each strip of land.

Contour Border: A surface irrigation method where water flows onto a field that has been contoured with built up borders such that, on the overall slope, each countour is level.
Corrugation: A surface irrigation method where corrugates (small rills) are plowed in to help the water flow more evenly accross the soil surface. This is more common in forage production.
Wild Flood: A surface irrigation method where water is turned out without grading, furrows, or corrugations to guide its flow accross the soil. More common in forage production in mountain valleys.
Subsurface Drip: Drip irrigation with the drip tubing or emitters buried beneath the soil surface.
Surface Drip: Drip irrigation with the drip tubing or emitters placed on the surface, or just above the surface of the soil.
Mobile Drip Irrigation: A center pivot or linear move irrigation system that drags drip tubing with integrated emitters.

Notes About Table 1

Wide Variation in Reported Values in Literature

Irrigation system application efficiency values reported in literature are almost always summaries quoting other summaries. There are very few recent studies that are reporting direct measurements of irrigation application efficiency for a particular type of irrigation system. The wide variations are because the individual irrigation efficiencies can vary significantly depending on many things!

For surface irrigation application efficiency depends primarily on the field soil, field size, slope, and flow rate used. For example, the variation for furrow irrigation can vary from 20% to almost 100% depending on the soil type, slope, run length and flow rate used. A slow flow rate in a sandy soil may never reach the end of the furrow resulting in a very low efficiency, yet a blocked-end furrow with a shorter run, higher flow rate, a very precise set time, and in a clay soil may result in almost 100% irrigation application efficiency.

For sprinkle irrigation methods, irrigation application efficiency depends primarily on pressure, nozzle sizes, sprinkler types, and nozzle height, but it depends mainly on the weather. The irrigation application efficiency for a hand-line may vary from 20% to 95% depending on the weather (primarily wind speed and vapor pressure deficit or aridity), the operating pressure, sprinkler nozzle size, sprinkler type, and sprinkler spacing that was used for the test.

Therefore, it is difficult to put a single value on irrigation application efficiency and this is why ranges are most often reported. However, it is acknowledged that a single efficiency value may be needed for general planning and routine water allocation purposes. In those situations when a field-specific value is desired, it could be measured by a Certified Agricultural Irrigation Specialist (USDA-NRCS, 1997).

Assumes 90% of Runoff Water is Recovered

The estimates of consumptive use assumes that WDE is forever lost to the farm and to the state. It assumes that all DP is eventually recoverable from groundwater or spring flow, but that only 90% of runoff water is recoverable and that 10% of that recovered water is lost to evaporation from the drainage ditch and/or plants and weeds that grow along those ditches.

Perfect Irrigation Scheduling Assumed

These efficiency estimates assume no water losses due to imperfect irrigation scheduling. In other words, it assumes perfect irrigation scheduling. This is difficult to achieve and thus uncommon. Most irrigation scheduling studies show a wide range of reductions in overall water applications when perfect irrigation scheduling is practiced because grower behavior across the board is extremely variable for a wide variety of reasons including labor availability, labor costs, time and skill, understanding of appropriate irrigation scheduling methods, understanding of their irrigation system in comparison to their soil and crop, keeping track of daily variations in ET, etc. Because of this, it is very difficult to plan for those savings. Many studies have shown a mean 10 - 15% reduction in overall water savings is reasonable (Navigant Consulting, 2010). These non-included-water-losses due to imperfect irrigation scheduling usually end up as deep percolation water losses.

Caveats

To have usable tools we need them to be simple and not require large numbers of inputs that users will not know. However, using a single number for efficiency estimates is always going to be problematic since efficiency can depend on so many other things! These include factors such as:

- Weather and Climate! We know that efficiency is strongly a function of wind speed and vapor pressure deficit (aridity) and thus irrigation efficiencies change drastically over the year, especially wind drift and evaporation losses! Sprinkler irrigation application efficiency can vary from close to zero to almost 100% depending on the system and weather conditions, for example.
- Sprinkler system operating pressure (both for wind drift and evaporation losses and proper uniformity to reduce deep percolation losses)
- Sprinkler wetted radius
- Sprinkler design (rotator plate design, spinners, wobblers, rotators, impacts vs rotators, etc.)
- Sprinkler height above ground level
- How things change as the rows close vs. a bare soil, perennial vs. annual crops, etc.
- Inter-row cover crops in perennial crops such as tree-fruit and vineyards
- Row spacing for furrow irrigation
- Whether furrows are irrigated in every row, vs. every-other row
- Subsurface drip irrigation burial depth (sometimes the surface is wetted, sometimes it isn't)
- Irrigation frequency! More frequent irrigations result in comparatively more water losses to evaporation from a wet crop and wet soil surface.
- Soil type (this affects water infiltration rates, soil surface evaporation rates and duration, and the soil water holding capacity affects irrigation frequency)
- Tillage and surface residue management (can affect infiltration and runoff)
- Crop canopy type (affects water interception, transpiration, and soil surface evaporation)
- Irrigation system maintenance (most estimates assume better maintenance than is common)
- Total water requirements, rainfall, and irrigation applied to the field
- Grower behavior and skill! Especially as related to irrigation scheduling, maintenance, and controlling runoff. Irrigator skill is especially important and variable for surface irrigation methods.

However, to help guide decision making, this table and conversion estimate tool contains our best, research-based estimates of what might be expected, on average, over time, in a large drainage basin. If you are aware of better research data, please contact us!

Detailed Notes about Irrigation System Efficiency and Estimates

Reference System

It is assumed that Table 1 will be used for comparing different irrigation systems. Therefore, a reference condition needs to be defined. Unfortunately, there hasn't been good research on the absolute water losses from soil surface evaporation on things such as furrow row spacing width, every furrow vs. every-other furrow, or the differences in drip soil surface evaporation for surface vs buried drip or drip vs sprinkle irrigation in a way that separates soil surface evaporation from other water loss components. Therefore, the reference system for comparison is one where the entire soil surface is wetted as in sprinkle irrigation.

It is also relevant to consider how these efficiency estimates are used or what they are compared against. It is assumed that these will be used primarily with weather-based estimates of evapotranspiration (ET) for estimating seasonal water requirements or used in a general way to compensate for inefficiencies with irrigation planning and management. When calculating ET, soil surface evaporation can be separated out from crop transpiration using a separate crop coefficient for transpiration (basal crop coefficient K_{cb}) and a separate one for evaporation (evaporation coefficient K_{ce}) that varies with irrigation frequency. This is called the dual crop coefficient approach. In Washington State, using the dual crop coefficient approach is uncommon, and no attempt is generally made to separate transpiration from evaporation since it requires soil data, irrigation frequency information, and wetted-surface condition data that are not generally available, especially for more general planning and management for an "average" field as opposed to precise management of an individual field. Thus, a single crop coefficient is used that includes averaged-in water losses to soil surface evaporation as if the soil surface was entirely wetted. This again means a reference condition where the entire soil surface is wetted as in sprinkle irrigation is warranted.

Sprinkle Irrigation Application Efficiency Details

Sprinkle irrigation application efficiency and uniformity values are primarily determined by using catch cans that are placed on the surface of the soil. The cans are set out, the sprinkler is run, and then the variability in the catch depths is analyzed to calculate DU or CU. The mean catch depth is compared to the depth of water that would have been caught if all water that left the sprinkler nozzles was collected in the cans (i.e. mean catch depth divided by the theoretical 100% efficiency depth calculated using nozzle flow rates and catch area). Unlike drip and surface irrigation application efficiency, which are primarily determined using irrigation uniformity, the literature-reported irrigation application efficiency values for sprinkle irrigation do not typically include the effects of nonuniformity. When they do, it is referred to as the "application efficiency of the low quarter". For a fair comparison, irrigation application efficiency should include the water losses to deep percolation that are unavoidable (Figure 1) if the irrigator adequately irrigates all areas of the field as in Equation 6 above.

Unlike surface irrigation, where the non-uniformity occurs on a large scale, or with drip irrigation, where there is much less overlap between the wetted areas from each emitter, several studies have shown that at least some of the catch-can-measured non-uniformity of sprinkler irrigation systems is not relevant and is unimportant. This is because of soil-surface redistribution of water, redistribution of water from wet areas to dry areas by the soil underneath the surface, and by the fact that plant roots can access the water in wetter areas of soil within their spreading root zones. Mohamed et al. (2019) showed that when accounting for this unimportant variability on a small scale from catch can measurements, the DU_{lq} increased by 6 to 8% resulting in a reduction in 9 to 13% of the estimated water required if the gross amount of water applied is adjusted to adequately irrigate the low quarter as in Equation 6.

In addition, poor irrigation system DUs and CUs as measured by an individual test can be partially compensated for by the changing wind effects over multiple irrigation events, and by moving irrigation systems. With moving irrigation systems (center pivots, hand-lines, wheel-lines, pods, etc.) there is a chance that on the following set the high application areas have a chance to fill into the low application areas from the previous set. In one experiment, CUs increased from a mean of 76% for individual CU evaluations to a seasonal CU of 86% (Dechmi et al., 2003) by offsetting hand-line sprinkler sets. Wind can also move the applied water around such that subsequent irrigation depths may also help compensate for low irrigation system uniformity. Because of this, using an individual DU or CU measurement in the equation to calculate seasonal gross irrigation is not warranted without some sort of correction.

Adjustment to Sprinkler Irrigation Application Efficiency for Deep Percolation Due to Nonuniformity

Since Table 1 is meant to be used as a comparison between irrigation systems, water losses to deep percolation from sprinkler irrigation systems need to be estimated and included. The minimum DU_{lq} that is often considered acceptable for sprinkler irrigation systems is 0.8 (WSDA minimum requirement for using sprinklers for chemigation). However, this is over-simplified because some of this non-uniformity doesn't matter much because of: surface and soil redistribution, the plant root’s ability to reach water, and because moving sprinklers or variable winds compensate for low application depths with higher depths on the next irrigation event (i.e. it averages out a bit).

Table 2. Demonstration of sprinkle irrigation application efficiency revisions for DU_{lq}.

Sprinkle Irrigation System	Catch-Can-Based Ea	Target DUlq	Moving or Static	Adjustment	Revised DUlq	Revised Ealq
Pivot/Linear MESA	85	80	Moving	0.67	95	79
Pivot/Linear LEPA	97	80	Moving	0.67	95	91
Pivot/Linear LESA	97	85	Moving	0.67	85	92
Pivot/Linear (Top of Pipe)	60	80	Moving	0.67	95	56
Hand move	73	80	Moving	0.67	95	68
Wheel Line	73	80	Moving	0.37	95	68
Microsprinkler	82	85	Static	0.45	92	75
Undertree Orchard	84	85	Static	0.45	92	77
Solid Set Sprinklers	76	80	Static	0.45	89	67
Big Gun - Traveler	65	70	Moving	0.67	90	59

The adjustment is based on research that shows that 55% of crop uniformity can be explained by DU issues. This means that 45% of DU variations don’t affect crop uniformity and thus might be discounted. Research also shows that 40% of the differences between DU values can be made up for by moving irrigation systems. Thus the *Adjustment* to DU_{lq} for static irrigation systems is 0.45, and the *Adjustment* for moving irrigation systems is 0.67. 0.67 is calculated from 0.45 + (1 – 0.45) x 0.4. The *Revised* DU_{lq} is calculated as: (100 – *Target* DU_{lq}) x *Adjustment* + *Target* DU_{lq}. The *Revised* Ea_{lq} is thus *Catch-Can-Based Ea* x *Revised* DU_{lq}. The target DU_{lq} is a number that is reasonable to expect for that system. i.e. on the high side of typical. An explanation for the values in Table 2 are given below.

Pivot/Linear MESA

This is the most common irrigation system currently in use in the arid western United States. There have been lots of tests on these types of systems and it has been shown that irrigation application efficiency varies widely depending on the weather; primarily the vapor pressure deficit (aridity) and wind speed. Most Ea tests average about 85% in humid climates, and 77% in arid climates (example Mohamed et al, 2019; Amini et al, unpublished data; Sarwar et al, 2019). Griffiths (2006) found an average of 86% in a wide variety of studies. We chose the value of 85% for our study.

The measured DU_{lq} values of various systems also vary widely depending on maintenance. Most evaluations of MESA systems have fairly low DU_{lq} values ranging from 0.5 to 0.75. In a summary of various evaluation reports worldwide, Griffiths (2006) found an average DU_{lq} of 0.73. DU_{lq} depends on design, and management practices, but a well operating system is about 0.8, and indeed a DU_{lq} of 0.8 is the standard threshold adopted by the Washington State Department of Agriculture (WSDA) for the minimum requirement when using a center pivot for chemigation. A DU_{lq} value of 0.8 was chosen for center pivots.

Figure 9. Water being lost to the wind on a center-pivot irrigation system. Only the droplets are visible. Water losses once converted to water vapor are no longer visible.

Pivot/Linear LESA

Low elevation spray application (LESA) is a modification of the sprinkler configuration on a center pivot such that the sprinkler nozzles are just a few inches off of the ground. At this height there is very little opportunity for wind drift and evaporation and they are significantly more efficient. Because of the smaller wetted radius, additional sprinklers are required for good irrigation uniformity. A wide variety of studies (Sarwar et al., 2019, Sarwar et al, 2020, Molaei et al, 2021) resulted in an average measured application efficiency of 97%. A real water savings of 15 to 20% over MESA! Uniformity measurements are typically lower than for MESA, but when adjusted for unimportant variability on a small scale (Mohamed et al, 2019), these even out. System design is particularly important for good DU_{lq} values for LESA and LEPA. We used a target DU_{lq} of 0.85 for LESA systems.

Pivot/Linear LEPA

Low energy precision application (LEPA) is defined below. These have been shown to be significantly more efficient as there is less opportunity for wind drift and evaporation than even LESA systems. Many studies have shown that these are about 95-98% efficient. (Bordovsky, 2019l; Lyle and Bordovsky, 1983; Fipps and New, 1990; Rajan et al., 2015). Because there is not a sprinkler head to spread the water, and because the water is applied directly to the soil, there is little time for infiltration resulting in additional runoff that must be controlled with tillage methods or furrow dikes. This means that good DU_{lq}s are more difficult to obtain, but are possible if the system is designed and operated well. Basin tillage (furrow irrigation with diked furrows) is critical for this to be used properly. If used without basin tillage, like for alfalfa or something similar, the uniformity was significantly worse. We assumed a catch-can based efficiency of 97% and a DU_{lq} of 0.80 for LEPA systems.

Pivot/Linear (Top of Pipe)

When pivots first came out, they had high pressure impact sprinklers mounted on the top of the pipe. A few center pivots are still outfitted this way. These systems are highly inefficient as there is so much opportunity for water losses to wind drift and evaporation as the water must travel a relatively long distance on its way to the soil surface and is much more subjected to wind drift and evaporation. Because of this, the measured irrigation application efficiency of these systems is similar to that of big guns at about 60%. They are also less uniform as the wind pushes the water application pattern around resulting in poor irrigation uniformity. However, because of their larger wetted radius, the DU_{lq} can be good if the sprinklers are designed right, the system is run at the right pressure, and there is little wind. An optimistic DU_{lq} of 0.8 is assumed similar to other center pivot systems.

Hand Move (Hand-line) and Wheel Move (Wheel-line)

These systems are grouped together because they operate similarly to each other, with higher pressure sprinklers with large wetted radii, operating in a single line, at similar heights above the crop canopy, connected to riser lines at the head of the field, and moved at about the same intervales. Wheel lines are essentially hand-lines with wheels to help them move easier. The efficiency and uniformity of these systems has been shown to be highly affected by wind speed and vapor pressure deficit (aridity). A variety of tests has shown that about a mean of 70-75% application efficiency can be expected using catch can results. Griffiths (2006) found an average of 73% from a wide variety of irrigation evaluation reports worldwide. Most evaluations are done under lower wind speed conditions and thus might be optimistic in general. A DU_{lq} of 0.8 is assumed, although lower values are more common (Griffiths, 2006).

Microsprinklers

Microsprinklers have limited wetted radii and thus their efficiency is estimated based primarily on the uniformity of flow rates from the various emitters instead of application uniformity of other sprinklers. A target DU_{lq} of 0.85 is used. They operate closer to the soil surface and thus have a higher catch-can-based Ea (82%) compared to hand-lines or wheel-lines. They are also static and thus can't benefit from the DU_{lq}-compensating effect of moving irrigation systems for season-long averages.

Undertree Orchard

Similar to microsprinklers and drip, sprinklers operating under trees in orchards have limited wetted radii and thus their efficiency is estimated based primarily on the uniformity of flow rates from the various emitters instead of application uniformity of other sprinklers. A target DU_{lq} of 0.85 is used. They also operate closer to the soil surface, but usually operate at higher flow rates than microsprinklers. These higher flow rates gives less total opportunity for WDE compared to microsprinklers. Thus have a catch-can-based Ea (84%). They are also static and thus can't benefit from the DU_{lq}-compensating effect for season-long averages.

Solid Set Sprinklers

These are also sometimes referred to as "permanent" sprinkler systems. Instead of a single line of sprinkler operating as with hand-lines or wheel-lines, a set of sprinklers in the field is often operated at the same time. The evaporating water from one sprinkler cools and humidifies the air decreasing the vapor pressure deficit in the microclimate that the neighboring sprinklers are operating in, and thus increasing the catch-can-based measured application efficiencies relative to hand-lines or wheel-lines (mean of 76% compared to 73% for hand-lines). However, because the system is static there are less opportunities for compensation moving sprinkler locations and thus the season-long uniformity is lower. A DU_{lq} of 0.8 is assumed but the moving sprinkler adjustment was lower.

Big Guns

Peters and McMoran used catch cans to measure the irrigation application efficiency of big guns on two systems at 58 and 60% with a DU_{lq} that were pretty low (0.2 and 0.57) but demonstrated that it was possible to get a DU_{lq} of 0.75 and 0.86 with different management techniques. It was noted that big guns are especially susceptible to wide variations in irrigation application efficiency and uniformity issues with changing weather conditions -- especially vapor pressure deficit (aridity) and wind speed. The tests shown were also done in more humid climates and under lower wind conditions than might be typical in Eastern Washington.

Surface Irrigation Application Efficiency Details

In surface irrigation, the soil is used to transport the water across the field. Water is often infiltrating at the top of the field for many hours before the bottom of the field receives any water, and water must often run off the bottom of the field in order to adequately irrigate the bottom areas (Figure 2). Because of this, irrigation uniformity is almost impossible, and there are large and often unavoidable water losses to deep percolation and runoff. The crop canopy is seldom wetted however, and there are less water losses to wind drift and evaporation than in sprinkle irrigation.

The water losses from surface irrigation are undeniably substantial. However, these water losses stay within the basin and can be recovered at a different time and location (from drainage ditches, or by pumping up from the groundwater). These losses are often difficult to track, and the recovery time and location may not be predictable, convenient, timely, or cost effective. However, they stay in the drainage basin and provide benefits (and sometimes problems). Whereas the wind drift and evaporation water losses from sprinkle irrigation leave the basin permanently and are unrecoverable.

The on-farm surface irrigation application efficiency is ea function of the flow rates into the furrow or basin, the soil's infiltration rates (a function of soil texture, structure, and tillage), and the run length (how far the water must be transported across the soil's surface). There are many things that can be used to help optimize this, such as using surge irrigation (the wetting and settling cycles lower the soil's infiltration rates in areas already wetted), blocked end furrows, level basins, land leveling, furrow modifications, tillage modifications, the use of polyacrylamide (PAM), and precise timing of water set times. Because of these, the application efficiency of surface irrigation can vary widely. Furrow irrigation application efficiency can vary from 20% to almost 100% in some cases! However, surface irrigation is most commonly practiced in areas where expertise, investment capital and time are in short supply, and these are required to improve surface irrigation application efficiency. Thus, most surveys of surface irrigation application efficiency have shown that the lower end of these very large ranges in application efficiency are more typical. The methods for optimizing surface irrigation methods are discussed in other publications. Larger flow rates and shorter set times are usually required for improved uniformity and therefore efficiency of surface irrigation systems competes with the desire to minimize erosion and reduce labor costs.

For the purposes of this publication and conversion table, a single irrigation application efficiency number must be chosen for each of these different irrigation systems. This is especially difficult with surface irrigation because of this very large variation in application efficiencies from system to system. It is also difficult to choose, because higher efficiencies are possible with precise modifications to flow rates, set times, and run lengths. Should surface irrigators be held to this higher, more difficult-to-achieve and often more expensive standard? For the purposes here, a number that we feel represents a reasonable, yet achievable standard with minimum time and capital investment, application efficiency was chosen. We acknowledge that this number is subjective. Because of the large variability and subjective nature of this estimate of application efficiency to begin with, no attempt was made to correct for reduced plant and soil surface water evaporation compared to sprinkle irrigation.

Because irrigation application efficiency for surface irrigation is already corrected for distribution uniformity of the low quarter (DU_{lq}), the irrigation application efficiency for the low quarter, Ea_{lq}, is assumed to be equivalent to just the irrigation application efficiency (Ea), i.e. not corrected for uniformity. The values used for Ea come from an amalgamation of a lot of different reported values (Rogers et al., 1997; Brouwer et al, 1989; Stetson and Mecham, 2011, Irrigation Association, 2010; Hanson and Fulton, 2004; Hanson and Bowers 1994; Burt et al, 2000; Alam, 1997; Irmak et al., 2011; Burt, 1995; Solomon, 1988; and Morris and Lynne, 2006).

The reported division of the water losses from surface irrigation from DP and RO vary from 30% to 60% (Brouwer, 1985; Kranz and Burr, 2005). Thus, we assumed the water losses to be roughly half to DP and half to RO. Runoff is assumed to be zero for basin and for furrow irrigation with tailwater re-use.

Surface irrigated fields are often (not always) irrigated less frequently than sprinkle or drip, and sometimes doesn't wet the entire soil surface (as for furrow). Thus, for comparison purposes and relative to our reference surface, the water losses to WDE are set to zero % since it wouldn't be different from sprinkle or drip. The only evaporation water losses are the 10% of additional water losses from the runoff (10% of 50% is 5%). This means that for those systems that have runoff (excluding tailwater reuse and basin), the fraction of losses to DP is 50%, 5% to WDE, and 45% to RO.

Furrow (Rill) Irrigation including Graded Furrow, Surge, and Tailwater Reuse

Furrow irrigation, often called "rill irrigation", is the most common form of surface irrigation used in Washington State. Because not all the soil surface is wetted, there is reduced soil surface evaporation compared to sprinkle or basin irrigation. Soil surface evaporation can be further reduced by irrigating every other furrow in row crops.

Many publications report an expected application efficiency of around 70% (e.g. Mehri et al, 2023), while most field-based evaluation data reports mean Ea values of 40-60% (Griffiths, 2006; Watto and Mugera, 2006). We used a compromised estimate of 62%.

Graded furrow improves irrigation application efficiency. Be used 73% based on an average of table-reported values. Surge irrigation also increases furrow irrigation application efficiency significantly. We assumed 73% based on an average of various reported values. Tailwater re-use reduces furrow irrigation runoff to zero. Since very roughly half of the water loss from furrow irrigation goes to runoff, we assumed that tailwater reuse increased furrow irrigation to 80%. This is supported by various research values.

Basin

Basin irrigation is defined below and is uncommon in Washington State. The Ea_{lq} is assumed to be 75% for border and 73% for contour border irrigation systems based on the mean of reported values.

Border and Contour Border

These methods of irrigation are defined above and are uncommon in Washington State. The Ea_{lq} is assumed to be 65% for border and 73% for contour border irrigation systems based on the mean of reported values.

Corrugation

Corrugation irrigation is defined below. The Ea_{lq} is assumed to be 50%.

Wild Flood

Wild flood irrigation lacks much control and is notoriously inefficient and ineffective. Although higher values are often reported as achievable, these are uncommon. Ea_{lq} is assumed to be 35%.

Drip Irrigation Application Efficiency Details

Drip irrigation is highly efficient. This is because there are significantly lower water losses to wind drift, evaporation (especially from the limited amount of soil surface that is wetted), and runoff. Drip irrigation application efficiency is primarily limited by the uniformity of flow rates from the individual emitters (emission uniformity, or EU) where additional water must be applied to adequately irrigate all areas of the field (Figure 6). Thus, all water losses from drip irrigation are assumed to go to deep percolation. The application efficiency is essentially equated to the (EU). An EU of 90-100 is considered excellent, 80-90 is good, 70-80 is fair, and < 70% is considered poor (Peacock and Handley). The emitters in older systems often get partially or fully plugged, reducing the EU significantly (Camp et al., 1997). The EU of most new irrigation systems is in the mid-90s (Sharu, 2021; Mostafa 2024). However, the mean EU of most drip irrigation system evaluations are in the range of 0.75. We used an assumed EU of 0.85 as a compromise (classified as good).

Drip irrigation most often has much less soil surface evaporation than sprinkle irrigation as the entire soil surface is seldom entirely wetted. Because this table is used for system comparisons and estimating the total gross water required, we compensated for the comparatively less soil surface evaporation by adjusting the efficiency estimate up slightly. Kisekka et al. (2016, 2017) showed that the soil evaporation component of evapotranspiration from MDI was 35% lower than the in-canopy LESA nozzles. Since MDI should have evaporation losses similar to stationary drip systems and LESA systems wet the entire soil surface, it is reasonable to assume that the soil surface evaporation differences between stationary drip and a sprinkler system that wets the entire soil surface (the reference system) is similarly about 35%. 35% of the difference in evaporation from a fully wetted soil surface to a limited soil surface was assumed to adjusted the Ea up by 4% for surface drip and MDI, and by 7% for buried drip systems (much less wetted soil surface area). This should be thought of as not necessarily increasing the efficiency of these systems, but as a way to compensate for the fact that ET is calculated with a single crop coefficient that assumes a uniformly wetted soil surface and these systems don't wet the entire soil surface and reduce the gross ET requirements from a net requirement that is calculated too high from weather data. i.e. if the EU of the system was very high and with deep subsurface drip irrigation, the adjustment could result in a revised Ea_{lq} greater than 100%.

The moving nature of the drip lines with MDI (pivots dragging drip tubing) compensates for low emission uniformity such that the comparative application efficiency is very high.

Table 3. Explanations of adjustments to drip irrigation application efficiency estimates for moving irrigation systems and for lower soil water evaporation due to less wetted soil surface area. The compensation value is the % efficiency added to compensate for the fact that drip irrigation has lower soil surface evaporation than the reference system.

Drip Irrigation System	Typical EU	Moving or Static	Adjustment	Revised DUlq	Lower Soil Evap Comp.	Revised Ealq
Subsurface drip	85	Static	0.00	85	7	92
Surface Drip	85	Static	0.00	85	4	89
Mobile Drip Irrigation	85	Moving	0.50	93	4	97

The emission uniformity of drip irrigation cannot be compensated for similar to sprinkler systems since the emission locations don't change over time and there is no similar opportunity for compensation by variation in wind redistribution. Thus, the EU is essentially the same as Ea_{lq}. The *Revised* DU_{lq} is calculated as: (100 – *EU*) x *Adjustment* + *EU*. The *Revised* Ea_{lq} is thus the *Revised* DU_{lq} + the *Lower Soil Evaporation Compensation*.

Subsurface Drip Irrigation

These are drip lines with regularly spaced emitters integrated into the drip tubing that are buried. The depth of burial can be important to the efficiency and effectiveness of the irrigation system and soil type, and crop play important roles in choosing a burial depth. All the inefficiently used water is assumed to be lost to deep percolation due to imperfect emission uniformity. Pitts et al (1996) found an average DU_{lq} of 0.70 in an evaluation of 174 drip and micro irrigation system evaluations. This is primarily due to system plugging. 75% of the systems had DU_{lq}s below 85%. An optimistic DU_{lq} (mathematically equivalent to EU for our purposes) of 0.85 was used. 7% was added to the E_{alq} to compensate for the fact that there is comparatively little evaporation from a wet soil surface compared to the reference condition.

Surface Drip Irrigation

Similar to subsurface drip irrigation, an EU (mathematically equivalent to DU_{lq} for our purposes) of 85% was used. 4% was added to the Ea_{lq} to compensate for the fact that there is comparatively little evaporation from a wet soil surface compared to the reference condition of sprinkle irrigated fields.

Mobile Drip Irrigation (MDI)

In a study comparing center pivot sprinkler irrigation to MDI in Germany found a 10–20% (Derbala 2003) and 25% (Hezarjaribi 2008) water savings by using MDI. Another study in Kansas comparing LESA with MDI showed that the soil evaporation component of evapotranspiration from MDI was 35% lower than the in-canopy LESA nozzles (Kisekka et al. 2016, 2017). This is because MDI does not completely wet the entire surface of the soil.

MDI trial reports presented by Jones (2015) found 31% water savings in Colorado in 2014, and another trial that showed 50% more available soil moisture for crops in Kansas in 2013. In an alfalfa field in Oregon that compared MESA system with MDI, the resulting soil moisture graphs showed that the available moisture at 38 inches under MDI was significantly greater than for MESA. In addition, since MDI has higher uniformity compared to LESA and MESA, it has the potential to increase yield (Schmidt et al. 2016). There was no significant difference in crop yield, aboveground biomass, leaf area index, or water use efficiency in the research studies compared to MDI, LEPA, or LESA (Kisekka et al. 2016; O'Shaughnessy and Colaizzi 2017; Swanson et al. 2016; Kisekka et al. 2017; Okera et al. 2018; Olson and Rogers 2006 and 2008).

Additional water losses to deep percolation due to non-uniformity in emitter flow rates are compensated for by having multiple emitters in the same location as the drip line is drug past that location, effectively averaging out these differences. Because of this ½ of the EU is assumed to be compensated for by the moving irrigation system. Because MDI is being compared to sprinkle irrigation systems that wet the entire surface and drip irrigation systems do not, an additional 4% was added to the Ea_{lq} value (see the discussion of this in the section on drip irrigation above).

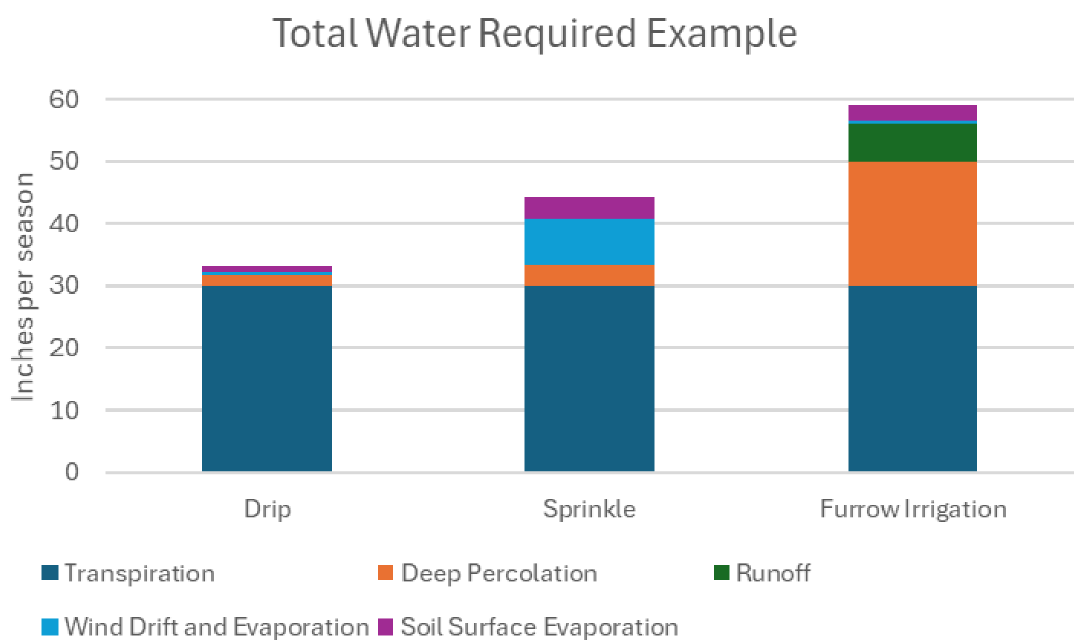


Figure 10. Example of the water requirements and losses from different irrigation system types.

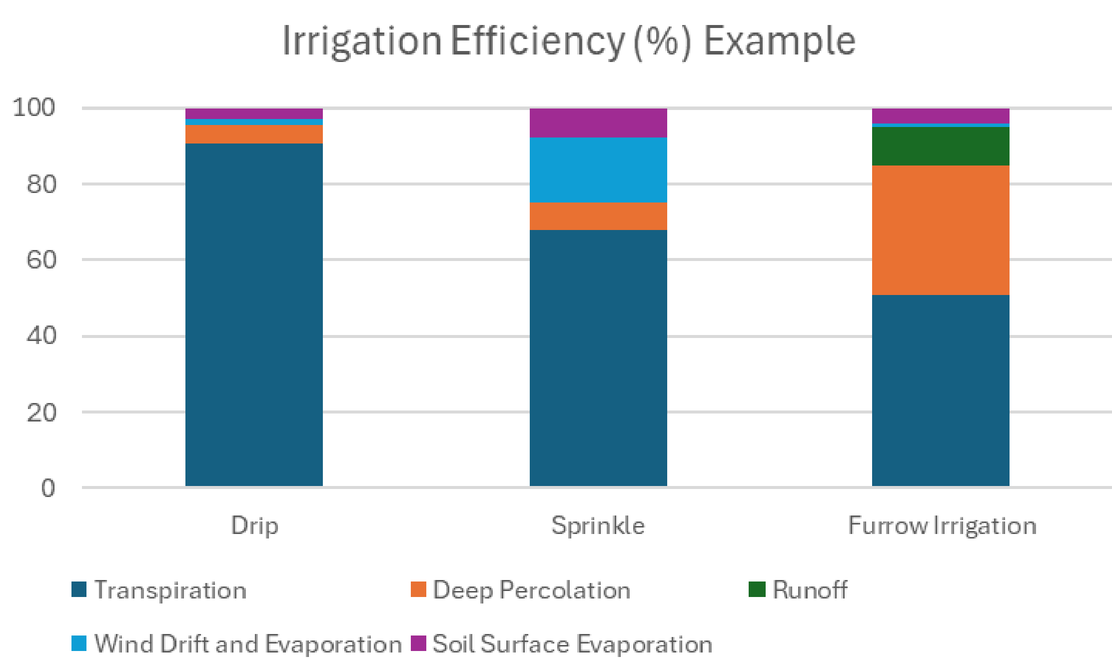


Figure 11. Example of how these might affect the comparisons of irrigation application efficiency as a percentage.

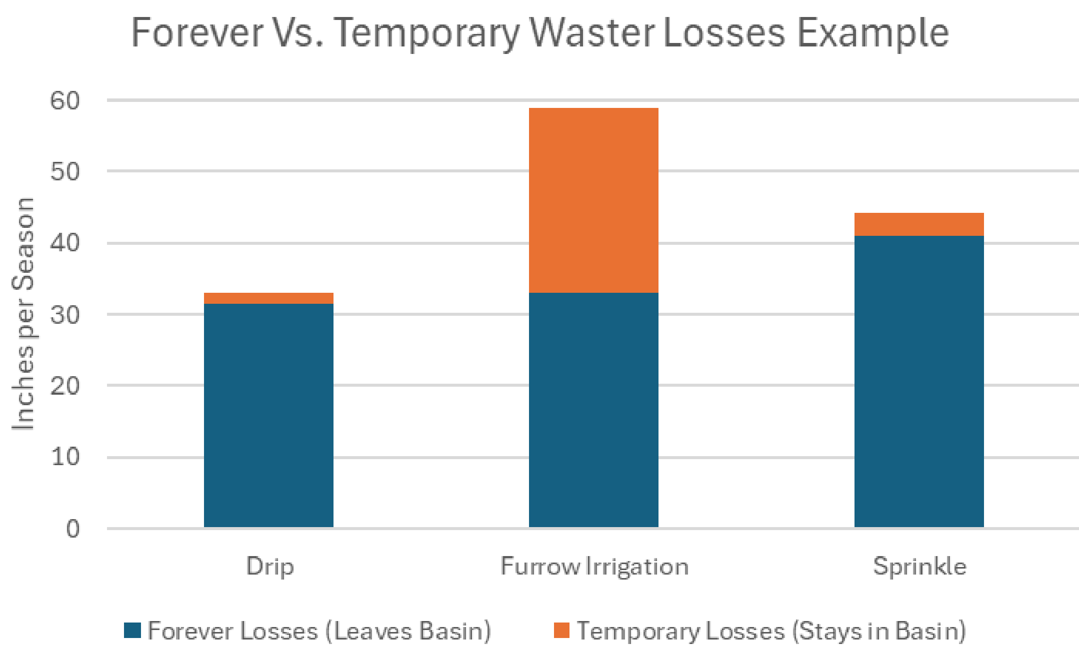


Figure 12. Example of how the water losses break out into recoverable vs. non-recoverable (forever) water losses.

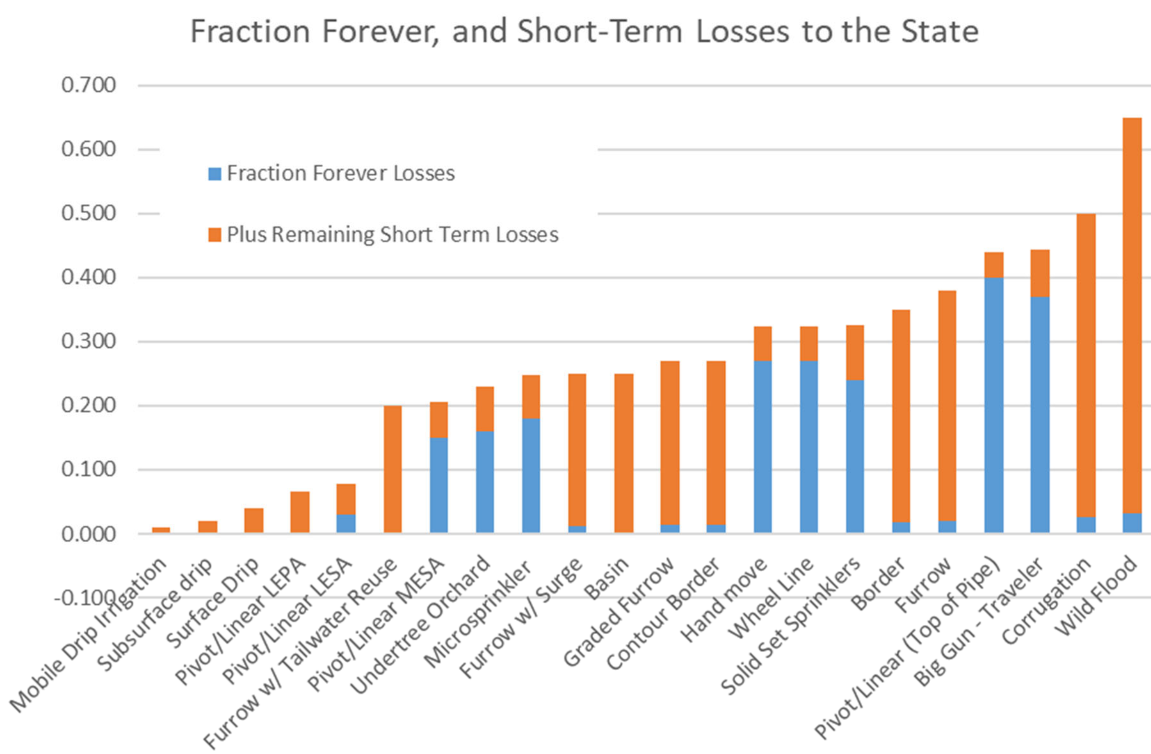


Figure 13. The fraction of the irrigation system losses that are 'forever' losses and short-term losses to the state *sorted by total losses* (100 - Ea) / 100. These assume that all deep percolation

and 90% of runoff losses are *eventually* recoverable.

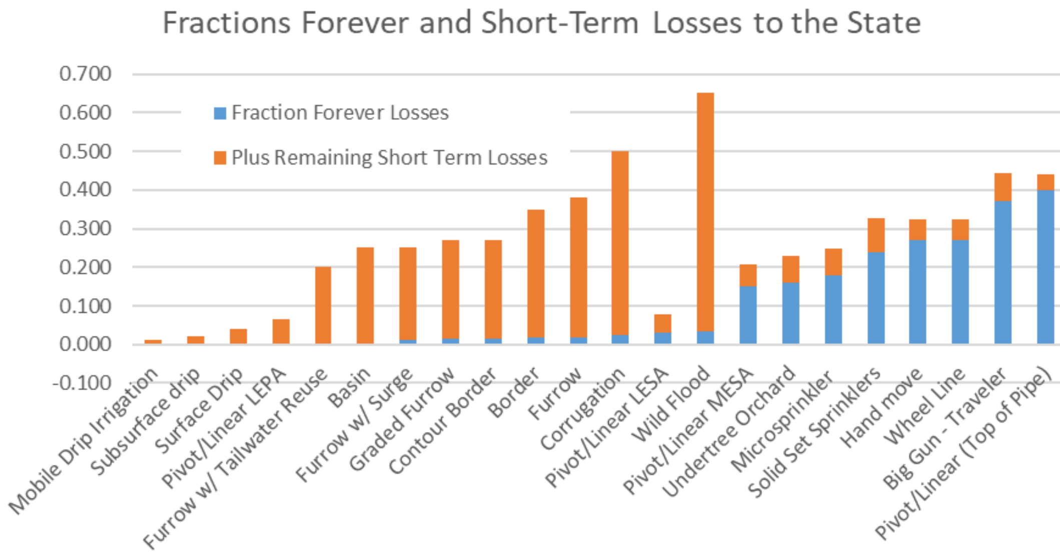


Figure 14. The fraction of the irrigation system losses that are 'forever' losses, or losses that go to water vapor, and overall short-term losses (100 – Ea_{lq}) / 100 to the state *sorted by the proportion that are 'forever' losses*. These assume that all deep percolation and 90% of runoff losses are *eventually* recoverable.

Additional Notes and Comments

Many components of "beneficial Use" are not included or discussed in this publication including irrigation water use for evaporative cooling, frost control, leaching salts, etc.

Surface Irrigation Isn't Always Bad

In overall water balance to the state and prioritizing 'forever' losses Figure surface irrigation in not always something to be fought. It is inefficient because we lose track of and control over the water. However, the water is still there, mostly in the groundwater. That is bad for the short term and from a water delivery and supply capacity point-of-view, especially with water time, but can be OK and may be beneficial in the long term. Surface irrigation may be the ideal and most efficient irrigation system for flat, saline, and high-clay-content soils. These surface irrigators can find improvements in their efficiency by using ideal flow rates, run lengths, and irrigation set times, which are key to good surface irrigation system efficiency and uniformity.

Figure 15. A big gun sprinkler operating on a windy day.

Irrigation Systems that Should not be Promoted

Big guns (Figure 5) typically have a measured irrigation water loss to evaporation of about 40% (permanent losses) and they are associated with poor irrigation uniformity because they are so affected by the wind (R.T. Peters & McMoran., 2009.). Because they require such high pressures, they are also an energy-intensive way to irrigate. Big guns can make the most sense for some applications, however.

End guns on center pivots have the same issues as big guns and have been similarly found to have poor irrigation application efficiency (around 40% losses), and poor irrigation uniformity. They also require high pressures which translate to higher energy costs. In addition, they are high cost and high maintenance pieces of equipment (personal communication with several irrigation dealers). End guns can pick up additional irrigated acreage for a low cost, however.

Center pivots with high-pressure impact sprinklers mounted on the top of the pipe (Figure6) also have very high spray losses to wind drift and evaporation (measured in several tests to be around 40%) and require high pressures making them an inefficient way to irrigate in terms of both water and energy. Because they have a large wetted radius these systems are often used on soils with runoff problems due to either the soil or the slope. However, runoff issues can be addressed with tillage methods to increase soil surface storage, and/or with boom-backs to physically spread out the sprinklers on alternate sides of the pivot to allow additional time for water to infiltrate into the soil as the pivot moves by.

Hand lines and wheel lines are more efficient than the above methods, but not by much. The typical measured catch efficiency of these systems is 70-75%, meaning there are 25-30% spray losses to wind drift and evaporation (forever losses). In a large-scale evaluation of 30 different systems of this type, Howard Neibling (University of Idaho, unpublished study) found an average of 12% water losses to leaks on Thunderbird wheel-lines, 16% on standard wheel-lines, and mean of 36% losses on hand-line systems, and this was just to leaks or poorly sized nozzles. In addition, hand lines and wheel lines require relatively high pressures to operate and therefore use greater amounts of pumping energy (and costs) compared to center pivots, drip, or surface irrigation systems. The low application rate, low cost, and ability to irrigate rectangular fields make these systems desirable for some growers, however.

Figure 16. A center pivot with high pressure impact sprinklers on the top of the pipe. Around 35-40% of the water that leaves the nozzles cannot be collected in catch cans at the soil surface.

There are ways to use the above-mentioned irrigation systems efficiently such as only operate under cool, humid, and low wind conditions, but since the weather rarely cooperates and because there is seldom the flexibility to shut down due to non-ideal weather, this is difficult to do in practice. Operating these high-pressure sprinkler systems under windy conditions makes the irrigation application efficiency and irrigation system uniformity drop drastically.

Opportunities

Wind not only causes large sprinkler water losses, but it increases the consumptive demand (water required for plant growth) considerably and makes the irrigation system distribution uniformity of sprinklers much worse. Some (not all) irrigators have the flexibility to be able to shut off their sprinkler irrigation systems under high wind conditions. This should be encouraged wherever possible.

There is also a large opportunity to promote converting center pivots to LEPA, LESA, or MDI as money permits, or water shortage pressures motivate. These save a large amount of water and energy, the water savings is all from reduced consumptive use (evaporation) water losses, and these systems have been shown to be effective despite their lower operating height (Reference to LEPA/LESA, and MDI extension pub). These should be considered especially in arid and windy areas.

Energy Use Benefits

Most technologies that conserve water also conserve energy. This is because energy is required to pressurize and distribute irrigation water. When less water is used, less energy is also used. Many of the more efficient irrigation technologies also require lower pressures, which also means lower energy requirements to pressurize the water.

Timing Matters

Most of the critical water shortages in the state occur during July and August when the irrigation water demand is highest, and there is less water available. By contrast the competition for the water flows in the winter and early spring is much lower. Some technologies, like irrigation scheduling, save a considerable amount of water, but most of those savings are early in the spring or late in the fall when there is less competition for water, and the water savings are from deep percolation losses. This is because crop water needs are so low during these times and consequently people often over-irrigate. By contrast, some technologies, like LEPA/LESA, which drastically reduce wind drift and evaporation water losses, have the greatest savings at the times of year when it is hottest, i.e. July and August, and the conserved water is a reduction in permanent water losses (evaporation). This is because wind drift and evaporation losses are highest when the vapor pressure deficit is highest (caused by higher temperatures and lower humidity). Thus, these save the greatest amount of water at the times of greatest need and greatest shortages. Water savings that reduce peak irrigation water demand can reduce the required overall capacity requirements of irrigation water delivery systems (canals and pipelines) as well as the capacity of on-farm irrigation systems. In addition, they conserve pumping power (pump less water at lower pressures) at the times of greatest energy shortages as more people are running air conditioners running during the hot parts of summer.

Conserving Water Doesn't Always Mean More Water Available

Often when farmers upgrade their surface irrigation systems to center pivot irrigation systems, they get better yields. This is often because of the center pivot's ability to irrigate more frequently, and because center pivots apply water more uniformly than surface irrigation can. These greater yields mean greater crop transpiration because the crops are bigger and healthier. Center pivots also lose more water to evaporation due to spraying water through the air, and because of more frequent wetting of the canopy, whereas surface irrigation water losses are primarily deep percolation and field runoff. Because of these factors converting farms from surface to center pivots, for example, may not automatically result in more water being available for alternative uses.

If conservation practices or more efficient irrigation systems are implemented in areas where the growers usually do not have enough water available for full irrigation (they are already deficit irrigating), then the conserved water will be used for irrigation to reduce the deficit. Again, additional water may not be made available, but the growers are more productive.

Efficiency is Limited by Water Delivery

The above efficiency estimates assume an adequate supply and delivery of water, which may not always be available. If a grower is already deficit irrigating, then there will be much lower losses to deep percolation and runoff and therefore water conservation may not be possible. The growers' ability to optimally irrigate also depends on a flexible and preferably on-demand irrigation water delivery systems to get the irrigation timing for that particular field just right. It is acknowledged that there are practical, organizational, geographical, financial, and political reasons why these types of water delivery systems may not be available. On-demand and highly flexible irrigation water delivery systems require large in-system storage and large delivery capacity systems for the unpredictable on-offs of large flow rates.

Efficiency Gains

The data in Table 1 was also built into a web calculator that estimates the water savings from converting from one system to another, and where that water will be saved from, and where the lost water will go here: http://irrigation.wsu.edu/Content/ConversionCalculator.html

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