Voluntary Clean Water Guidance for Agriculture Chapters

The purpose of this guidance is to describe best management practices (BMPs) that agricultural producers can use to protect water quality. It is intended to both support healthy farms and help producers meet clean water standards. The Voluntary Clean Water Guidance introduction[1] provides overall goals and objectives, as well as information on how the guidance will be used. Readers are encouraged to read the overall introduction before this chapter.

This report is available on the Department of Ecology's website at https://apps.ecology.wa.gov/publications/SummaryPages/2010008.html

[1] https://apps.ecology.wa.gov/publications/documents/2010008.pdf

Chapter 7

Water Management: Irrigation Systems & Management

Voluntary Clean Water Guidance for Agriculture

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Washington State Department of Ecology
Water Quality Program

July 2025
Publication Number 20-10-008h

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Recommendations for Irrigation Systems & Management to Protect Water Quality

Introduction

Irrigation is a critical component of production agricultural, ensuring that crops receive adequate water for optimal growth. The purpose of irrigation management is to control the timing and amount of irrigation water to meet crop need while promoting soil quality and protecting surface and groundwater. There are a wide range of irrigation systems in both the way water is applied and their suitability for different soils, crop systems and water source, and each has advantages and disadvantages. A preferred irrigation system is one that precisely applies water at specific amounts and times while facilitating infiltration, reducing losses through evapotranspiration and preventing erosion, runoff or excess leaching of nutrients.

Scope of Guidance

The purpose of this chapter is to outline best management practices (BMPs) that can be used to efficiently apply irrigation water while limiting impacts to surface and groundwater. Practices outlined in this chapter are primarily source control BMPs meant to prevent erosion, runoff and excess leaching of nutrients that can result from irrigation. Irrigation systems should be complemented by additional practices improve soil health and fully protect water quality including management strategies such as nutrient, pesticide, tillage, and residue management, as well as practices that further limit water quality impacts such as sediment basins, cover crops and native riparian vegetation.

Definitions Used in this Document

Allowable plant water stress – an irrigation scheduling method where irrigation occurs before soil water has been depleted below a lower limit.

Allowable soil water depletion – an irrigation scheduling method where irrigation occurs before the soil water tension at one or more depths in the root zone, or averaged over the root zone, reaches a predetermined limit.

Allowable soil water tension – an irrigation scheduling method where irrigation occurs before the plant water stress in some part of the plant reaches a limit as indicated by one of several measurement techniques.

Basin irrigation – a type of flood irrigation where water is applied to enclosed fields surrounded by small earthen embankments.

Border irrigation – a type of flood irrigation where water flows down gradient via gravity between small levees or ridges and water soaks into the soil at it travels downhill.

Deficit irrigation – irrigation strategy that deliberately apply less water than optimal to achieve water savings while maintaining acceptable crop yields.

Direct root zone (DRZ) irrigation – irrigation techniques that precisely target water delivery to plant root systems.

Furrow irrigation - a type of flood irrigation where water flows by gravity through small, parallel channels (furrows) between crop rows.

Irrigation and drainage tailwater recovery – a system designed to collect, store, and convey irrigation tailwater, rainfall runoff, field drain water, or combination thereof for reuse and distribution to crops.

Irrigation scheduling - procedure used to determine the timing and quantity of water application.

Irrigation management - practice that involves determining and controlling the volume, frequency, and application rate of irrigation water to optimize crop yields while conserving water resources.

Micro-irrigation – irrigation methods that combine low-pressure sprayers, misters, and specialized emitters for precise water application.

Moved lateral - a system where laterals can be moved to multiple locations.

Moving lateral – a system where laterals are moved mechanically.

Saline soils - soils containing high levels of soluble salts. Ions most commonly associated with soil salinity include chloride, sulfate, carbonate, sodium, calcium, magnesium and potassium.

Sediment basin – a constructed basin with an engineered outlet used to capture and detain sediment-laden runoff or other debris for a sufficient length of time to allow it to settle out in the basin.

Surface and subsurface drip systems – irrigation system that delivers water through buried or surface-level tubes, providing consistent moisture while minimizing evaporation losses.

Set time - the duration a particular zone or field will be watered.

Single-sprinkler - a system designed to irrigate an entire area with only one sprinkler that is moved periodically or automatically moves across an area.

Sodic soils – soils that have a high concentration of exchangeable sodium relative to other cations.

Soil aeration - process of ensuring adequate oxygen is present in the soil pore spaces to support the respiration of plant roots and soil organisms, while also allowing for the removal of carbon dioxide and other gases.

Solid set - a system that uses a mainline and one or more laterals where the laterals are placed permanently in one location in a field.

Sprinkler irrigation - a method of applying water to crops by spraying it through the air using as system of pipes, pumps and sprinkler heads that operate under pressure.

Surface irrigation – an irrigation system that involves applying water directly to the soil surface where water flows across a crop field by gravity and a portion of the water infiltrates as it advances.

Water and sediment control basin - an earthen embankment or ridge and channel constructed across the slope of a minor drainageway used to reduce gully erosion, trap sediment and reduce and manage runoff.

Best Management Practices

The following are best management practices for managing the timing, amount and efficient application of irrigation. The goals of these practices are to reduce water loss from evaporation, prevent deep percolation and nutrient leaching, and minimize runoff and erosion.

Irrigation Water Management Plans

Irrigation water management planning involves the strategic use of water to meet crop needs while conserving resources and preventing negative impacts to surface or groundwater. It includes evaluating water sources, understanding soil and crop requirements, selecting suitable irrigation systems, and scheduling water applications based on climate and plant growth stages. The goal is to apply the right amount of water at the right time to maximize yields, reduce waste, and protect water quality.

All irrigators should develop an irrigation management plan that, at minimum, includes the following information.

- Crop Specific Water Requirements
    - Crop water requirements should, at a minimum, account crop water use characteristics, rooting depth, moisture stress resistance, evapotranspiration and weather.
- Soil Characteristics
    - Include a description of soil properties for all crop fields. See the Soil Characteristics section below for more information.
    - Tailor field-specific irrigation application rates and amounts based on soil characteristics.

- Irrigation Schedules
    - Outline protocols for applying water when needed and at amounts that match crop requirements.
    - Schedules should be based on crop-specific water requirements and account for weather, soil characteristics, soil moisture, growth stage, weather and predicted precipitation. See the section below for more information about scheduling.
- Soil Moisture Monitoring
    - Describe soil moisture monitoring practices that will be used to ensure irrigation is based on actual field conditions and crop need. See the Soil Moisture Monitoring section below for more information.
- System Maintenance and Efficiency Testing
    - Describe methods that will be used to periodically evaluate the efficiency of the irrigation system and its ability to apply water at correct amounts and times while preventing leaching, runoff and erosion.
    - Include a schedule for evaluating the system and conducting routine maintenance such as checking for leaks, blockages, and pressure problems, cleaning filters and emitters, and calibrating sensors and controllers to ensure uniform water distribution.
- Water Source and Quality
    - Describe the source, availability, reliability, and quality of irrigation water, discuss how each may affect crops and/or irrigation systems, and outline strategies to mitigation potential impacts.
- Record Keeping and Evaluation
    - Outline records that will be kept to assess system performance and identify areas for improvement. Useful records include daily and/or weekly water use by field, crop growth and yield data, soil moisture readings and rainfall, and maintenance activities conducted.
- Additional Equipment & Tools
    - Include a description of additional practices that will be used to ensure proper irrigation rate and timing and efficient use by crops.
- Use resources such as the Natural Resource Conservation Service (NRCS) Field Office Technical Guidance (FOTG) for Irrigation Water Management (449), NRCS National Engineering Handbook, Part 623, Section 15, and NRCS National Engineering Handbook, Part 652, when developing an irrigation management plan.

Irrigation Application Considerations

- Use more efficient systems such as sprinkler and micro-irrigation systems whenever possible. See the Irrigation System Types & Recommendations subsections below for more information and system specific recommendations.
- Schedule irrigation based on soil moisture, crop rooting depth, growth stage, volume of water needed to meet crop need, soil characteristics, weather and predicted precipitation.
- Use precise water application rates to control the rate of water application to prevent over-irrigation and limit the transport of nutrients and chemicals through the soil profile to groundwater or subsurface drainage.
- Ensure the volume and rate of application does not result in irrigation-induced erosion and runoff.
- Use flow meters to determine the amount of water applied. This information is critical for good water management and to ensure water is applied at the right amount.
- Adjust the timing and rate of irrigation based on soil type to limit the potential for runoff, erosion or leaching of nutrients.
- Consider topography, the presence or absence of subsurface drainage and depth to groundwater when planning irrigation.
- Monitor irrigation applications to evaluate application uniformity and adjust as needed.
- Irrigate during cooler times of the day such as early morning or late evening to minimize losses from heat and wind.
- Coordinate irrigation with the scheduled application of nutrients and chemicals to avoid leaching below the root zone to the groundwater or runoff to surface waters.
- Precision irrigation techniques, such as variable rate irrigation and soil moisture monitoring, can be used optimize water application rates and minimize runoff.
- Consider using mulch to reduce surface evaporation.
- Consult a qualified professional to help develop a plan and irrigation schedules when needed.

Soil Characteristics, Irrigation Scheduling and Soil Moisture Monitoring

Soil characteristics play a fundamental role in determining how water moves and is retained in the soil and is a critical factor influencing irrigation scheduling and soil moisture monitoring approaches. Understanding the physical characteristics of different soil types enables agricultural producers to tailor irrigation schedules and design effective soil moisture monitoring systems. The following are recommendations for evaluating soil characteristics, developing irrigation schedules and monitoring soil moisture.

Soil Characteristics and Soil Health

Soils are generally classified based on their texture, which is determined by the relative proportions of sand, silt, and clay particles. These textural differences significantly influence water-holding capacity, drainage rates, and aeration. Understanding soil characteristics is essential because they determine how often and how much water needs to be applied to maintain optimal soil moisture levels for plant growth, and also affect the potential for runoff, erosion, and water and nutrient leaching below crop root zones. The following are recommendations for evaluating soil characteristics for irrigation purposes.

- Identify and use soil characteristic information when selecting an irrigation system and developing irrigation management strategies.
    - Evaluate soil properties such as texture, structure, water holding capacity, depth, organic matter content, bulk density, cation exchange capacity, and potential for sodic or saline conditions.
    - Use soil characteristics to determine the potential for leaching and runoff and use this information to develop irrigation schedules and soil moisture monitoring strategies including timing, duration and frequency. For example:
        - Light-textured soils, such as coarse sand, have lower water-holding capacity and higher permeability compared to finer-textured soils like clay, making them more susceptible to water moving beyond the root zone and nitrate leaching.
        - Clay-texture soils, absorb water slowly and have higher water-holding capacity making them more prone runoff.
        - Loam soils contain a balanced mixture of sand, silt, and clay, offer moderate water retention and good drainage.
- Use resources such as the National Cooperative Soil Survey (NCSS) data and NRCS Handbook 296 to help identify local and field-specific soil conditions and to select an appropriate irrigation system and develop site-specific irrigation schedules.

Irrigation Scheduling

- Optimize irrigation efficiency by carefully planning and scheduling each irrigation event based on an accurate measurement of soil-water depletion, crop requirements, crop rooting depth, growth stage, soil characteristics, weather and predicted precipitation.
- Avoid irrigating based on calendar dates or other fixed schedules.
    - Irrigation systems that continuously deliver water or operate on a fixed schedule are less beneficial, inefficient, and have limited options for managing water delivery in comparison to on-demand irrigation systems.
- When irrigating clay soils, water should be applied slowly over a long period to allow for infiltration and to prevent runoff.

- Irrigation on sandy soils should be applied quickly but for short periods to avoid water moving beyond the root zone and to limit nutrient leaching.
    - For efficient water use, sites with sandy soils may need daily irrigation for short periods.
    - Quick application can contribute to a broader wetting area which provides a larger zone for roots to access. This approach may not be suitable for flood irrigation.
- Use scheduling approaches such as deficit irrigation, allowable soil water depletion, allowable soil water tension or allowable plant water stress to help determine irrigation timing.
- Use information such as weather data, estimated evapotranspiration rates or evapotranspiration models, soil moisture sensors, and plant status monitoring to determine irrigation timing and to optimize schedules.

Soil Moisture Monitoring

- Monitor soil moisture to determine when soil water within the root zone has been depleted to a prescribed level.
- Use real-time moisture sensors to monitor water at the root zone to schedule irrigation whenever possible. Scheduling based on real-time, sensor measurements reduces the risk of runoff, erosion and nutrient leaching.
    - Soil sensors such as tensiometers, moisture blocks, time-domain reflectometry and capacitance probes can be used to evaluate soil moisture conditions.
    - Variable rate irrigation can be used in conjunction with real-time soil moisture monitoring to spatially adjust irrigation rates and avoid areas where water is undesirable.
    - Use crop rooting depth when evaluating soil moisture.

Tailwater Runoff Management and Surface Water Protection

- Use best management practices to collect, store, and reuse water and prevent return flows from discharging directly to surface waters whenever irrigation application practices are likely to cause runoff.
    - Use practices such as sediment basins and water and sediment control basins to reduce erosion, trap sediment, and manage runoff.
    - Use tailwater recovery to collect, store, and reuse applied water. Collecting and reusing irrigation runoff can conserve water and minimize nutrient and sediment loading in nearby waterways.
    - Tailwater management practices must ensure sediment is settled and water is filtered before leaving the field.

    - Consult NRCS Field Office Technical Guides for Sediment Basins (350), Water and Sediment Control Basins (638), and Irrigation and Drainage Tailwater Recovery (447) when designing and installing these practices.
- Use additional best management practices to protect surface water.
    - Plant grass filter strips on the downhill side of fields where runoff and erosion may occur to filter nutrients or other chemicals.
    - Establish native riparian vegetation along streams that border crop fields in accordance with Chapter 12 of the Clean Water Guidelines.

Irrigation System Types and Recommendations

The main types of irrigation systems used in agriculture are surface, sprinkler and micro-irrigation, and each system has its own advantages, disadvantages and limitations. The following is a brief description of each irrigation system type and recommended best management practices.

Sprinkler Irrigation

Sprinkler irrigation is a method of applying water to crops by spraying it through the air using as system of pipes, pumps and sprinkler heads that operate under pressure. These systems allow for more precise water application rates than flood irrigation systems and more efficient water use. Sprinkler systems can be used for frost protection as well.

Sprinkler systems are divided into four basic types including single-sprinkler, solid-set, moved lateral, and moving lateral systems. The following is a brief description of each type.

- Single-sprinkler – a system designed to irrigate an entire area with only one sprinkler that is moved periodically or automatically moves across an area.
- Solid set – a system that uses a mainline and one or more laterals. The mainline is a pipe network designed to carry water from the water source to the laterals. When the laterals are placed permanently in one location in a field, the system is called a solid-set system.
- Moved lateral - a system where laterals can be moved to multiple locations. The simplest version of these systems can be carried by hand or pulled. Laterals can also be mounted on wheels that suspend the pipeline above the crop, called side roll systems. Given labor requirements, moved lateral systems often apply large amounts of water before they are moved to a new location.
- Moving lateral – a system where laterals are moved mechanically. Examples include center pivots and linear systems. These systems use one lateral to irrigate a large area, but since the lateral moves at a controlled speed, the depth of water applied can be varied.

Adaptability and Considerations

- Sprinkler irrigation systems are suitable for most crops and are adaptable to most soils given their wide range of discharge capacities.
  - Design involves the selection of proper nozzle size, operating pressure, and sprinkler spacing to apply water uniformly at the design rate.
- The flexibility of sprinkler systems and their ability to control application rates make them suitable for most topographic conditions.
- Fixed or continuously moving systems are better-suited for conditions where light, frequent irrigations are required such as for shallow-rooted crops or for soils with low water-holding capacities.
- Manually moved systems are best suited for crops that don't require frequent irrigation.
- Sprinkler systems require sediment and debris free water to prevent clogging and damage.
- Evaporation from wet foliage may cause plant damage through scalding.
- Some crops such as grapes, apples and cherries may be damaged by salt deposits on the fruit.
  - Where these potential problems exist, consider under-tree sprinklers.
  - Consider using micro-irrigation (drip) for sensitive crops.
- Sprinkler systems can be designed and operated to provide frost and freeze protection.

Best Management Practices

- Use efficient sprinkler packages along with automation sensors and timers to improve efficiency and uniformity.
- Use low-pressure, low-application rate nozzles such as rotary sprinklers or micro-sprinklers that apply water slowly, allowing it to soak in without causing runoff.
- Utilize drag hoses to apply water closer to the ground. This can reduce droplet impact energy, promote infiltration and minimize runoff and soil erosion.
- Know the soil infiltration rate characteristics of fields and adjust applications accordingly to avoid deep percolation, ponding and runoff.
- Use short irrigation cycles when needed to avoid surface saturation and potential runoff (e.g., clay soils).
- Avoid overlapping spray patterns especially near slopes or field edges to prevent deep percolation, pooling and runoff from overlap zones.
- Minimize deep percolation below the crop root zone by applying water according to crop evapotranspiration and soil moisture.

- Minimize surface runoff and increase uniformity on sprinkler irrigated fields by decreasing application depth or by changing nozzle and pressure configuration, height, or droplet size as appropriate.
- Maintain sufficient surface residue to reduce overland water flow, increase moisture retention, and prevent runoff, erosion and surface crusting.
- Use soil conservation practices such as minimum tillage or contour planting to reduce erosion of soil sediments containing nutrients or pesticides.
- Given that sprinkler irrigation systems discharge water into the air, evaporation must be considered.
    - Time irrigation during cooler times of the day.
    - Avoid windy conditions.
    - Frequent, light irrigations tend to result in more evaporation than less frequent, heavy irrigations.
- Conduct routine inspections and proper maintenance. Regularly check sprinkler heads for:
    - Pressure, uneven spray and depth and uniformity of application,
    - Misaligned heads, leaks or overspray that can cause excessive watering in certain, spots, leading to erosion.
    - Clogged nozzles.

Micro-Irrigation

Micro-irrigation systems use laterals that contain emitters (drip irrigation), micro-sprinklers or drip lines with continuous outflow along their lengths. Micro-irrigation is designed to irrigate individual or groups of plants and not the entire soil surface and are often permanently installed but may also be installed seasonally. Drip systems may be installed on the soil surface or buried. Buried systems are referred to as subsurface drip irrigation which uses drip tubes or drip tape to meet crop water needs.

Adaptability and Considerations

- Micro-irrigation systems are often used for high-value crops where sprinkler irrigation may case crop damage or disease issues.
- Advantages of micro-irrigation systems include: 1) high efficiency, due to limited evaporation loss; 2) reduced potential for runoff because of lower application rates; and 3) easy of system automation.
    - Evaporation is reduced due to enhance infiltration and reduced wetted area.
- Micro-irrigation requires less water which is especially true for wider spaced plants such as in orchards.

- Limiting evaporation can reduce the potential for salt accumulation in the soil or allow for the use of unfiltered water containing high mineral content.
    - Note: salt accumulation can occur even with reduced evaporation rates. Therefore, continued evaluation of soil mineral concentrations should be done especially in arid locations and/or when water sources are known to have higher concentrations of dissolved minerals.
- Frequent, light water applications associated with micro-irrigation can maintain soil water within a narrow range, which may enhance growth and yield of some crops.
- Weed growth may be reduced in areas that aren't wetted.
- Micro-irrigation systems are often permanently installed and can have higher upfront costs but can reduce labor costs.
- Micro-irrigation is generally not applicable to row crop production due to the expense and the need to remove the system each season. However, subsurface drip irrigation may be installed beneath the tillage zone of some crops.

Best Management Practices

- Facilitate uniform distribution by matching emitters with soil type and crop need.
- Adjust emitter spacing based on soil type. Spacing is often increased on clay soils and decrease on sandy soils.
- Adapt the system to account for slopes by maintaining constant flow, using check valves and placing irrigation laterals along slope contours.
- Since the emitters and micro-sprinklers have small orifices or outlets, it is necessary to prevent plugging by soil particles or microorganisms.
    - Emitter clogging adversely affects the rate and uniformity of water application and can results in decreased crop yield if not detected and corrected.
    - Preventive measures include water filtration, chemical water treatment, periodic flushing and field inspection.
- Conduct routine inspections and proper maintenance. Regularly evaluate the system for pressure, uniformity of application, and clogged emitters.

Surface Irrigation

Surface irrigation, often referred to as flood irrigation, involves applying water directly to the soil surface where water flows across a crop field by gravity and a portion of the water infiltrates as it advances. Surface irrigation systems are used on fields with moderate, uniform slopes which are needed to facilitate dispersion, and in many situations, have been graded for this purpose. Surface irrigation relies on applying large amounts of water in a short period of time to initiate flow across fields or down furrows, and water is commonly delivered to fields through gated pipes, siphons, or gated inlets.

Surface irrigation is commonly used for crops where water spray on crop leaves can cause damage or when disease problems may occur from wetting the vegetation with sprinklers. The suitability of surface irrigation and type of system used often depends on factors such soil type, soil uniformity, slope, topography, crop type and the potential for soil salinization.

Flood irrigation is not a preferred irrigation method, and Ecology recommends the use of more efficient systems such as sprinkler and micro-irrigation systems. However, when flood irrigation is used, practices should be used prevent deep percolation, soil erosion, nutrient and chemical leaching, and excess runoff.

There are three types of surface irrigation.

- Furrow irrigation – a type of flood irrigation where water flows by gravity through small, parallel channels (furrows) between crop rows. Furrow irrigated fields are typically graded to facilitate the flow of water and allow water to reach the end of crop rows.
- Basin irrigation – a type of flood irrigation where water is applied to enclosed fields surrounded by small earthen embankments. Basin irrigated fields are relatively level and water is allowed to pond in the basin where it gradually infiltrates into the soil.
- Border irrigation – a type of flood irrigation where water flows down gradient via gravity between small levees or ridges and water soaks into the soil at it travels downhill.

Considerations

- Surface irrigation requires access to large volumes that can be applied in a short period of time, and to irrigate uniformly, water must move across fields relatively quickly.
- Flood irrigation is prone to uneven water distribution, water loss through evaporation, deep percolation, soil erosion, nutrient and chemical leaching, and excess runoff (tailwater) which can carry sediments, fertilizers, and pesticides to nearby water bodies.
- Soil infiltration rate (soil texture) is especially critical for surface irrigation systems.
    - Surface irrigation is most suitable for medium-textured soil (moderate infiltration rates) that are uniform with high water-holding capacity.
    - Soils with high infiltration rates (e.g., sandy soils) are less suitable for surface irrigation as they limit water from dispersing over fields or flowing the length of fields without excess infiltration.
    - Low infiltration soils (e.g., clay soils) can result if excess runoff, pooling and waterlogging.
    - Fine texture soils are prone to erosion.
- Slope uniformity is critical to ensure even water distribution and prevent accumulations in surface depressions; therefore, surface irrigation commonly requires grading and leveling.

    - Surface irrigation is most suitable for flat (basin irrigation) or gentle and uniform slopes (border and furrow irrigation) that allow water to slowly cover or flow over a field.
    - Slopes that are too steep cause excess runoff and erosion.
    - Flat slopes limit dispersion.
- Deep percolation resulting from nonuniform distribution and excess infiltration is a common problem with surface irrigation which can lead to nutrient and chemical leaching and soil salinization.
    - Excess water infiltration can transport nutrients and chemicals to groundwater.
    - Raising the water table can increase soil salinity if an underlying aquifer contains high levels of dissolved salts. Once the water table nears the surface, it can evaporate and leave salts behind.
    - Ponded water and large areas of saturation are more susceptible to evaporation which also leaves salts behind especially when water sources contain higher levels of dissolved minerals.

Best Management Practices

- Whenever possible, convert fields from flood irrigation to sprinkler or micro-irrigation systems.
    - Producers currently using flood or furrow irrigation on coarse-textured soils should install sprinkler or micro-irrigation systems when feasible.
    - Avoid flood irrigation especially where evaporation or the rising of a saline groundwater tables can cause soil salinization.
- When conversion to high efficiency irrigation systems is infeasible, use practices to minimize leaching, excess runoff and soil salinization.
- Choose irrigation frequencies, set times and flow rates that match soil infiltration capacity, slope and soil water holding capacity.
- Maintain gentle, uniform grades to promote even water distribution and prevent pooling, erosion, and deep percolation.
- Keep furrows as short as possible.
- Use tailwater recovery and reuse systems to prevent return flows from discharging directly to surface waters.
- Maximize efficiency and uniformity on surface irrigated fields by installing surge flow irrigation.
    - Surge irrigation sends water in timed, intermittent releases of water, using on and off periods instead of continuous flow.

    - Surge flow can be used to reduce set times, facilitate more uniform infiltration and reduce deep percolation.
    - Surge flow is implemented using valves equipped with a programmable control to cycle the water as desired
- Avoid fertigation with flood irrigation systems.
- Consider using water-soluble anionic polyacrylamide (granular or tablet) when irrigation practices are unable to control excess runoff and erosion and converting to a more efficient system is infeasible.
    - Avoid the use of oil-based polyacrylamide as they could result in significant hazard to aquatic life especially if there is a potential for transport to surface water soon after application.
- Careful management is critical given the volume of water typically applied and the potential for erosion, excessive runoff and deep infiltration.

Soil Salinity Management

- Prevent sodic or saline soil conditions by regularly testing the soil and irrigation water.
- Effective management of soil salinity involves a multi-faceted approach that includes:
    - Regularly testing soils for salinity levels especially in locations with higher potential for soil salinization,
    - Monitoring irrigation water quality,
    - Implementing efficient irrigation practices, and
    - Adopting strategies to reduce salt accumulation in the soil profile.
- Evaluate the potential for sodic or saline soil conditions and use irrigation approaches best suited to prevent sodium and salt accumulations.
- In some locations, salt leaching maybe needed to maintain productivity. When leaching of soluble salts is needed to maintain productivity:
    - Time leaching to coincide with periods of low residual soil nitrate. Do not intentionally irrigate to leach salts until the growing crop has taken up fertilizer nitrogen.
    - Limit leaching only to what is required for the root zone.
- Use land grant university guidance when considering the use of amendments such as gypsum or sulfuric acid to facilitate the leaching of sodium or other ions causing sodic conditions.

- In Washington, the Department of Ecology established water quality standards for irrigation water (**Groundwater Water Quality Standards**[3] and **Surface Water Quality Standards**[4]), and sources that exceed these limits may require treatment or blending with higher-quality water to minimize the risk of soil salinization.

Improve Soil Health to Increase Water Retention and Irrigation Efficiency

Soil health plays a critical role in determining the effectiveness and efficiency of irrigation practices. Healthy soil, rich in organic matter and well-structured, improves water infiltration, retention, and drainage, reducing the frequency and volume of irrigation needed. Healthy soils also allow plant roots to access water more easily and evenly and are more resistant to crusting and drought. Therefore, its recommended to use practices that improve soil quality in conjunction with any irrigation strategy. Example of practices that improve soils quality include:

- Conservation tillage and residue management,
- Using diverse crop rotations with varying rooting depths,
- Planting cover crops,
- Utilizing organic sources of nutrients,
- Mulching, and
- Limiting heavy equipment traffic.

Related NRCS Practices:

- Irrigation Water Management (449)
- Irrigation and Drainage Tailwater Recovery (447)
- Irrigation Land Leveling (464)
- Irrigation System Micro-irrigation (441)
- Irrigation System, Surface and Subsurface (443)
- Nutrient Management (590)
- Sediment Basin (350)
- Water and Sediment Control Basin (638)

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[3] https://apps.ecology.wa.gov/publications/documents/9602.pdf
[4] https://app.leg.wa.gov/WAC/default.aspx?cite=173-201A

Commonly Associate Practices

- Chapter 1: Tillage & Residue Management
- Chapter 2: Crop Systems
- Chapter 3: Nutrient Management
- Chapter 4: Pesticide Management
- Chapter 5: Soil Stabilization & Sediment Capture (Vegetative)
- Chapter 6: Soil Stabilization & Sediment Capture (Structural)
- Chapter 7: Irrigation Management
- Chapter 8: Field Drainage & Subsurface Drainage Management
- Chapter 12: Riparian Areas and Surface Water Protection

Chapter 7 Appendix Part A: Effectiveness Synthesis (Water Management: Irrigation Systems & Management)

Effectiveness

Introduction

Conservation irrigation practices provide the necessary water supply to crops while promoting water and soil quality. There are a wide range of irrigation systems in both the way water is applied and their suitability for different crops and crop systems. With this, the environmental impact of irrigation depends on the nature of the water source, the water quality, and how water is delivered to the irrigated land. The effectiveness of irrigation systems in protecting water quality is impacted by an irrigation system's ability to apply water in precise amounts and locations to ensure efficient use by crops and limit runoff, erosion, and/or excessive leaching. Inefficient systems can often lead to water misapplication in ways that can cause runoff, erosion, and leaching, which are the primary mechanisms for irrigation induced transport of nonpoint source pollutants (e.g., nutrients, pesticides, sediment) to surface water and groundwater. Irrigation should be complemented by nutrient, pesticide, tillage, and residue management to be protective of water quality. Irrigation systems should also maintain the desired growth of crops while minimizing costs, labor, water loss, and nutrient loss. Overall, efficient irrigation systems can help reduce on-farm energy use, soil compaction, excessive water use and groundwater and surface water pollution.

Scope

Table 1 provides a list of BMPs covered in this chapter. Though these practices are individually investigated for effectiveness, they are typically part of a larger system. This chapter, to the extent possible, considers the relative effectiveness of combined BMPs in various settings with a lens towards the different land conditions across Washington state. Information in this chapter is based on Natural Resources Conservation Service (NRCS) Field Office Technical Guides (FOTG) and existing literature on irrigation practices. The effectiveness of practices in this chapter significantly relies on proper implementation, maintenance, testing, and monitoring, which will be discussed in more detail in the Implementation Section of this chapter. Ultimately, each landowner scenario is unique and practices from this section should be considered on a case-by-case basis.

Irrigation Practices

Irrigation Pathways

Water applied to a field from irrigation or rainfall can follow various pathways including:

- Immediate evaporation.
- Consumption by crops (evapotranspiration).
- Return flow (water that returns to accessible surface or sub-surface water sources).
- Surface runoff (if applied water does not infiltrate into the soil).
- Deep percolation (water that infiltrates the soil may be used by the crop to become evapotranspiration or percolate below the root zone).
- Root zone storage (eventually used by the crop and transpired to the atmosphere).

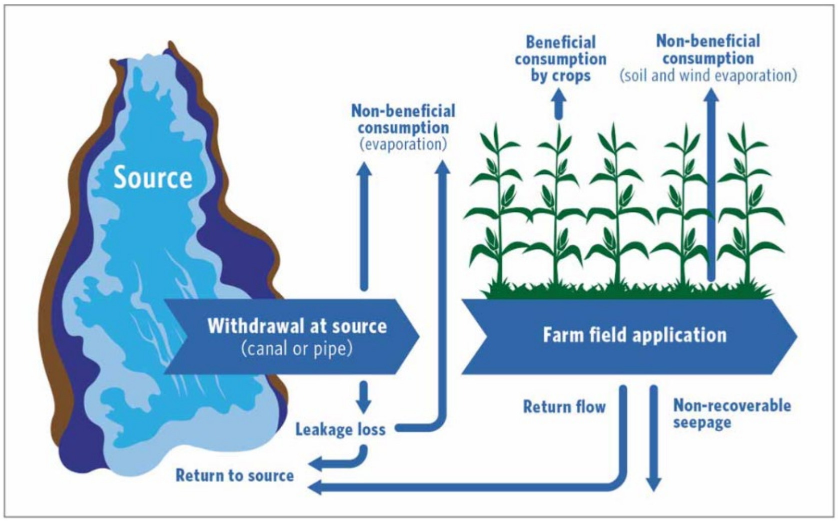

Figure 1. Richter, B. D., et al. (2017). Opportunities for saving and reallocating agricultural water to alleviate water scarcity. Water Policy, 19(5), 886-907.

Deep percolation or surface runoff from irrigation or rainfall can be transporters of contaminants. In some situations, there may be a need for some level of intentional deep percolation to reduce accumulated minerals in the soil to maintain fertility. Soil mineral build-up (high soluble salts or high sodium) can result from using hard water or when applied water evaporates leaving behind salts. Mineral accumulation from evaporation is primarily a concern in arid regions and can impact the quality of irrigated land and the sustainability of agricultural production supported by this land.

Table 1. Irrigation Practices and Application Methods

Practice	Description
Deficit Drip Irrigation	This is a fusion of drip irrigation and direct deficit irrigation. This practice has gained traction for its precision in delivering water to roots, curbing waste.
Deficit Irrigation	Plants are supplied with water below the crop's actual water requirement thereby allowing the plants to go through some extent of water stress. Through deficit irrigation, water is saved but this should be done with minimal negative impacts on the crop yield and quality.
Direct Root-Zone Irrigation	Delivers water directly to the root zone at specific irrigation rates and delivery depths.
Drip Irrigation	Precisely provides water and can achieve greater precision with flow meters and soil moisture sensors. Water is applied slowly and directly to the roots of plants through small, flexible plastic pipes and flow-control emitters or by perforated or porous pipes.
Irrigation Canal or Lateral	A permanent channel that conveys irrigation water from the source to one or more irrigated areas.
Irrigation Ditch Lining	Lining the irrigation ditch, canal, or lateral with an impervious material or chemical treatment. This practice can improve conveyance of irrigation water, prevent waterlogging and erosion, reduce water loss, and maintain water quality.
Irrigation Field Ditch	A permanent irrigation ditch conveys water from the source of supply to a field or fields in an irrigation system. Field ditches are used to convey and distribute irrigation water in many parts of eastern Washington. Lining these ditches can help reduce water loss through seepage.
Irrigation Land Leveling	Reshapes the land surface according to the planned lines and grades for irrigation. Land leveling is important for improving irrigation efficiency and uniformity in the Columbia Basin and Yakima Valley, where many fields have been converted from furrow irrigation to sprinkler or micro irrigation systems.
Irrigation Pipeline	A pipeline conveys water for storage or application as part of an irrigation water system. Given the long distances that water often needs to be conveyed in Washington's irrigated areas, pipelines are essential for reducing water loss through seepage and evaporation. Plastic pipelines, both high and low pressure, are commonly used in the Columbia Basin and Yakima Valley due to their durability and cost-effectiveness.
Irrigation Reservoir	A constructed dam, pit, or tank used to store water for irrigation. Irrigation reservoirs are crucial for managing water supply in the Yakima River Basin, where snowmelt runoff is stored for use during the dry summer months. These reservoirs help ensure a reliable water supply for the basin's diverse agricultural operations.
Irrigation Water Management	A conservation practice that involves determining and controlling the volume, frequency, and application rate of irrigation water to optimize crop yields while conserving water resources. In the Pacific Northwest, NRCS promoted IWM through soil moisture sensors, evapotranspiration-based irrigation scheduling, and installation of more efficient irrigation systems.

Practice	Description
Micro-Irrigation	An irrigation system for frequent application of small quantities of water on or below the soil surface as drops, tiny streams, or miniature spray. Micro-irrigation is well-suited for high-value crops, which are prevalent in Washington's Columbia Basin, Yakima Valley, and Walla Walla regions. The arid climate in eastern Washington makes water conservation crucial, and micro-irrigation can significantly reduce water loss.
Sprinkler System	This practice includes a distribution system that applies water by means of nozzles operated under pressure. Upgrading these systems with more efficient sprinkler packages and automating them using sensors and timers can greatly improve irrigation efficiency and uniformity across the large fields in this region.
Surface and Subsurface Irrigation System	This system delivers irrigation water by surface means (e.g., furrows, borders, and contour levees) or by subsurface means through water table control. Surface irrigation is common in the Columbia Basin for crops like corn and alfalfa. Subsurface irrigation is less common but can be effective in certain locations.
Tailwater Recovery Irrigation System	This system is designed to collect, store, and convey irrigation tailwater, rainfall runoff, field drain water, or combination of these sources for reuse in water distribution to the crop. By collecting and reusing irrigation runoff, farmers can conserve water and minimize nutrient and sediment loading in nearby waterways.

Irrigation Systems and Pollution Prevention

With increasing demands for water, the quality of water available for irrigation is declining in some regions. Irrigation water quality can be measured via (1) the total amount of dissolved salts in the water and (2) the percentage of sodium in the water compared to calcium and magnesium. Common sources of pollution for irrigation water include nutrients, trace elements and heavy metals, pesticides, salinity, sediment, pathogens, and temperature. Low quality irrigation water can negatively impact soil quality, soil salinization, crop productivity and quality, and ultimately contribute to increased water pollution. Additionally, the combination of low water quality supply and raising water tables can eventually lead to waterlogging and salinization, threatening the sustainability of existing irrigation systems. The quality of water used for irrigation can be protected by managing water use, pests, nutrients, animal waste, and industrial waste. Other practices that reduce soil erosion by (1) minimizing mechanical soil disturbance; (2) establishing a permanent organic soil cover; and (3) promoting diversification of crop species, can also maintain the quality of water used for irrigation. Advanced irrigation technologies enable farmers to prioritize crop yield and water use efficiency by precisely delivering water to the root zone, rather than focusing solely on the quantity of water applied (Castillo, 2024). This shift in approach can help reduce water usage while maintaining crop productivity.

The water quality impacts from irrigation are difficult to identify and measure. With this, there are various practices that can help minimize water pollution by effectively managing irrigation systems overtime (e.g., chemigation can help manage pesticide application via irrigation). These systems can reduce water pollution with prescriptive chemical application for the crops and prevent excessive chemical application that can lead to increased water pollution. The literature presents many other practices that can be implemented with an irrigation system to manage irrigation water quality and sources of pollutants. Methods to assess irrigation water quality vary by region, therefore practices to manage water quality impacts from irrigation should be tailored to specific land conditions.

Irrigation Application Systems

Irrigation systems can be designed to prevent over- or under-application of water to crops. As a first step to identifying suitable irrigation methods, landowners can measure short and long-term rates of water use. Calculating the daily and weekly rate of crop water use can (1) inform appropriately scheduled irrigation applications and (2) define minimum irrigation system capacities.

Irrigation may be applied via sprinkler, surface, trickle, subsurface drip, or below surface subirrigation. A summary of factors that can impact which irrigation system is used is shown in Table 2 (Eisenhauer et al., 2021). **Sprinkler irrigation** includes center pivot or fixed, solid set sprinklers among other options. Sprinkler systems may also be used for frost protection. **Surface irrigation** distributes water as it flows over the soil surface and includes practices such as flood irrigation and furrow irrigation which can be implemented on sloped or un-sloped fields. **Drip and micro-sprinkler** systems use laterals lines with emitters (drip lines or sprinklers) and are intended to irrigate individual or groups of plants and not the entire soil surface. **Subsurface drip irrigation** uses drip tubes or drip tape that are buried beneath the surface to meet crop water needs. **Subsurface irrigation** is used where site conditions and a water supply are available to raise and maintain the water table in a crop root zone during the growing season. Efficient irrigation systems should be tailored to the crop being grown and include adequate monitoring of the irrigation system and water delivery. Through ongoing monitoring, application rates can be adjusted given the growth stage of the crop.

Table 2: Factors affecting the selection of a water application method. Eisenhauer, D. E., Martin, D. L., Heeren, D. M., & Hoffman, G. J. (2021). Irrigation systems management. American Society of Agricultural and Biological Engineers (ASABE).

Water Application Method	Land Slope	Water Intake Rate of Soil	Water Tolerance of Crop	Wind Action
Sprinkler	Adaptable to both level and sloping ground surfaces.	Adaptable to any soil intake rate.	Adaptable to most crops. Typical systems may promote fungi and disease on foliage and fruit	Wind may affect application efficiency and uniformity
Surface	Land area must be leveled or graded to slopes less than 2% for most systems. It is sometimes possible to flood steeper slopes that are sodded.	Not recommended for soils with high intake rates of more than 2.5 in/hr. or with extremely low intake rates such as peats or mucks.	Adaptable to most crops. Typical systems may promote fungi and disease on foliage and fruit	No effects.
Drip/ micro	Adaptable to all land slopes	Adaptable to any soil intake rate.	No problems.	No effects.
Subsurface drip irrigation	Adaptable to all land slopes.	Best adapted to medium and fine-textured soils with moderate to good capillary movement.	Adaptable to most crops. Saline water tables limit application.	No effects.
Subsurface Irrigation	Land area must be level or contoured.	Adaptable only to soils which have an impervious layer below the root zone, or a high, controllable water table.	Adaptable to most crops. Saline water tables limit application.	No effects.

Practices for Irrigation Induced Pollutant Transport and Leaching

Various practices can be implemented to address challenges associated with irrigation-induced pollutant transport and nutrient leaching:

- Adopting precision irrigation techniques, such as drip irrigation and soil moisture sensor-based scheduling, can significantly reduce the risk of pollutant transport and nutrient leaching. These techniques optimize water management by closely matching irrigation to crop water requirements and soil moisture conditions, minimizing deep percolation and runoff (Brown et al., 2010; Alva et al., 2009).
- Implementing nutrient management plans can help limit nutrient leaching by ensuring that nitrogen fertilizer application rates and timing are aligned with crop nutrient demands.
- Incorporating cover crops into crop rotations and adopting conservation tillage practices can help limit pollutant transport and nutrient leaching. Cover crops can scavenge residual nitrogen from the soil profile, reducing the amount of nitrate available for leaching. (Brown et al., 2010).
- Certain irrigation systems can be used to apply nutrients directly to the crop, minimizing the risk of nutrient loss through leaching or runoff. Fertigation, the application of fertilizers through irrigation water, allows for precise nutrient delivery and timing (Brown et al., 2010).
- Organic nitrogen sources, such as cover crops, compost, and manure, can be used to supply nitrogen to crops while reducing the risk of nitrate leaching compared to mineral fertilizers. These organic sources release nitrogen more slowly and can improve soil structure and water retention (Gaskell and Smith, 2007). However, careful management is still required to avoid over-application and potential nitrogen losses. Because the release rate of these organic sources is slow producers must conduct both soil and tissue testing of plants and the organic nutrient source to help align crop needs with nutrient release. Otherwise, crops may not have the nutrients needed when they are needed.

Continued research, education, and outreach efforts are essential to promote the widespread adoption of these practices and ensure the long-term sustainability of irrigated agriculture in the region.

Irrigation by Crop Type

Irrigation is critical for successful production of many annual and perennial crop species in the Pacific Northwest. The **Crop Irrigation Requirement (CIR)** is used to quantify the amount of water that must be applied to meet a crop's evapotranspiration needs without a significant reduction in crop yield or quality. Additional quantities of water that are required for leaching, frost-protection, cooling, and other miscellaneous crop requirements, are also factored into the CIR. All farmers schedule their irrigation to some degree.

Irrigation scheduling as defined in the literature involves:

- Understanding how much available water capacity the farm has in its root zone for the crop being grown.
- Estimating crop evapotranspiration to predict the interval between watering.
- Assessing evapotranspiration with soil-moisture measurement.

Irrigation efficiency represents the amount of water that needs to be applied for a particular type of irrigation system. Low irrigation efficiency can impact yield depression and crop loss, therefore understanding how crops respond to soil water throughout their growing season is necessary when designing an irrigation system. Crop response to irrigation is affected by soil conditions, fertility, plant types, stage of growth, and the local climate. Adjusting irrigation amounts during noncritical water demand periods minimizes impacts on crop yield and crop size while enhancing water-saving effectiveness. Additionally, water-saving techniques trigger plant responses and can improve resistance to water deficits, promote reproductive growth, and protect against drought-related damage.

Woody crops

Woody crops, due to large size, extensive roots, and prolonged growth cycles, have greater water storage and consumption. Applying water-saving irrigation to woody crops requires tailoring to their distinct characteristics and growth patterns. Different woody crops exhibit varying levels of drought tolerance:

- High tolerance: apricot and olive
- Moderate tolerance: apple and pear

In addition to these crops, Washington is a significant producer of cherries, peaches, and grapes, which are widely grown across the state and play a crucial role in the agricultural economy (USDA NASS, 2023). Irrigation practices for these crops must account for the region’s diverse soil types, ranging from sandy to silt loam soils (Davenport et al., 2003). Sandy soils, have lower water holding capacities and require more frequent irrigation, while finer-textured soils may necessitate less frequent but longer irrigation cycles to ensure adequate moisture reaches the root zone (Davenport et al., 2003).

One study measured how partial root-zone drying and deficit drip irrigation can be efficient water-saving techniques for woody crops:

- Apple – 20-25% of water without a notable impact on yield.
- Apricot – 25-35% of water is conserved.
- Plum – 23% of water is conserved.
- Grape vines – 16-23% of water is conserved.

Partial root-zone drying (PRD) and deficit irrigation (DI) have shown promise as water-saving strategies for woody crops in Washington (Leib et al., 2006). These techniques can reduce water use by 15-20% without significantly impacting fruit yield or quality, depending on the crop and soil type (Fereres & Soriano, 2007).

Orchards

Applying deficit irrigation through subsurface drip irrigation (SDI) has gained wider acceptance for woody perennial crops in recent years due to its advantages in conserving water and fruit production, along with improved irrigation equipment and scheduling tools.

Grapes

Grape production in southcentral Washington relies on supplemental irrigation because of its arid climate with around 200 mm of annual rainfall, resulting in natural water deficits for crop production (Keller et al., 2016). Recent studies showed that SDI results in greater water use efficiency without altering grape composition and provides the potential to change the structure and composition of groundcover vegetation, which alters root-associated fungal communities and lowers the negative effects from soil borne pathogens (Davenport et al., 2008).

One crucial aspect of grape production and perenniality is the practice of fall irrigation before the winter dormancy season. This management practices ensures that the rooting zones are well-watered during the transition into winter. Wet soils provide insulation and protect roots and plants from extreme cold temperatures that could otherwise damage or kill them. This practice is not limited to vineyards; it is also employed in orchards and alfalfa hay fields to safeguard plants against the detrimental effects of cold temperatures. Wet soils have a higher heat capacity and thermal conductivity compared to dry soils, which allows them to retain heat more effectively and prevent rapid cooling and freezing (Davenport et al., 2008).

The choice of irrigation practices in vineyards is heavily influenced by the intended use of the grapes, whether for juice or wine production. Careful irrigation management is essential to optimize fruit quality and yield while minimizing water use and environmental impacts. By tailoring irrigation strategies to the specific needs of the grapevines and the local climate conditions, growers can ensure the long-term sustainability and productivity of their vineyards.

Hops

Hop yield can increase with increased irrigation levels. When water is available, deficit irrigation of hops grown might not be an economically viable practice. However, during water short years, applying moderate stress to hop plants might be a practical choice. One study found that deficit irrigation maintained the quality of hop cones across various cultivars similar to those for fully irrigated hops. Hop cone quality also improved due to the plants having a more developed root system (Nakawuka et al., 2017).

Soil Considerations

Soil characteristics play a crucial role in determining how irrigation water should be managed to optimize crop yield and quality while minimizing negative environmental impacts. Washington's diverse topography and microclimates result in varying soil types and moisture levels across the state, requiring careful consideration of soil properties when making irrigation decisions (Hipple, 2002). This is particularly important for moisture sensitive crops like potatoes, which are a major commodity in the Columbia Basin. Soil characteristics that inform irrigation management include:

- **Soil Texture, Structure, and Depth**: These properties influence water retention, infiltration, and percolation rates, which in turn affect irrigation frequency and duration. In the Pacific Northwest, soils are highly variable due to the region's diverse geology and climate. For example, the Columbia Basin is characterized by coarse-textured soils formed from glacial outwash and wind-blown deposits, while the Palouse region of eastern Washington has deep, loess-derived soils with high silt content (Schillinger et al., 2010). Differences in soil texture and structure in these regions greatly influence irrigation practices and the potential for erosion and runoff.
- **Organic Matter**: Higher organic matter content improves soil structure, water-holding capacity, and nutrient retention (Ritter and Shirmohammadi, 2001). Soil organic matter levels are generally low in the Pacific Northwest region due to the semi-arid climate and prevalence of cultivation (Machado, 2011). Conservation practices such as reduced tillage, cover cropping, and organic amendments help increase soil organic matter and improve soil health in irrigated cropping systems.
- **Bulk Density**: Soils with high bulk density have reduced pore space, which can limit water infiltration and root growth. Practices such as controlled traffic farming and cover crops can help reduce soil compaction and improve water infiltration in irrigated fields (Williams et al., 2014).
- **Salinity and Acidity**: High levels of salinity or acidity can negatively impact crop growth and yield. Addition of lime and gypsum are common practices used to manage soil salinity and acidity.
- **Drainage and Topography**: Poor drainage and high-water tables in irrigated areas are prevalent in the Yakima Valley of Washington (Fuhrer et al., 2004). Proper design and maintenance of drainage systems to support adequate surface and subsurface drainage is crucial for water-efficient irrigation and improving crop yields.
- **Fertility**: Soil fertility affects crop growth and water use efficiency (Ritter and Shirmohammadi, 2001). In the Pacific Northwest, soil fertility is generally high due to the region's volcanic heritage and the use of fertilizers in irrigated agriculture. However, over-application of fertilizers can lead to nutrient leaching and water quality problems, particularly in areas with coarse-textured soils or high rainfall.

Tillage practices can have a significant impact on soil health and water management in irrigated agriculture. Conventional tillage can lead to soil compaction, reduced water infiltration, and increased evaporation. In contrast, conservation tillage practices like no-till and reduced tillage can improve soil structure, increase water-holding capacity, and reduce evaporation losses (Chapter on Tillage & Residue Management, Ecology, 2022). Adopting these practices in irrigation systems can help optimize water use efficiency and minimize the environmental impacts of irrigation.

When developing an irrigation management strategy, it is crucial to consider the complex interactions between climate, soil, and crop factors. Integrating soil management practices like cover cropping, organic amendments, and conservation tillage can improve soil health and water use efficiency in irrigated systems. For more detailed information on the relationships between tillage practices and soil health, please refer to the Chapter on Tillage & Residue Management[5].

The National Cooperative Soil Survey (NCSS) provides data that can be used to identify soil limitations for irrigation. These data can help landowners determine which crops or irrigation methods are most suitable for their specific soil conditions. In some cases, the soil properties may limit the types of crops that can be grown or the irrigation methods that can be effectively employed. By using the information provided by the NCSS, landowners can make informed decisions about their irrigation management practices, considering factors such as soil texture, depth, drainage, and fertility.

Soil Salinity

Soil salinity is a critical issue for irrigated agriculture in arid and semi-arid regions, particularly in areas like the Columbia Basin and Yakima River Basin in Washington, where irrigation water with high salt content is applied to poorly drained soils.

Salts in the soil migrate with water movement, and the dynamics of soil moisture under different irrigation methods can lead to varying patterns of salt accumulation. The balance between salt accumulation and leaching is a function of the soil water status, which is influenced by the irrigation method and management practices employed. When water is removed from the soil through evapotranspiration, salts can concentrate in the root zone, leading to osmotic stress and reduced crop yields. The presence of high levels of sodium in the soil can also cause the dispersion of soil aggregates and the formation of impermeable layers, further reducing infiltration and soil productivity (Horneck et al., 2007).

Irrigation management plays a key role in controlling soil salinity. Applying water in excess of crop requirements can lead to the rise of shallow groundwater tables, which can bring salts to the upper layers of the soil profile. This is particularly problematic in poorly drained soils, where

[5] https://apps.ecology.wa.gov/publications/parts/2010008part2.pdf

the absence of a sufficient downward flux of water to leach salts from the root zone can result in the concentration of salts near the soil surface. Salinization is likely to occur when groundwater is within three meters of the surface, depending on soil type. The use of surface irrigation methods, which are associated with higher evaporation losses, can exacerbate soil salinity problems by leading to the accumulation of salts in the topsoil. Conversely, insufficient irrigation can also result in the buildup of salts in the root zone due to inadequate leaching.

Technical problems that have contributed to irrigation-induced salinity include:

- Poor on-farm water use efficiency.
- Inadequate construction, operation, and maintenance of irrigation canals, causing excessive seepage losses.
- Inadequate or lack of drainage infrastructure.
- Poor quality construction, operation, and maintenance of existing drainage facilities.

Effective management of soil salinity involves a multi-faceted approach that includes monitoring irrigation water quality, implementing efficient irrigation practices, and adopting strategies to reduce salt accumulation in the soil profile. In Washington, the Department of Ecology established water quality standards for irrigation water (Groundwater Water Quality Standards[6] and Surface Water Quality Standards[7]), and sources that exceed these limits may require treatment or blending with higher-quality water to minimize the risk of soil salinization. Regular monitoring of soil salinity levels is also essential for identifying potential problems before they impact crop yields. Soil salinity can be measured using various methods, such as electrical conductivity (EC) meters alongside soil and water sampling (Horneck et al., 2007; Ward (2017)).

To address soil salinity issues, farmers can employ various practices, such as leaching to remove excess salts from the root zone, install drainage systems to manage shallow groundwater tables, and use salt-tolerant crops and amendments (Grattan, 2002). Leaching is a common practice in areas with high soil salinity, while drainage systems, such as tile drains or drainage ditches, can help remove excess water and salts from the soil profile (Evans, n.d.). In addition, soil amendments like gypsum and sulfuric acid can be used to replace exchangeable sodium with calcium and improve soil structure in salt-affected soils (Horneck et al., 2007). Proper management of irrigation water quality, soil salinity levels, and crop selection and management practices are essential to ensure the long-term sustainability of irrigated agriculture.

[6] https://apps.ecology.wa.gov/publications/documents/9602.pdf
[7] https://app.leg.wa.gov/WAC/default.aspx?cite=173-201A

Impacts on Surface Water, Groundwater, Erosion, and Leaching

Surface Water and Groundwater

Understanding how irrigation systems impact natural watershed hydrology, water quality, and stream habitat involves a deeper understanding of the interaction between surface water and groundwater flow. Irrigated agriculture depends on surface water and groundwater supplies and over application could result in erosion, contaminated surface water or groundwater, and increased maintenance costs. Irrigation systems' effects on surface water and groundwater are largely determined by the system's water source and irrigation method, timing and amount. Groundwater and surface water pollution can be caused by agricultural chemicals when irrigation water runoff and deep percolation transports pollutants to surface and groundwater. Additionally, the proximity of agricultural fields to surface water affects the likelihood of irrigation negatively impacting water quality. Landowners can prevent or reduce irrigation-related pollution by preventing erosion or removing sediment from surface runoff. Modern irrigation practices rely on real-time measurements from underground moisture and nutrient sensors to monitor water at the root zone, reducing the amount of water applied and minimizing the risk if pollutant transport (Castillo, 2024). By prioritizing soil moisture monitoring and precision irrigation, farmers can maintain crop health while protecting water quality.

Withdrawing groundwater or surface water for irrigation can impact the natural hydrology of rivers and streams, water temperature, and aquatic ecosystems. Stream diversions, groundwater discharge to streams, and the application of irrigation water can further impact stream flow and stream temperature. Increased groundwater discharge from excessive irrigation can decrease warm-season stream temperature and vice versa. Moreover, withdrawing groundwater for irrigation may change nearby land conditions, create seasonal groundwater stress on aquifers, or accelerate other types of groundwater pollution. Irrigation systems that promote continuous plant uptake of soil nutrients can potentially improve groundwater quality. One study found that irrigation can increase groundwater recharge relative to pre-irrigation conditions because not all water applied was removed by evapotranspiration (Scanlon et al., 2007). However, the study also noted that increased groundwater recharge from irrigation can lead to water quality issues, such as nitrate contamination, if not properly managed. Therefore, it is essential to implement best management practices that optimize irrigation efficiency and minimize the risk of groundwater pollution.

Impacts via Runoff

Sediment is one of the primary pollutants transported by irrigation tail waters when this water makes its way back to streams, rivers, and other water bodies. This sediment can impair water conveyance structures, reduce the storage capacity of reservoirs through sedimentation, and significantly degrade the quality of receiving waters.

In the Pacific Northwest, sediment pollution from irrigation return flows has been recognized as a leading cause of water quality issues in multiple river systems. In south-central Washington's lower Yakima River Basin, for example, irrigation return flows account for practically the entirety of the river's flow during the summer months. Steadily increasing sediment loads in these return flows created major sediment pollution problems in downstream diversion canals and in the Yakima River itself (Santos et al., 2003).

Beyond its physical impacts, sediment pollution from irrigation runoff also acts as a transport mechanism for other contaminants. As runoff carries eroded sediment to receiving waters, it also transports nutrients like nitrogen and phosphorus, pesticides, and other pollutants that readily attach to sediment particles. These contaminants can further impair water quality in the receiving streams, rivers, and reservoirs (Santos et al., 2003). In the Yakima River Basin, for instance, DDT and other organochlorine pesticides historically used in irrigated agriculture have been detected in river sediments and aquatic organisms. Elevated nutrient loads from irrigated lands are a common issue, contributing to eutrophication and algal blooms in downstream water bodies (Santos et al., 2003; Fuhrer et al., 2004).

The effect of irrigation on surface water quality extends beyond sediment and sediment-associated pollutants. Using and reusing water for irrigation tends to concentrate dissolved mineral salts in the residual water that drains from irrigated lands and returns to rivers. Through processes of transpiration, leaching, evaporation, and storage in reservoirs, irrigation significantly increases the total dissolved solids content and shifts the chemical composition of stream water. The repeated cycling of water through agricultural fields and back to streams can increase concentrations of total dissolved solids, hardness, chloride, and sulfate in stream water (Cunningham et al., 1953).

Sprinkler irrigation systems can specifically contribute to runoff and erosion issues if not properly designed and managed. The application rate of the sprinkler system needs to match the infiltration rate of the soil to avoid runoff. This is an especially notable concern with lower pressure sprinkler packages on center pivots which have higher application rates. Management practices like minimizing irrigation on bare soils, utilizing surface storage, implementing conservation tillage, and employing reservoir tillage techniques can help reduce runoff potential. In some cases, surfactants may also enhance infiltration and reduce runoff on water repellent soils specifically (Hansen & Trimmer, 1997; Aase et al., 1998).

A study by King and Bjorneberg (2012) evaluated the runoff and erosion potential of different sprinkler packages on center pivot irrigation systems in southern Idaho. They found that low-pressure sprinklers with higher application rates generated up to 15 times more runoff and 2-4 times more sediment loss compared to high-pressure impact sprinklers. The study recommended using sprinklers with lower application rates, increasing sprinkler wetted diameters, and adopting conservation tillage practices to reduce runoff and erosion under center pivots.

Effective measures are increasingly needed to mitigate the water quality impacts from irrigation return flows. This is especially true in heavily irrigated, erosion-prone regions like the Pacific Northwest. Expanded monitoring of irrigated areas and receiving waters is essential to track trends and guide mitigation efforts to reduce water quality impacts in the planning and management of irrigation systems.

Impacts on Erosion

Irrigation practices can have significant impacts on soil erosion and the subsequent transport of sediments and adsorbed chemicals. When excess irrigation water runs off from cropland, it can cause soil particles to detach and be carried away by the flow of water. This process not only leads to the loss of valuable topsoil but also contributes to the degradation of water quality in nearby streams, rivers, and other water bodies.

The severity of erosion caused by irrigation depends on various factors, such as soil type, topography, crop type, and the specific irrigation method employed. Among the different irrigation techniques, furrow irrigation causes more erosion compared to sprinkler or drip irrigation systems. In furrow irrigation, water is applied to the soil surface and allowed to flow down the furrows between crop rows. This method can lead to higher runoff volumes and velocities, which increases the risk of soil erosion, particularly in fields with steeper slopes or soils that are more susceptible to erosion (Sojka et al., 1998).

Irrigation-induced erosion can decrease land productivity by removing fertile topsoil and exposing less productive subsoil layers. This reduction in soil quality can lead to lower crop yields and increased production costs, ultimately resulting in reduced farm income and higher commodity prices for consumers.

Sediment transported by irrigation tail waters can negatively impact various components of the irrigation system and the surrounding environment. Sedimentation in canals, reservoirs, and other structures can reduce their efficiency, storage capacity, and lifespan. Sediment-laden irrigation tail waters returning to streams and rivers can also have detrimental effects on aquatic ecosystems, altering stream morphology, degrading water quality, and harming aquatic life.

Furrow irrigation-induced erosion can be severe, with annual soil losses of 5-50 metric tons per hectare (5-55 tons per acre) being common in the Pacific Northwest, and losses can be three times higher near furrow inlets at the top of fields (Carter, 1993). In southern Idaho, studies have shown that crop yield potential has been reduced by 25% due to 80 years of furrow irrigation-induced erosion (Carter, 1993). The impacts of irrigation-induced erosion extend beyond the farm, with sediment in irrigation return flows causing major water quality problems in several rivers in the western U.S. (Koluvek et al., 1993). While sprinkler and drip irrigation systems generally have a lower impact on erosion compared to furrow irrigation, they can still contribute to soil erosion if not properly managed. The kinetic energy of falling water drops from sprinklers can detach soil particles, initiating the erosion process (Trout and Neibling, 1993). Under center-pivot sprinkler systems, annual sediment yields as high as 33 metric tons per hectare (15 tons per acre) have been measured (Koluvek et al., 1993).

To mitigate the impacts of irrigation-induced erosion, farmers in the Pacific Northwest and Washington State can adopt various best management practices designed to reduce soil erosion, improve water quality, and enhance the overall sustainability and productivity of agricultural operations:

- Converting from furrow irrigation to more efficient sprinkler or drip systems.
- Utilizing low-pressure sprinklers, booms, and drag hoses to apply water closer to the ground can reduce droplet impact energy and minimize soil erosion.
- Adopting conservation tillage practices, such as minimum tillage and maintaining surface crop residues, can improve soil structure, reduce erosion, and enhance soil organic matter.
- Cover crops protect the soil surface, improve soil structure, and reduce erosion.
- Precision irrigation techniques, such as variable rate irrigation and soil moisture monitoring, can optimize water application rates and minimize runoff.
- Conservation buffers, such as riparian buffers and filter strips, can intercept sediment and nutrients in irrigation runoff before they reach water bodies (see the Chapter on Riparian Areas & Surface Water Protection[8] for more details).

While these best management practices can effectively reduce irrigation-induced erosion and improve water quality, their adoption may be limited by factors such as cost, complexity, and lack of awareness (Osmond et al., 2015). To overcome these barriers, continued research, education, and outreach efforts are needed to promote the adoption of these practices among farmers in the Pacific Northwest and Washington State.

Nitrate-Nitrogen Leaching in Groundwater

Irrigation is a critical component of agricultural production, ensuring that crops receive adequate water for optimal growth and yield. However, certain irrigation practices can lead to various environmental issues, particularly the leaching of pollutants, such as nitrate-nitrogen, into groundwater.

The risk of nitrate leaching is influenced by a complex interplay of factors, including crop characteristics, soil properties, irrigation practices, and the timing and rate of nitrogen application. Crops with low nitrogen requirements or shallow root systems are more prone to nitrate leaching, as they may not effectively capture and utilize the available nitrogen in the soil profile (Meisinger and Delgado, 2002). For example, shallow-rooted crops like lettuce,

[8] https://apps.ecology.wa.gov/publications/parts/2010008part6.pdf

blueberries, and onions are more susceptible to leaching compared to deep-rooted crops such as many forage crops and dryland pulses and cereals.

Several factors contribute to nitrate leaching from irrigated agricultural systems. In addition to crop characteristics, the timing and rate of nitrogen application play a crucial role in determining the risk of nitrate leaching. When nitrogen is applied in excess of a crop's requirements or at a time when the crop is not actively taking up nutrients, the excess nitrogen becomes vulnerable to leaching. This is particularly relevant for crops where only a small portion of the nitrogen is removed during harvest, as the remaining nitrogen in the soil can be leached by subsequent irrigation or rainfall events.

Crops with high water requirements, shallow rooting depth, and shorter growing periods tend to increase the potential risk of nitrate pollution to groundwater, especially when irrigation and fertilizer application exceed the crop's uptake capacity. Light-textured soils, such as coarse sand, have lower water-holding capacity and higher permeability compared to finer-textured soils like clay, making them more susceptible to nitrate leaching (WSDA & Yakima County, 2018; Meiseinger & Delgado, 2002). The combination of light-textured soils, shallow-rooted crops, and excessive or poorly timed nitrogen application can significantly increase the risk of nitrate leaching in irrigated agricultural systems. The amount of nitrate leached is directly related to the percolation or drainage volume (Ritter, 1989). Over-irrigation or unexpected rainfall events can create deep percolation, increasing the risk of nitrate leaching. The WSU AgriMet tool [9]has been valuable to farmers as they plan the timing and amount of water moving through their irrigation systems. When the amount of water applied exceeds the soil's holding capacity and the crop's water requirements, the excess water moves through the soil profile, carrying dissolved nitrates with it. On "heavy" soils with less infiltration capacity, water may also move overland and not through the soil profile.

It is important to recognize that nitrate leaching occurs with great variability across time (seasonality) and within a cropping cycle, as well as within a field (Quemada et al., 2013). This variability can be influenced by factors such as irrigation practices, soil properties, and crop growth stages. For example, nitrate leaching may be higher during periods of high rainfall or irrigation, particularly if these events occur when crops are not actively growing or taking up nutrients. Similarly, within a field, areas with lighter-textured soils with good drainage may be more prone to nitrate leaching compared to areas with heavier soils or poor drainage. Understanding these temporal and spatial variations is crucial for developing targeted management strategies to minimize nitrate leaching.

In the western region of Washington, the relationship between hydrology and nitrate leaching is particularly pronounced. Irrigation practices that result in runoff can lead to the off-site movement of nitrogen, potentially impacting surface water quality (Mitchell et al., 2003; WSDA

[9] https://www.usbr.gov/pn/agrimet/irrigation.html

& Yakima County, 2018). Managing and reducing irrigation application time and quantity is crucial for minimizing leaching and improving water quality on crop land. This is especially important in areas with coarse-textured soils or high precipitation, where the risk of nitrate leaching is greater (Sullivan et al., 2013; WSDA & Yakima County, 2018).

Table 3, adapted from the WSDA and Yakima County report (2018), shows the estimated nitrogen available for transport in the Lower Yakima Valley from various sources. For irrigated agriculture, the evaluation location for available nitrogen is at the bottom of the root zone, where it can no longer be taken up by plants. In contrast, for lagoons, the location is at the bottom of the lagoon liner, where nitrogen can enter the soil and move through it under some conditions. Irrigated cropland amounts for the largest contributor to potential nitrogen availability, accounting for 46% to 73% of the total estimated nitrogen available for transport Lower Yakima Valley Groundwater Management Area (GWMA), depending on the scenario evaluated. The report also identified specific crops, such as silage corn, triticale, and juice grapes, as having higher estimated nitrogen surpluses per acre compared to other crops. CAFO lagoons were the second-largest contributor to potential nitrogen availability in the GWMA, accounting for 14% to 22% of the total estimated nitrogen available for transport, depending on the scenario evaluated.

Table 3. Estimated nitrogen available for transport in the Lower Yakima Valley, Washington (adapted from WSDA & Yakima County, 2018)

Sources	Low Scenario		Medium Scenario		High Scenario	
	Tons N/year	% of total N	Tons N/year	% of total N	Tons N/year	% of total N
Irrigated Cropland	298	47	2,595	63	7,452	73
Dairy CAFO Pens	70	11	502	12	935	9
Dairy CAFO Lagoons	142	22	781	19	1,421	14
All septic (ROSS, LOSS, COSS)	47	7	83	2	135	1
Residential fertilizer	10	2	26	1	41	0
Small scale farms	4	1	11	0	18	0
Atmospheric deposition	67	11	89	2	268	3

The Department of Ecology has developed the Nitrate Prioritization Project to characterize nitrate risk in groundwater across the state (Ecology, 2016). This project outlines soil and cropping practices in areas that are vulnerable to nitrate leaching into groundwater, providing valuable information for developing targeted management strategies to minimize nitrate pollution.

Nitrate leaching from irrigated agricultural systems can have significant impacts on groundwater quality, land productivity, and ecosystems. Contamination of groundwater aquifers by nitrate is a major concern in areas with irrigated agriculture due to the large amounts of nitrogen fertilizer typically used to ensure crop production. Proper irrigation timing and management can minimize nitrate in runoff and nitrate leaching from soil to groundwater. Irrigation scheduling based on soil moisture measurements or evapotranspiration requirements is the most practical water management method for controlling nitrate leaching (Ritter, 1989). In addition, inclusion of irrigation water quality, such as knowing the nitrogen load from irrigation water, is important for nutrient management. However, even with best irrigation management practices, it may not be impossible to eliminate nitrate leaching to zero on coarse-textured soils while maintaining adequate crop yields (Watts and Martin, 1981; Ritter, 1989; Weitzman et al., 2022). Some leaching below the root zone will still occur.

Careful nitrogen fertilizer management is also critical for reducing nitrate leaching. Applying only enough nitrogen to meet realistic yield goals, timing applications to coincide with periods of peak crop demand, using slow-release fertilizers, and accounting for nitrogen inputs from irrigation water and other sources can help minimize excess nitrogen in the soil that is susceptible to leaching (Ritter, 1989; Meisinger and Delgado, 2002).

Nitrate leached below the root zone during the growing season may not be immediately transported to groundwater but rather stored in the deeper unsaturated zone (Ritter, 1989). This nitrate can then be susceptible to further downward movement to groundwater during subsequent periods of high drainage. Considering this time lag effect and potential nitrogen storage in the vadose zone is important for fully assessing the long-term impacts of agricultural practices on groundwater quality.

Simulation models coupling nitrogen cycling and hydrologic transport processes have been developed to predict nitrate leaching under various agricultural management scenarios (Watts and Hanks, 1978; Hutson and Wagenet, 1991). However, these models are often limited by a lack of site-specific field data for calibration and validation (Ritter, 1989). Direct field measurements of nitrate leaching using methods like lysimeters, porous cup samplers, or monitoring wells are needed to improve our understanding of nitrogen transport and to test model performance.

Implementing irrigation management plans that optimize the timing, rate, and placement of irrigation water is an effective strategy for reducing nitrate leaching. In addition, it is important to consider the full spectrum of nitrogen loading sources, including biosolids, septic systems, food processing waste, and manure produced by concentrated animal operations and dairies (WSDA & Yakima County, 2018). The Natural Resources Conservation Service (NRCS) offers technical assistance and cost-share programs, such as the Conservation Stewardship Program (CSP) 447 for Irrigation and Drainage Tailwater Recovery and the Conservation Practice Standard (CPS) 449 for Irrigation Water Management, to support farmers in adopting these practices. By understanding the complex interactions between irrigation practices, soil properties, and crop characteristics, farmers can make informed decisions to reduce the environmental impacts of irrigated agriculture while maintaining productivity.

Frost Protection

Frost damage is a significant concern for many agricultural producers, particularly those growing temperature-sensitive crops such as fruits and vegetables. In the Pacific Northwest, where the climate is characterized by cool winters and the potential for late spring frosts, farmers employ various methods to protect their crops from frost damage. These methods include overhead sprinkler irrigation, under canopy sprinklers, man-made fog, and flooding.

Overhead sprinkler irrigation is one of the most common methods used for frost protection in the Pacific Northwest, particularly in fruit orchards. This method relies on the principle that heat lost from the plant to its environment is replaced by heat released as the applied water changes to ice. As long as ice formation continues, the latent heat of fusion maintains the plant temperature near 0°C (32°F), preventing damage even if air temperatures drop several degrees below freezing (Landers & Witte, 1967). In Washington State, overhead sprinkler irrigation is widely used for frost protection in fruit orchards, especially in the Yakima Valley and Wenatchee areas, where apple and cherry production is significant. The rate of water applied for protection depends on various factors, including plant characteristics, environmental conditions, and the severity of the frost event. Adjusting for wind speed and humidity is also crucial, as higher wind speeds and drier air increase evaporative cooling and thus the water application needed (Landers & Witte, 1967).

Heat is available to the plant through several mechanisms when using overhead sprinkler irrigation for frost protection:

- Enhanced soil heat conduction: As water is applied to the soil, it increases the soil's thermal conductivity, allowing more heat to be conducted from deeper soil layers to the surface.
- Heat lost by cooling sprinkler drops: As water droplets travel from the sprinkler to the plant and soil surface, they cool through evaporation and convection, releasing heat to the surrounding air.
- The release of latent heat by water freezing on the ground: When water droplets freeze on the soil surface, they release latent heat, which helps to maintain the temperature around the plant above the critical damage threshold.

While under canopy frost protection is not as common in Washington State as overhead sprinklers, some orchards in the Columbia Basin and Okanogan regions have experimented with this method. Under canopy sprinklers are designed to provide a more targeted application of water directly to the crop, reducing the amount of water needed and minimizing the potential for ice buildup on the plant canopy. However, the achievable temperature gains are limited and highly dependent on ground coverage, application rate, and weather conditions. Under canopy sprinkling is generally only recommended for areas where severe frosts are rare.

Man-made fog is an experimental approach to frost protection that aims to duplicate the greenhouse gas effect. The goal is to produce a "cloud" that blankets the crop area, decreasing radiative cooling and preventing plant parts from dropping to the critical temperature. While there has been some experimental success, a practical system has not been developed (Chastain et al., 2016). The difficulty lies in producing droplets large enough to block the outgoing longwave radiation and keeping them in the atmosphere without losing them to evaporation. Research institutions in the Pacific Northwest, such as Washington State University and Oregon State University, have conducted studies on the potential of man-made fog for frost protection. However, it remains an experimental approach and has not been widely adopted by farmers in the region.

In the Pacific Northwest, flooding is not a common frost protection method due to the region's topography and the prevalence of sprinkler irrigation systems. However, some low-lying areas near rivers or streams, such as parts of the Snoqualmie Valley in Washington State, may use flooding for frost protection in certain crops. Flooding works by increasing the thermal mass of the soil, which can help maintain temperatures above the critical damage threshold during a frost event.

When designing and implementing frost protection strategies, it is essential to consider soil characteristics such as texture, structure, and cation exchange capacity (CEC). CEC is a measure of the soil's ability to hold and exchange cations, which is influenced by the amount and type of clay and organic matter present (Brady & Weil, 2008). Soils with higher CEC, typically those with higher clay and organic matter content, have a greater capacity to retain water and nutrients (Horneck et al., 2007). For example, for every 1% of organic matter, the soil can retain approximately 20,000 gallons of water per acre. This means that a soil with 5% organic matter can hold significantly more water than a soil with only 0.5% organic matter, which has implications for irrigation management and the potential for leaching.

In the Pacific Northwest, soil CEC varies widely depending on the region and soil type. Sandy soils, which are common in some parts of the region, tend to have low CEC values and are more prone to leaching and deep percolation. In contrast, soils with higher clay content have higher CEC values and are less susceptible to leaching (Brady & Weil, 2008).

Table 4: CEC ranges for different clay types (Adapted from UGA Cooperative Extension (Saha, 2014). The table depicts CEC at pH 7.0 of different soil types, textures, and soil organic matter.

Clay Type	CEC (meq/100g)
Kaolinite	3-15
Illite	15-40
Montmorillonite	80-100

Table 5: CEC ranges for different soil textures (Adapted from UGA Cooperative Extension (Saha, 2014). The table depicts CEC at pH 7.0 of different soil types, textures, and soil organic matter.

Soil Texture	CEC (meq/100g)
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	>30
Organic Matter	200-400

When developing an irrigation management strategy, growers should consider both soil texture and CEC, as these properties influence water retention, nutrient holding capacity, and the potential for leaching. While soil texture is often the primary factor in designing irrigation systems, understanding CEC can help growers make more informed decisions about irrigation scheduling and nutrient management. Crop selection and rooting depth also play a crucial role in extracting water and nutrients from the soil before they reach the groundwater pool. Deep-rooted crops can access water and nutrients from lower soil layers, reducing the potential for leaching (Thorup-Kristensen, 2001; Kristensen and Thorup-Kristensen, 2004). Advances in irrigation technology, such as the widespread adoption of center pivot systems and the use of soil moisture sensors, have given producers more control over water and nutrient application, allowing for more precise management based on crop needs and soil conditions.

The effectiveness of frost protection methods in the Pacific Northwest region depends on a complex interplay of crop characteristics, microclimate, and management factors. Crop-specific critical temperatures, growth stage, and leaf wettability all influence the degree of protection achieved. Regional climate differences also play a significant role. Colder and drier conditions in eastern Washington necessitate higher water application rates compared to the milder, wetter climate in western parts of the state. Moreover, the risk of frost damage varies with local topography, as cold air tends to pool in low-lying areas and create frost pockets. Proper sprinkler system design, maintenance, and operation are critical to success. Growers must also consider the trade-offs between protection effectiveness and potential issues such as waterlogging, nutrient leaching, and ice loading on plants.

As climate change alters the frequency and severity of frost events, continued research and adaptation of protection strategies will be essential to maintain the region’s agricultural resilience and profitability. Key areas for further investigation include optimizing application rates and timing for specific crops and locations, evaluating the economic trade-offs of different approaches, and developing best practices to minimize unintended consequences such as nutrient leaching and soil degradation. Ongoing outreach and education efforts will also be crucial to help growers navigate the complex landscape of frost protection options and tailor solutions to their unique contexts.

Advantages and Disadvantages of Irrigation Methods

In general, irrigation management can be beneficial for water conservation, efficient water distribution, stress alleviation in plants, and enhanced root growth. For woody crops, efficient irrigation methods are advantageous for water utilization and sustainable growth. Irrigation systems that continuously deliver water or operate on a fixed schedule are less beneficial, inefficient, and have limited options for managing water delivery in comparison to on-demand irrigation systems. Conventional irrigation systems (e.g., flood irrigation or overhead sprinklers) can contribute to inefficient water use and uneven distribution. These types of irrigation systems can also hinder root water uptake, increase irrigation costs, and reduce woody crop productivity. Table 6 provides an overview of the various advantages and disadvantages of different irrigation systems.

Table 6. Advantages and Disadvantages of Irrigation Systems

Irrigation System	Advantages	Disadvantages
Drip Irrigation Systems	• Loses practically no water to runoff, deep percolation, or evaporation. • Works well where other irrigation systems are inefficient due to excessive infiltration, water puddling, or runoff. • Increases crop yield and water and fertilizer utilization efficiencies. • Precisely meets crop demands and can be an automated system. • Reduces water contact with crop leaves, stems, and fruit. • Reduces nutrient loss from leaching. • Reduces excessive evaporation loss from soil surface. • Reduces erosion and runoff potentials. • Requires no land grading, can be used in irregular shaped fields. • Does not require landowners to “over-water” parts of a field to adequately irrigate more difficult areas.	• Is not readily feasible in perennial forage, seed, and pulse crops (grass, alfalfa, lentil, wheat) planted in full width seedbeds. • Requires more time for initial installation. • Requires higher up-front costs in both materials and labor. • Insects, rodents, and mammals can damage emitters or the drip tape. • Requires annual and ongoing maintenance and repair. • Damage can negate benefits. • Drip tape emitter holes can become clogged with soil particles, algae, or mineral precipitates. ○ Cannot be used with high iron content water since the emitters can become clogged. • Requires additional maintenance for drip tape disposal, recycling, or reuse.
Flood Irrigation	• Requires low up-front costs. • Can recycle runoff water. • Contributes to water conservation.	• One of the least efficient methods of irrigation. • Contributes to more water loss from evaporation, infiltration, and runoff.

Irrigation System	Advantages	Disadvantages
		• Involves labor intensive activities to build and takedown levees. • Requires the land to be graded to enable uniform water distribution.
Furrow Irrigation	• 2 to 3 acre-inches of irrigation water can be applied at once to recharge depleted moisture in the root zone. • Requires low up-front costs. • Can use water with moderate amounts of colloidal material. • Does not directly apply water to the plants, which reduces scalding of crop foliage.	• Is not efficient on sandy soils. • Presents challenges with applying small amounts (<1 acre-inch) of irrigation water. • The lateral spread of water across beds is inadequate for full irrigation. • Requires the land to be graded to enable uniform water distribution.
Sprinkler Irrigation	• Demonstrates efficiency on medium and course-textured soils. • Applies water at low rates (<0.1 acre-inches). • Center pivot systems can be programmed to start and stop at specified angels or time.	• Deep ruts can form on clay soils from center pivot tires. • Frequent applications may be needed to recharge soil depleted by crop. • Sprinkler nozzles can clog with poor quality water. • Scalding can occur on crop foliage. • Requires greater water usage. • Contributes to greater weed growth. • Can potentially lead to soil erosion. • Can potentially lead to surface water or groundwater contamination.
Subsurface Drip Irrigation	• Helps regulate water stress in crops. • Ensures an accessible water source for crops. • Decreases water loss through evaporation. • Less labor-intensive than other methods. • Suitable for soils with low water retention capacity. • Can double as a drainage system.	• Creates challenges with monitoring and repairing buried drip lines. • Susceptible to clogging with soil and debris, as well as chewing damage by burrowing rodents. • Higher up-front costs. • Requires fairly uniform and permeable soils. • Most effective with smooth, level topography. • Cannot use water with high salt content. • Requires adequate water supply throughout growing season.

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This was a 22-month study on the Abbotsford–Sumas aquifer to identify nitrate sources and distribution patterns. They found that nitrate contamination primarily originated from agricultural activities, with higher concentrations in shallow regions linked to local practices in Washington and deeper contamination associated with sources in Canada

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The study evaluated the impact of deficit irrigation on the yield, quality, water productivity, and economic returns of four hop cultivars in the Yakima Valley. The study found that while deficit irrigation reduced hop yield, it did not significantly affect hop cone quality, suggesting potential water savings without compromising product quality.

32) Natural Resources Conservation Service. (2002). Washington Soil Atlas. U.S. Department of Agriculture. Retrieved from https://www.nrcs.usda.gov/sites/default/files/2022-09/Washington%20Soil%20Atlas.pdf

The Natural Resources Conservation Service (2002) provides a comprehensive overview of the diverse soil types found in Washington State in the Washington Soil Atlas. This resource aids in understanding soil variability and its implications for land management and conservation practices.

33) Richter, B. D., Brown, J. D., DiBenedetto, R., Gorsky, A., Keenan, E., Madray, C., ... & Ryu, S. (2017). Opportunities for saving and reallocating agricultural water to alleviate water scarcity. Water Policy, 19(5), 886-907.

The study explores strategies for reducing water consumption in irrigated agriculture and reallocating saved water to alleviate scarcity. The study emphasizes the potential for significant water savings through improved irrigation efficiency and proper water budget accounting, which can benefit environmental restoration and other uses.

34) Osmond, D. L., Hoag, D. L., Luloff, A. E., Meals, D. W., & Neas, K. (2015). Farmers' use of nutrient management: Lessons from watershed case studies. Journal of environmental quality, 44(2), 382-390.

The study analyzed farmers' adoption of nutrient management practices through case studies across different watersheds. The study reveals that despite having nutrient management plans, farmers often do not fully implement them, highlighting the need for better education, technical support, and incentives to encourage proper nutrient management.

35) Proebsting, E. L., & Middleton, J. E. (1980). The behavior of peach and pear trees under extreme drought stress. Journal of the American Society for Horticultural Science, 105(3), 380-385.

This study examined the effects of extreme drought stress on peach and pear trees, finding that peach trees experienced severe defoliation and fruit growth arrest, often leading to death. In contrast, pear trees showed better survival rates, with regrowth occurring from trunks and lower scaffolds, especially when heavy pruning was applied.

36) Quemada, M., M. Baranski, M.N.J. Nobel-de Lange, A. Vallejo, and J.M. Cooper. 2013. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. Agric. Ecosyst. Environ. 174: 1-10.

This study involved a meta-analysis to evaluate various strategies for controlling nitrate leaching in irrigated agricultural systems and their impact on crop yield. The study found that optimizing water and fertilizer management significantly reduced nitrate leaching without compromising crop yields, highlighting the importance of tailored agricultural practices for environmental sustainability.

37) Ritter, W. F., & Shirmohammadi, A. (2001). Agricultural drainage and water quality. Agricultural nonpoint source pollution: Watershed management and hydrology, 207-231.

This article discusses the impact of agricultural drainage on water quality, highlighting the challenges of managing nonpoint source pollution from agricultural runoff. They emphasize the need for integrated watershed management practices to mitigate the adverse effects on water resources.

38) Ritter, W.F. 1989. Nitrate leaching under irrigation in the United States – a review. Journal of Environmental Science and Health, Part A 24(4): 349-378.

The study provides a comprehensive review of nitrate leaching under irrigation in the United States, highlighting the significant impact of agricultural practices on nitrate levels in groundwater. The study emphasizes the need for improved irrigation and nitrogen management strategies to mitigate environmental contamination.

39) Saha, U. K. “Cation Exchange Capacity and Base Saturation.” University of Georgia Extension, February 26, 2014.

The study explains the concepts of cation exchange capacity (CEC) and base saturation, detailing their significance in soil fertility and nutrient management. The publication provides insights into how soil pH affects CEC and offers guidelines for calculating CEC from routine soil tests.

40) Santos, F. L., Reis, J. L., Martins, O. C., Castanheira, N. L., & Serralheiro, R. P. (2003). Comparative assessment of infiltration, runoff and erosion of sprinkler irrigated soils. Biosystems Engineering, 86(3), 355-364.

The study assessed the impacts of sprinkler irrigation on infiltration, runoff, and erosion across ten soil types in Southern Portugal. Their laboratory simulations revealed that all soils exhibited low permeability, highlighting the need for tailored irrigation practices to minimize runoff and erosion.

41) Scanlon, B. R., Jolly, I., Sophocleous, M., & Zhang, L. (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water resources research, 43(3).

The study reviewed the global impacts of converting natural ecosystems to agricultural use on water resources, highlighting the trade-offs between water quantity and quality. The study found that while agricultural expansion increased water availability through reduced evapotranspiration, it also degraded water quality due to salt mobilization and fertilizer leaching.

42) Schillinger, W. F., Papendick, R. I., & McCool, D. K. (2010). Soil and water challenges for Pacific Northwest agriculture. Soil and water conservation advances in the United States, 60, 47-79.

The study discusses the significant soil and water conservation challenges faced by agriculture in the Pacific Northwest. They highlight issues such as water erosion on steep slopes, wind erosion in dryland areas, and the need for improved management practices to enhance soil health and water use efficiency.

43) Sojka, R. E. (2018). Understanding and managing irrigation-induced erosion. In Advances in soil and water conservation (pp. 21-37). Routledge.

The study discusses the critical importance of preventing irrigation-induced erosion due to its significant role in sustaining agricultural productivity. The chapter outlines various strategies for managing erosion, emphasizing the need for tailored approaches to address the unique challenges posed by irrigated agriculture.

44) Sullivan, D. M., Cogger, C. G., & Bary, A. I. (2013). Fertilizing with biosolids. Oregon State University Extension Service.

The study provided a detailed guide on the use of biosolids as fertilizer, highlighting their nutrient content and benefits for soil health. The article covers application rates, potential environmental impacts, and BMPs for integrating biosolids into agricultural systems.

45) Thorup-Kristensen, K. (2001). Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured?. Plant and Soil, 230(2), 185-195.

The study investigated the root growth of various nitrogen catch crops and their effectiveness in reducing soil nitrate-N content. The study found significant differences in rooting depth among species, with deeper-rooted crops more effectively depleting subsoil nitrate, highlighting the importance of measuring root growth in deep soil layers for accurate assessment.

46) Trout, T. J., & Neibling, W. H. (1993). Erosion and sedimentation processes on irrigated fields. Journal of irrigation and drainage engineering, 119(6), 947-963.

The study examined the mechanics of soil erosion and sedimentation on irrigated fields, focusing on detachment, transport, and deposition. The results emphasized the need for understanding these processes to inform effective management practices that reduce irrigation-induced erosion.

47) United States Department of Agriculture, National Agricultural Statistics Service (USDA NASS). (2023). 2023 State Agriculture Overview: Washington.

This report provides a detailed overview of Washington State’s agricultural landscape, including data on crop acreage, yield, production, and value. The report highlights the state’s significant contributions to national agriculture, covering a wide range of commodities from wheat and potatoes to fruits and livestock.

48) Washington State Department of Agriculture (WSDA) & Yakima County. (2018). Estimated Nitrogen Available for Transport in the Lower Yakima Valley Groundwater Management Area. AGR PUB 103-691.

The study provides a scientific baseline estimate of nitrogen available for transport from various sources in the Lower Yakima Valley. The study emphasizes the importance of understanding nitrogen dynamics to manage groundwater quality effectively.

49) Watts, D.G., and D.L. Martin. 1981. Effects of water and nitrogen management on nitrate leaching loss from sands. Trans. ASAE 24(4): 911-916.

The study used a field-calibrated computer model to estimate the impact of water and nitrogen management BMPs on nitrate leaching in sandy soils. The study found that controlling irrigation amounts and selecting appropriate nitrogen sources reduced nitrate leaching, although it was impossible to completely eliminate losses while maintaining production levels.

50) Watts, D.G., and R.J. Hanks. 1978. A soil-water-nitrogen model for irrigated corn on sandy soils. Soil Sci. Soc. Am. J. 42(3): 492-499.

Thes study describes a soil-water-nitrogen model that was developed to simulate the interactions between irrigation, nitrogen application, and crop growth in sandy soils. The model demonstrated that precise irrigation and nitrogen management could significantly reduce nitrate leaching while maintaining optimal corn yields

51) Weitzman, J.N., Brooks, J.R., Compton, J.E., Faulkner, B.R., Mayer, P.M., Peachey, R.E., Rugh, W.D., Coulombe, R.A., Hatteberg, B. and Hutchins, S.R., 2022. Deep soil nitrogen storage slows nitrate leaching through the vadose zone. Agriculture, ecosystems & environment, 332, p.107949.

The study investigated the role of deep soil nitrogen storage in reducing nitrate leaching. The study found that nitrate leaching significantly decreased with soil depth and highlighted the importance of deep soil nitrogen retention in mitigating groundwater contamination.

52) Williams, J. D., Wuest, S. B., & Long, D. S. (2014). Soil and water conservation in the Pacific Northwest through no-tillage and intensified crop rotations. Journal of Soil and Water Conservation, 69(6), 495-504.

The study evaluated the effectiveness of no-tillage and intensified crop rotations in reducing soil erosion and runoff in the Pacific Northwest. The study found that these practices significantly decreased soil erosion and runoff in comparison to conventional tillage, without compromising winter wheat yields.

Chapter 7 Appendix Part B: Implementation Considerations (Water Management: Irrigation Systems & Management)

Implementation

Washington Agriculture, Climate & Irrigation

Where agriculture occurs in Washington is largely determined by terrain, soil, climate and the availability of water for irrigation. Furthermore, the relationship between soils and climate often determines where crops can be economically produced (U.S. Department of Agriculture, Natural Resources Conservation Service, 2025; Western Regional Climate Center, n.d.).

Despite its northerly latitude, Washington's climate is relatively mild due to several controls which significantly influence the climate, namely, Washington's western border with the Pacific Ocean, a semi-permanent summer high-pressure system, and the Cascade Mountains which effectively divides the state into two primary regions (Western Regional Climate Center, n.d.). West of the Cascades, the climate is predominantly marine-influenced Mediterranean and receives abundant rainfall from fall through early spring due to its proximity to the Pacific Ocean. Summers are cool and comparatively dry. During July and August, the driest months, it is not unusual for weeks to pass with only a few showers. In contrast, Eastern Washington lies in a rain shadow caused by the Cascade Range and is much drier and has characteristics of continental and mediterranean climates depending on location. This section of the state is part of a large inland basin between the Cascade and Rocky Mountains which shields the area from the winter season's cold air masses traveling southward across Canada and forms a barrier to the easterly movement of moist and comparatively mild air in winter and cool air in summer ((Western Regional Climate Center, n.d.).

Agriculture west of the Cascades is confined to river valleys and well-drained areas in the Puget Sound lowlands which are favorable for growing berry crops, cool season vegetable crops, flower bulbs, seed potatoes and grass. Most of these crops rely on supplemental irrigation due to dry conditions during the growing season (Western Regional Climate Center, n.d.).

Most of the state's agricultural areas are in eastern Washington where agriculture is highly specialized in some localities and diversified in others, and most crops require extensive irrigation. The fruit producing areas are in irrigated valleys along the Okanogan, Columbia, Wenatchee and Yakima Rivers, while grazing is common in the Okanogan highlands, northeastern valleys and channeled scablands. Washington's Central basin, Yakima and Walla Walla valleys are major producers of many important crops including sugar beets, potatoes, alfalfa, corn, onions, beans, peppermint, spearmint, hops, grapes, and a variety of vegetable crops which rely on irrigation made available through many major irrigation projects. Wheat production is also a major commodity in Washington. While most wheat is grown under dryland, non-irrigated conditions, it is often included in crop rotations under irrigation (Western Regional Climate Center, n.d.).

In summary, Washington State is a significant producer of agricultural products and is known for its diversity and quality of crops grown for both domestic used and export production. This diversity is directly related to the unique climatic factors that influence the state's growing conditions and the availability of irrigation, which is especially important in locations where agricultural production would be limited or unfeasible without irrigation. Given that agricultural production in Washington relies extensively on irrigation, it is important to understand how irrigation can affect water quality and to identify best management practices to ensure crops receive the water needed while preventing waste and protecting surface and ground water quality.

Irrigation Practices

Conservation irrigation practices provide the necessary water supply to crops while promoting water and soil quality. There is a wide range of irrigation systems in both the way water is applied and their suitability for different crops and crop systems. With this, the environmental impact of irrigation depends on the nature of the water source, the water quality, and how water is delivered to the irrigated land. Inefficient irrigation systems can often lead to water misapplication in ways that can cause runoff, erosion, and leaching, which are the primary mechanisms for irrigation induced transport of nonpoint source pollutants (e.g., nutrients, pesticides, sediment) to surface water and groundwater. Irrigation systems should be complemented by nutrient, pesticide, tillage, and residue management to be protective of water quality. Irrigation systems should also maintain the desired growth of crops while minimizing costs, labor, water loss, and nutrient loss. Overall, conservation irrigation can help reduce on-farm energy use, soil compaction, excessive water use, and groundwater and surface water pollution.

The practices outlined in this section are primarily source control best management practices (BMPs) that are intended to prevent pollutants from coming into contact with water or are designed to capture polluted runoff. According to the National Resources Conservation Service (NRCS), consider the following when choosing an irrigation system:

- Crops you grow
- Available water supply
- Soils and slopes on the field
- How much you are willing to initially invest in the system
- How much labor is available
- How much time you can spend managing the system

Ultimately, the goal is to prevent pollution from leaving the site or entering groundwater or surface water by irrigation.

Irrigation Practices in this Section

According to guidance from NRCS, there are four types of classes for categorizing irrigation systems:

- Surface
- Subsurface
- Drip
- Sprinkler

This section provides detailed implementation considerations for the following practices given land conditions and crops found in Washington and the effectiveness of these systems in protecting water quality:

- Surface and subsurface drip irrigation
- Deficit drip irrigation
- Direct root zone irrigation
- Microirrigation

Growing Conditions and Major Land Resource Areas

Agriculture in Washington is highly diverse which reflects the significant range of soil types, terrain, climates and water resources found throughout the state. When considering irrigation practices it's important to understand how the regional setting affects growing conditions and how those conditions may also affect irrigation practices.

The United States Department of Agriculture Handbook 296[10] provides a broadscale evaluation of land areas of the United States based on patterns of geology, climate, water resources, soils, and biological resources (U.S. Department of Agriculture, Natural Resources Conservation Service, 2025), and this information is used to establish unique boundaries of major land resource areas (MLRA).

MLRAs are geographic land resource units based on similarities in natural features and environmental factors. Since these factors affect growing conditions, it's recommended that MRLA attributes are considered when selecting irrigation systems and when implementing associated best management practices.

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[10] https://www.nrcs.usda.gov/sites/default/files/2025-04/AgHandbook296_508.pdf

Water Rights

The Department of Ecology (Ecology)[11] states that "waters of the state belong to the public and can't be owned by any individual or group. Instead, a person or group may be granted a right to use a volume of water, for a defined purpose, in a specific place". In Washington, water is closely regulated and using water for agricultural purposes requires landowners to have a "Water Right" (WSU). Ecology manages water rights and water law states that "minimum in-stream flows must be maintained to protect fish, wildlife, and water quality." (WSU, 2009). Water rights are typically attached to land and automatically transferred when land is bought or sold. Water rights can be transferred to other pieces of land too. Even if water is available, irrigating additional land from the same water source may be illegal, unless approved by Ecology. Landowners do not need to apply for water rights if they are pumping water from groundwater to water stock, irrigating a half-acre or less of non-commercial lawn and/or garden, or if they are using less than 5,000 gallons per day for domestic or industrial use. Water rights are necessary when planning to divert water for any use from surface waters (WSU, 2009). Washington State University (WSU) provides additional resources[12] for landowners to understand their Water Rights.

Before applying for water rights or changing an existing water right, Ecology recommends pre-application consultation with regional staff. Water availability is directly impacted by annual rainfall and Ecology monitors water and snowpack supply as well as future weather conditions that could impact water supplies. Since water rights are complex, individuals are encouraged to connect with regional Ecology staff for support with understanding their water rights. Ecology's website also provides these additional resources for individuals to determine if a property already has a water right:

- Find a water right using the Water Rights Search[13]
- Request information on an existing water right[14]
- Landowner's Guide to Washington Water Rights[15]

Costs of Irrigation Systems

Since irrigation systems can be expensive to implement, landowners should determine that the increased yield and crop quality from using irrigation will offset the cost of installing and operating the system (NRCS, 2022). Landowners should consider costs to initially set up their

[11] https://ecology.wa.gov/water-shorelines/water-supply/water-rights
[12] https://wine.wsu.edu/extension/irrigation/
[13] https://ecology.wa.gov/regulations-permits/guidance-technical-assistance/water-rights-search
[14] https://apps.ecology.wa.gov/publications/summarypages/ecy04067.html
[15] https://appswr.ecology.wa.gov/docs/WaterRights/wrwebpdf/landownerguide-2019.pdf

irrigation system and then the longer-term costs for operating the system. Estimated costs for irrigation systems provided by NRCS include the following:

Table 7. NRCS cost estimates for irrigation systems.

Component	Estimated Cost
Well and Pump	$5,000 to $10,000 each
Hand Move System	$2,000 to $3,000 per acre
Solid Set System	$4,000 to $8,000 per acre
Traveling Gun	$1,000 to $8,000 per acre
Drip System	$2,000 to $4,000 per acre
Subsurface System	$3,000 to $6,000 per acre

Implementation Challenges

The implementation of advanced irrigation practices, while offering significant water conservation and production benefits, presents numerous challenges for Washington-based producers. These challenges span technical, economic, environmental, and operational considerations that must be carefully evaluated and managed to ensure successful system performance and longevity. Understanding and addressing these challenges is critical for producers who are considering adoption or upgrade of irrigation systems.

Technical and Design Challenges

Achieving uniform water distribution across varying soil and topographic conditions requires precise engineering considerations and sophisticated system design. **Surface drip systems** face particular challenges with water loss through surface evaporation and inefficient root access, often resulting in root biomass concentrating within the top 18 inches of soil profile, which can expose crops to increased stress during extreme heat or cold (Jacoby & Ma, 2018b). The exposed nature of these systems leads to greater maintenance requirements and significant irrigation inefficiencies due to indirect root access (Yang et al., 2022).

Subsurface drip irrigation presents additional complexities that affect both installation and operation. Small wetting patterns in coarse soils can create limited crop root zones, particularly affecting woody perennial crops. Enhanced water infiltration may reduce root development, hampering crops' ability to avoid diurnal water stresses even in well-watered conditions (Lamm & Camp, 2007; Ma et al., 2019b). The buried nature of these systems introduces unique challenges including soil ingestion risks at system shutdown, zone size limitations from hydraulics, and dripline compression from soil overburden. These issues become particularly critical since design errors are difficult to resolve once the system is buried (Lamm & Camp, 2007).

Water Quality and System Maintenance

Irrigation systems, particularly micro-irrigation, are highly vulnerable to various operational issues that require constant attention. The complexity of these systems means that water quality management often requires more sophisticated approaches than surface systems (Ayars et al., 2023). Physical and mechanical issues include:

- Clogging from particles and debris requiring multi-stage filtration systems.
- Compression damage from soil weight and field operations.
- Mechanical damage during cultivation or harvest activities.
- Progressive system deterioration affecting pipes, fittings, and emitters.
- Damage from rodents and insects to buried components.

Water quality concerns present significant operational challenges for irrigation systems ranging from biological contaminants to mineral content that can compromise the system's efficiency:

- Biological growth in lines and emitters are problematic with surface water sources containing organic material.
- Chemical precipitates from high mineral content are particularly challenging with hard water from deep wells.
- Iron bacteria buildup can accelerate clogging in high iron content regions.
- There are ongoing, complex chemical treatment needs including pH adjustment and biocide applications.
- There may be risk of biological plugging requiring regular chlorination treatments.

Environmental and Regional Considerations

The Pacific Northwest's climate and geography present unique challenges that require specific adaptations. Washington's diverse growing regions face distinct challenges based on local conditions as described below.

Climate patterns create unique seasonal management requirements that affect both system operation and maintenance throughout the year. These include complete system drainage before winter to prevent freeze damage, careful spring startup procedures to avoid frost impacts, and management of temperature fluctuations between day and night affecting system pressure. Systems must also be protected against strong winds and increased filter cleaning is required due to wind-blown dust. Adaptation to unexpected rain events during typically dry summers adds another layer of complexity to management activities.

Soil and topographic conditions significantly impact irrigation system design, installation, and operation. Sandy soils in the Columbia Basin require different irrigation scheduling than clay soils, while variable soil depths, particularly in areas with underlying basalt, affect water distribution patterns. Areas with steep slopes need specialized pressure regulation and system design. These challenges with topographic conditions can be further complicated by the need to manage irrigation across multiple soil types within single fields, requiring sophisticated zone control and monitoring systems.

Economic and Implementation Barriers

The financial requirements for implementing advanced irrigation systems present significant challenges, particularly for small and medium-sized operations (Yang et al., 2022). Initial system costs can be substantial, with additional expenses for specialized equipment and labor for installation and maintenance. Common financial requirements and barriers include:

- High initial capital investment for system components and installation.
- Substantial costs for infrastructure redesign when converting existing systems.
- Ongoing maintenance and operational expenses.
- Limited access to credit and financing options.
- Need for specialized technical expertise in system design and operation.
- Grower unfamiliarity with new technologies like direct root zone irrigation (Jacoby & Ma, 2018b).

State and Federal Resources, Programs, and Guidelines

Washington State, known for its diverse agricultural landscapes and valuable crop production, faces challenges related to water scarcity, drought, and the need for sustainable irrigation practices. Over the past five decades, advances in irrigation technology have reduced water usage by approximately 25% while simultaneously increasing crop yields (Castillo, 2024). As the population grows and production pressures mount, irrigation will play an increasingly critical role in meeting food and fiber demands. Experts predict that irrigation technology will become a central component of many more farms in the coming years, with center pivots rivaling the importance of tractors in terms of their impact on productivity and return on investment (Castillo, 2024).

To address these challenges and support farmers in implementing sustainable water conservation measures, federal and state agencies have developed a range of programs and guidelines that promote efficient irrigation techniques. These initiatives aim to enhance agricultural productivity, improve drought resilience, and minimize environmental impacts.

NRCS Practices and Programs

NRCS Environmental Quality Incentives Program (EQIP) WaterSMART Initiative

The EQIP WaterSMART Initiative (WSI) is a collaborative effort between the Natural Resources Conservation Service (NRCS) and the Bureau of Reclamation to address water conservation and drought resilience in priority areas. The Initiative leverages EQIP funding to provide farmers with the resources and tools needed to improve irrigation efficiency and protect water sources from depletion. In the Fiscal Year 2024, NRCS allocated $29.7 million in EQIP funding through the WSI, targeting 9 new priority areas and 36 previously approved areas across 16 states, including Washington.

Through the WSI, NRCS works with eligible EQIP applicants to implement a range of water conservation practices and technologies, tailored to the specific needs and challenges of each priority area. These practices may include:

- Irrigation system improvements, such as converting to more efficient sprinkler or drip systems
- Soil moisture monitoring and irrigation scheduling technologies
- Drought-tolerant crop varieties and cover crops
- Water-conserving crop rotations and tillage practices
- Irrigation water management planning and technical assistance

NRCS provides financial assistance to cover a portion of the costs associated with implementing these practices, as well as technical support to ensure their effective adoption and management.

Conservation Stewardship Program (CSP)

The Conservation Stewardship Program (CSP) is designed to encourage farmers to maintain and enhance existing conservation practices, including measures to improve irrigation efficiency. The program provides financial and technical assistance to farmers who implement a variety of conservation practices tailored to their specific needs and goals. In the Pacific Northwest, CSP has been particularly effective in supporting practices that promote water conservation and improved irrigation management. These practices include:

- Soil moisture monitoring: By using sensors and other tools to track soil moisture levels, farmers can make informed decisions about when and how much to irrigate, reducing water waste and improving crop yields.
- Irrigation scheduling: Farmers can optimize irrigation efficiency by carefully planning and scheduling irrigation events based on factors such as crop type, growth stage, weather conditions, and soil characteristics.
- Cover cropping: Planting cover crops between main crop rotations can help conserve water by reducing evaporation, improving soil structure, and increasing organic matter content, which enhances the soil's water-holding capacity.

By participating in CSP and implementing these practices, farmers can enjoy a wide range of benefits that extend beyond water conservation. These benefits include:

- Enhanced resilience to weather and market volatility: By improving soil health and water-use efficiency, farmers can better withstand the impacts of drought, extreme weather events, and fluctuations in commodity prices.
- Decreased need for agricultural inputs: Improved soil health and more efficient irrigation can reduce the need for costly inputs such as fertilizers, pesticides, and water, leading to lower production costs and increased profitability.
- Improved wildlife habitat conditions: Many conservation practices supported by CSP, such as cover cropping and buffer strips, can create more diverse and hospitable habitats for wildlife, promoting biodiversity and ecosystem health.

Agricultural Management Assistance (AMA)

The Agricultural Management Assistance (AMA) program is designed to help farmers in states with historically low participation in the Federal Crop Insurance Program. The program provides financial and technical assistance to farmers for implementing conservation practices and managing risk through diversification, marketing, and natural resource management. As part of the AMA program, NRCS works closely with producers to develop a customized AMA plan of operations that addresses their specific needs and goals. This plan may include a variety of strategies and practices, such as:

- Constructing or improving water management or irrigation structures to enhance water use efficiency and reduce water loss.
- Planting trees as windbreakers or to improve water quality by reducing soil erosion and nutrient runoff.
- Mitigating risk through production diversification, which involves expanding the range of crops grown or livestock raised to reduce dependence on a single product.
- Implementing resource conservation practices, such as soil erosion control measures, integrated pest management techniques, or transitioning to organic farming methods.

Regional Conservation Partnership Program (RCPP)

The Regional Conservation Partnership Program (RCPP), a collaborative initiative led by the NRCS, provides funding to address natural resource challenges on agricultural lands through a variety of strategies and activities. These include land management practices, land improvements, restoration efforts, land rentals, entity-held easements, U.S.-held easements, and public works/watershed projects.

In 2024, the RCPP is prioritizing funding for projects that promote climate-smart agriculture, urban agriculture, conservation, and environmental justice factors as part of the Justice40 Initiative. This initiative is a government-wide effort to ensure that 40% of the overall benefits from certain federal investments in climate, clean energy, and other areas are directed to disadvantaged communities that have been historically marginalized by underinvestment and disproportionately burdened by pollution. By focusing on these priorities, the RCPP aims to support projects that not only address critical natural resource challenges but also promote social equity and environmental justice. This approach aligns with the America the Beautiful initiative, a decade-long, locally led, and nationally scaled conservation effort that seeks to engage farmers, ranchers, and private landowners in voluntary conservation activities.

By combining the expertise and resources of federal agencies, state and local governments, conservation organizations, and private landowners, the RCPP and the America the Beautiful initiative aim to create a more resilient, equitable, and sustainable future for agricultural landscapes and the communities that depend on them.

Conservation Innovation Grants (CIG)

Conservation Innovation Grants (CIG) provide funding to stimulate the development and adoption of innovative conservation approaches and technologies, including those related to irrigation efficiency and water conservation. A prime example of CIG's impact is the grant awarded to Viva Farms in 2023, a non-profit organization in Washington's Skagit Valley, for their project titled "From Farmers to Soil Health Managers."

The grant supports participatory on-farm trials and training sessions to help underserved, small-scale farmers adopt innovative conservation techniques and become better managers of their farms' natural resources. By focusing on soil health practices such as cover crops, intercropping, and no-till farming, the project aims to improve the productivity and sustainability of agricultural operations in the region. Viva Farms works with local agricultural service providers to offer outreach and training for underserved producers, with all materials translated into Spanish and interpreters available at each session. Farmers learn to measure key soil properties and health indicators, developing individual trials on plots of land to test the techniques. As these small-scale and non-traditional farmers gain knowledge from the USDA grant-funded trials, they may be encouraged to increase these practices as their operations grow, leading to a greater impact on soil health and nutrient-dense produce over time.

Wetland Reserve Program (WRP)

The Wetland Reserve Program (WRP) is a voluntary conservation program that provides landowners with a unique opportunity to protect, restore, and enhance wetlands on their property. By participating in the program, landowners can contribute to the improvement of water quality and quantity while also supporting irrigation efficiency through reduced runoff and increased groundwater recharge. The program offers a range of benefits to participants, including:

- Financial and technical assistance: Landowners who enroll in the WRP receive financial support and expert guidance in exchange for their commitment to restoring, protecting, and enhancing the functions and values of wetlands on their property. This assistance can help offset the costs associated with wetland conservation and restoration activities.
- Reduced challenges associated with farming difficult areas: Wetlands can often pose challenges for agricultural production due to their unique hydrological and ecological

characteristics. By enrolling these areas in the WRP, landowners can alleviate the problems associated with farming these potentially difficult sites, allowing them to focus their efforts on more suitable agricultural lands.

- Incentives for developing wildlife recreational opportunities: The WRP encourages landowners to create and enhance wildlife habitat on their wetland properties. This not only benefits local biodiversity but also provides landowners with the opportunity to develop wildlife-related recreational activities, such as birdwatching, hunting, or ecotourism. These activities can potentially generate additional income streams and diversify the economic benefits derived from the land.

This collaborative approach to wetland conservation ultimately contributes to the long-term sustainability of agricultural landscapes and the health of our nation's water resources.

Washington State Conservation Commission Programs

Irrigation Efficiencies Grant Program (IECP)

The Irrigation Efficiencies Grants Program (IEGP) is a flagship initiative administered by the Washington State Conservation Commission (SCC) in partnership with local conservation districts. The program's primary objective is to promote water savings by working directly with agricultural irrigators and water purveyors to install efficient irrigation systems and adopt best management practices. By providing financial incentives and technical assistance, the program works to restore instream flows, reduce demand on aquifers, mitigate drought vulnerability, enhance water quality, retime water availability, and increase farm productivity.

The IEGP operates through a grant-based system, where funds are allocated to conservation districts across the state. These districts employ technicians who work closely with irrigators and water purveyors to assess, design, develop, and administer water-saving projects. The technicians provide comprehensive support throughout the process, including:

- Conducting site assessments to identify water-saving opportunities.
- Assisting with project design and development.
- Providing guidance on selecting appropriate irrigation technologies.
- Developing irrigation water management plans for project recipients.
- Ensuring the effective implementation and management of new practices.
- Monitoring and reporting on project outcomes.

Maintenance and Operation

Implementing irrigation strategies requires careful management and monitoring to avoid negative impacts on crop health and productivity. Achieving proper stress levels at critical growth stages is particularly challenging due to weather variability and complex crop water use dynamics (Fereres & Soriano, 2007). Deficit irrigation can increase risks of yield loss, reduced fruit quality, and disorders like sunburn if not properly managed (Hansen, 2017). There is also a wide range of technical challenges related to managing irrigation systems:

- Difficulty with accurately predicting soil moisture contribution.
- Developing reliable estimates for crop coefficients and understanding the complex impacts of water stress on crop development.
- System operation requires sophisticated decision support tools to optimize performance (English, 2015), along with continuous monitoring of both system function and crop response to irrigation treatments.
- Regular maintenance and system adjustments are necessary to maintain optimal operation, requiring significant time investment and technical expertise to ensure proper water delivery and distribution throughout the growing season.

Despite these challenges, Washington growers can successfully implement efficient irrigation systems with proactive planning and adaptive management. Conducting site assessments, consulting with experts, investing in system maintenance and monitoring, and participating in conservation initiatives can help address these challenges and barriers. By combining these strategies with a commitment to stewardship, farmers can harness the benefits of efficient irrigation to improve both productivity and sustainability.

Implementation Considerations

This section outlines the practical implementation of water-efficient irrigation methods, including technical specifications, cost considerations, equipment requirements, and maintenance guidelines. BMPs covered in this section include:

- **Surface and subsurface drip systems** that deliver water through buried or surface-level tubes, providing consistent moisture while minimizing evaporation losses.
- **Deficit irrigation** strategies that deliberately apply less water than optimal to achieve water savings while maintaining acceptable crop yields.
- **Direct root zone (DRZ) irrigation** techniques that precisely target water delivery to plant root systems, ensuring maximum nutrient uptake efficiency.
- **Traditional drip irrigation** using a network of tubes and emitters to deliver water slowly and directly to the soil surface.
    - **Micro-irrigation** methods that combine low-pressure sprayers, misters, and specialized emitters for precise water application.

Surface and Subsurface Drip Irrigation

This section focuses on two primary irrigation technologies that offer precise water management capabilities: surface drip irrigation and subsurface drip irrigation. These systems represent significant advancements in agricultural water management, particularly valuable in addressing water scarcity and climate variability challenges.

Surface Drip Irrigation

Surface drip irrigation is a precise water delivery system utilizing an intricate network of plastic tubing—comprising mainlines, submains, manifolds, headers, and lateral lines—to deliver controlled amounts of water and nutrients to the soil surface near plant roots through strategically placed emission devices. Each emitter provides carefully controlled, uniform distribution of water and dissolved solutions directly to the plant's root zone (Zaccaria & Bali, 2024).

Use Cases

Effective for both perennial and annual row crops, particularly valuable in regions with water constraints and challenging topography. Well-suited for operations requiring precise water and nutrient management across diverse growing conditions. Regional implementation has driven numerous innovations, including specialized winterization protocols, wind-resistant emitter spacing configurations, and advanced filtration systems tailored to specific water quality parameters. System designs have evolved to accommodate diverse growing conditions, through features such as dual-line configurations for tree fruit operations and precision pressure regulation systems for sloped terrain.

Benefits

- The system achieves significant water conservation, demonstrating water savings of 20-40% compared to conventional irrigation methods (Ayars et al., 2023). Crop quality and health improvements include enhanced fruit quality and lower disease incidence due to precise water delivery.
- The automated operation reduces labor requirements, while integrated fertigation capabilities enable precise nutrient delivery.
- The uniform distribution of water and dissolved solutions allows growers to optimize plant growth and maximize yields, supporting superior production quality across diverse cropping systems.

Subsurface Drip Irrigation

Subsurface drip irrigation is an advanced irrigation system delivering water with precision through a network of underground pressurized lines and emitters, providing water directly to the root zone through buried lines or tapes. This subsurface delivery method bypasses traditional surface irrigation challenges, while ensuring uniform and efficient water distribution when properly maintained. Success depends on proper system design and maintenance, with particular emphasis on filtration and water quality management. Research demonstrates that successful implementation requires careful calibration of installation depth, emitter spacing, and flow rates based on soil characteristics and crop requirements (Ayars et al., 2015).

Use Cases

Subsurface drip systems are implemented through two distinct approaches:

- **Shallow burial systems:** Temporary installations with drip lines placed just centimeters below the soil surface, protecting tubing from wind damage while maintaining irrigation efficiency. Ideal for annual crops such as vegetables, melons, and strawberries.
- **Deep burial systems:** Permanent installations at depths of 10 centimeters (4") or greater, designed for multi-year crops including corn, caneberry, vineyards, orchards, tomatoes, and alfalfa.

In Washington state, these systems have been successfully adapted to local conditions with specialized innovations including optimized installation depths to prevent freeze damage, enhanced filtration systems for local water quality conditions, and modified spacing configurations tailored to local soil characteristics (Peters, 2011).

Benefits

- Subsurface drip irrigation systems offer comprehensive benefits for agricultural operations through their unique below-ground delivery approach. By providing water directly to the root zone, these systems eliminate common water losses associated with surface irrigation, including evaporation, soil crusting, and runoff.
- The technology maintains dry soil surfaces while ensuring consistent root zone moisture, which serves multiple purposes - reducing weed pressure and improving field access for operations.
- Through integrated fertigation capabilities, the system enables precise nutrient application exactly where crops need it. This precision leads to significant improvements in water use efficiency while reducing operational costs.
- The technology has proven particularly valuable in water-scarce regions, delivering benefits for both water conservation and crop productivity. Through its precise water delivery mechanism, the system consistently supports improvements in crop productivity.

Both surface and subsurface drip irrigation systems can be enhanced through the integration of fertigation capabilities, enabling precise nutrient delivery and improved resource efficiency across diverse cropping systems. The following sections provide detailed implementation considerations for these irrigation technologies, including technical requirements, costs, maintenance needs, and other key factors for successful adoption.

Table 8. Implementation Considerations for Surface and Subsurface Drip Irrigation systems

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
Lifespan	The lifespan of a drip irrigation system depends on the quality of the components, maintenance, water quality, and environmental conditions. Drip lines can last approximately 1-3 seasons. Components such as emitters, filters, mainlines and fittings can last between 5-15 years depending on maintenance, water conditions and UV exposure.
Land Area Requirements	**Soil Considerations and Site Selection** • Successful implementation of subsurface drip irrigation requires careful evaluation of soil conditions. • Proper ground cover must be maintained over the dripfield to ensure adequate soil aeration and prevent erosion. However, certain soil conditions preclude the use of subsurface drip irrigation, including variable or shallow soils over rock, coarse sands, non-bridging soils, and heavy clay soils prone to cracking. • The effectiveness of the system heavily depends on lateral water movement characteristics, requiring careful consideration of soil layering and textural transitions throughout the installation zone. **Topographical and Location Requirements** • Subsurface drip systems can be installed in areas approved for pressure distribution, with slope restrictions of less than 30% for systems serving developments with daily design flows exceeding 1,000 GPD. Installation becomes more complex on undulating terrain, requiring careful evaluation of several factors: • Landscape position and drainage patterns • Existing vegetation and impermeable surface coverage • Property boundaries, structural elements, and utility locations • Proximity to surface water bodies and wells. • The installation area must be protected from development activities and potential damage sources to ensure long-term system integrity. **Crop Suitability and Performance** • The system is particularly well-suited for row crops, tree crops, vineyards, and high-value vegetables. However, implementation can be challenging for certain crops, including peanuts in arid regions, root crops such as potato and onion, and crops requiring precise spacing. When properly implemented, these systems can satisfy 80-85% of crop

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
	irrigation needs compared to sprinkler systems, offering superior water use efficiency over surface irrigation methods (Lamm, 2009).

Associated Costs	**Surface Drip Irrigation System Costs**
	• Installation costs include initial drip line placement and removal costs averaging $80.00/acre; system design and layout expenses; and site preparation and grading if needed.
	• The annual operational costs include system repair and maintenance costs averaging $15.00/acre annually; and labor and water charges accounting for approximately $90.00/acre.
	• The primary variable costs for operating subsurface drip irrigation systems include the following:
	  ○ **Scenario:** Based on a 2011-2012 study at Washington State University's Irrigated Agriculture Research and Extension Center near Prosser examining surface drip irrigation costs for native spearmint production (Nakawuka et al., 2014):
	    ▪ Full irrigation may require $92.00/acre
	    ▪ Reduced irrigation at 54% level costs $49.68/acre
	    ▪ Cost savings increase proportionally with irrigation reduction up to 60% deficit
	• Subsurface drip irrigation systems must operate within specific parameters to maintain cost-effectiveness and optimal performance:
	  ○ The recommended maximum deficit irrigation threshold is 60% of full irrigation capacity. When operations excel this 60% deficit threshold, growers face increased costs from reduced plant populations and subsequent yield losses.
	  ○ The system demands regular maintenance to preserve its efficiency and prevent performance degradation. Additionally, various system components need replacement at scheduled intervals to maintain optimal performance levels, representing an ongoing cost consideration throughout the system's operational life.
	  ○ These limitations directly influence both short-term operational expenses and long-term capital investment planning for agricultural operations implementing subsurface drip irrigation.

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
	Subsurface Drip Irrigation System Costs • **Initial Investment Considerations** ○ Installing a subsurface drip irrigation system requires significant upfront capital, typically exceeding costs of traditional surface irrigation methods. Once installed, these systems offer minimal to no resale value, making the initial investment a critical consideration in long-term financial planning (Lamm, 2002). ○ Installation costs can vary considerably based on several site-specific factors, including field dimensions and layout, existing soil conditions and topographical features, specific design requirements for the intended crops, and local availability of qualified labor and specialized equipment. • **Operational Expenses** ○ From an operational standpoint, subsurface drip systems generally offer lower energy costs compared to sprinkler irrigation alternatives. ○ These systems require consistent maintenance to maintain optimal performance. ▪ This includes routine system inspections and repairs, regular filter maintenance and replacement, chemical treatments to prevent root intrusion, and ongoing component replacement due to normal wear and tear. • **Financial Planning Considerations** ○ The permanent nature of subsurface drip systems often leads to higher equity or collateral requirements from lending institutions. ○ The relatively shorter design life of these systems, compared to some alternative irrigation methods, necessitates increased annual depreciation costs in financial planning. ○ Agricultural operations must also establish and maintain both a system replacement fund and an emergency repair fund to address unexpected issues promptly. • **Long-term Maintenance Considerations** ○ Maintaining a subsurface drip system involves several ongoing chemical treatment costs associated with:

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
	○ Root intrusion prevention protocols ○ Mineral deposit control measures ○ Management of biological growth within the system • The system requires more frequent component replacement compared to surface irrigation systems, and demands regular monitoring and maintenance labor.
Technical Requirements	**Subsurface Drip Irrigation** • Material and Structural Specifications • System components must meet rigorous specifications to ensure reliable operation. Transport piping, including supply and return manifolds, must be constructed of Schedule 40 PVC or stronger materials. The system requires: ○ High-quality compression and barb fittings ○ Pressure-regulated emitters ○ Corrosion-resistant filtration systems ○ Strategically placed air/vacuum relief valves ○ Chemical injection capabilities. • All materials must carry warranties for sewage applications and demonstrate resistance to common operational challenges such as solid accumulation, bacterial growth, and root intrusion. • Dripline specifications must be carefully selected based on application requirements (Lamm. 2009): ○ Wall thickness ranging from 254-653 µm ○ Installation depth typically between 12-20 inches for commodity crops ○ Line spacing from 0.8-16 feet, depending on crop type ○ Diameters up to 1.375 inches available ○ Emitter spacing varying from 4-30 inches.

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
	• A complete subsurface drip system must include comprehensive filtration systems; air-vacuum relief valves at elevation highpoints; pressure regulation equipment; flow monitoring devices; end-of-zone flush lines; and chemical injection systems. **Permitting and Regulatory Compliance** • Installation requires adherence to specific regulatory requirements. Only proprietary system products registered with the department and listed in current Registered On-Site Treatment and Distribution Products may receive local health jurisdiction permits, as specified in Chapter 246-272A WAC. The system requires both installation and operational permits, and construction permits must include provisions for a reserve area meeting minimum pretreatment requirements.
Operational and Maintenance Requirements	**Surface Drip Irrigation Specifications** • Installation and Operational Guidelines ○ According to the Natural Resources Conservation Service (NRCS) Conservation Practice Standard Code 441 for Irrigation System, Micro irrigation, Surface drip systems require specific installation considerations for optimal performance. ○ Lateral lines should be installed parallel to plant rows, with an additional 2% length allowance for thermal expansion and contraction. ○ Above ground lines require proper anchoring or pinning to prevent movement. In some applications, laterals may be shallow buried 2-4 inches below the soil surface, particularly when used in conjunction with mulch or plastic row covers. **Subsurface Drip Irrigation Specifications** • System Operation Requirements ○ Successful operation of subsurface drip irrigation systems depends on precise installation and management parameters. Lateral lines must be positioned no more than 24 inches from crop rows in annual cropping systems ○ Tubing depth and spacing specifications must align with specific soil characteristics and crop requirements. The system must maintain consistent water distribution while preserving unsaturated subsurface flow conditions.

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
	○ Operating pressures need to exceed soil pressure to prevent emitter clogging, with typical flow rates ranging from 0.16 to 1.1 gallons per hour per emitter. Emitter discharge rates must be carefully matched to soil infiltration characteristics (Lamm, 2009). The system requires precise irrigation scheduling with particular attention needed during crop germination periods. **Monitoring Protocols** • Effective system management requires vigilant monitoring practices. This includes regular assessment of system pressure flows, routine inspections for leaks and physical damage, comprehensive record-keeping of system performance metrics, and ongoing monitoring for potential root intrusion issues. These monitoring activities help ensure early detection of potential problems and maintain optimal system efficiency. **Maintenance Requirements** • Regular maintenance is crucial for system longevity and includes: • Systematic flushing of system components • Regular cleaning and maintenance of filtration systems • Implementation of chemical treatments to prevent root intrusion • Active rodent control measures • Management of timed dosing systems. **Cold Weather Operations** • Cold climate management requires specific attention to prevent system damage. The system must maintain continuous service through winter months, with manifolds designed to enable gravity drainage. All components must either be insulated or installed below the frost line. Installation requirements include: • Manual or automatic drain valves in flush/return manifolds • Insulation for headworks, filtration systems, valves, zone dosing equipment, and air vacuum relief valves • Implementation of frequent dosing schedules to maintain adequate soil moisture levels.

Category	Implementation Considerations for Surface and Subsurface Drip Irrigation
Resources	• Refer to the Recommended Standard and Guidance (RS&G) established by the Washington State Department of Health for implementation standards and resources for subsurface drip irrigation systems.

Deficit Drip Irrigation

Deficit drip irrigation is a management strategy where irrigation is deliberately reduced during specific crop growth stages while maintaining economically viable yields, requiring precise timing and monitoring of water stress during appropriate phenological stages (English & Raja, 1996).

Use Cases

Particularly effective in wine grape production and tree fruit operations, especially valuable for regions with limited water availability or junior water rights. Suitable for operations with comprehensive monitoring capabilities and ability to manage precise irrigation scheduling.

Benefits

- Deficit irrigation strategies offer multiple advantages for agricultural operations focused on water conservation and crop quality. The approach achieves substantial water savings of 20-35% compared to conventional irrigation methods while supporting quality improvements in specialty crops like wine grapes and tree fruits.
- This strategic reduction in water use enables growers to maintain production even under water resource constraints, providing valuable adaptation options for regions with limited water availability.
- The practice demonstrates that economic viability can be maintained while significantly reducing water use, offering a practical solution for growers facing water availability challenges.

The success of deficit irrigation systems depends heavily on accurate monitoring of soil moisture and plant stress indicators to avoid yield-limiting water deficits (Yorgey et al., 2018). Farmers have developed crop-specific protocols that integrate multiple monitoring systems, combining soil moisture, plant stress, and weather data to optimize irrigation timing. These sophisticated approaches include established thresholds for major regional crops, becoming increasingly important as growers face growing pressure on water resources while maintaining productive agricultural operations (Evans, 2001). This helps producers implement deficit irrigation strategies effectively across diverse cropping systems, ensuring water stress occurs at appropriate growth stages while maintaining crop quality and yield targets.

Table 9. Implementation Considerations for Deficit Drip Irrigation systems

Category	Implementation Considerations for Deficit Drip Irrigation
Lifespan	N/A
Land Area Requirements	**Soil Conditions** Successful implementation of deficit drip irrigation demands specific soil conditions to ensure optimal system performance. The soil profile must maintain a minimum depth of 4 ft to support adequate root development. • Loamy fine sand soil textures provide optimal performance for these systems (Yang et al., 2022), while soils with high water holding capacity are ideal for deficit irrigation practices (Champaneri et al.,2024). • Critical soil considerations include: ○ Thorough evaluation of soil moisture content distribution patterns ○ Assessment of water holding capacity ○ Analysis of soil texture and structure ○ Evaluation of root zone characteristics ○ Understanding of drainage properties. • Soil conditions that should be avoided include coarse sands requiring heavier walled compression resistant driplines; non-bridging soils that may compromise system performance; and those with inadequate drainage characteristics (Lamm & Camp, 2007). **Topography and Layout Requirements** • Field layout planning must carefully consider multiple site-specific factors. The system is not recommended for undulating topography due to pressure regulation challenges and potential distribution uniformity issues. Successful implementation requires evaluation of (English & Hillyer, 2015): ○ Water source position and accessibility ○ Plant location and spacing requirements ○ Existing geological conditions ○ Building locations and infrastructure placement

Category	Implementation Considerations for Deficit Drip Irrigation
	○ Distribution system capabilities relative to field configuration.

Associated Costs	• Implementation of deficit drip irrigation systems involves careful consideration of both fixed and variable costs, along with potential economic benefits. The economic viability of these systems depends heavily on energy costs, water availability, and operational requirements.
	• System planning must account for immediate capital investments while balancing long-term operational expenses against potential yield impacts and water conservation benefits.
	• The initial system installation requires substantial capital investment in several key areas (Capra et al., 2008):
	  ○ Precision irrigation equipment and components
	  ○ System installation labor and expertise
	  ○ Field preparation and modification
	  ○ Monitoring and control systems
	  ○ Basic harvesting infrastructure
	  ○ Fixed tillage and planting equipment.
	• The system's ongoing expenses can be categorized into several variable cost components that require regular financial planning:
	  ○ Energy and Resource Expenses include water acquisition costs, pumping system operation, peak demand considerations, system pressure maintenance, and operating schedule optimization (English & Hillyer, 2015).
	  ○ Labor and Maintenance costs encompass regular system monitoring, routine maintenance, equipment calibration, field operations management, and harvest operations which are yield dependent.
	  ○ Operational costs can also fluctuate based on several production factors such as chemical inputs for system maintenance, field operation requirements, yield dependent harvesting expenses, seasonal labor needs, and equipment maintenance and repair (Capra et al., 2008).
	• Despite significant investment requirements, deficit drip irrigation system offer several financial advantages:
	  ○ Enhanced water use efficiency reducing overall water costs
	  ○ Improved economic returns under water limited conditions

Category	Implementation Considerations for Deficit Drip Irrigation
	○ Potential expansion of irrigated acreage through water savings ○ Optimization of input resource utilization ○ Reduced long-term labor requirements.
Technical Requirements	**System Planning Parameters** • Operational design must adhere to specific technical parameters that ensure system efficiency. For example, the maximum irrigation deficit cannot exceed 70% ETc (crop evapotranspiration) (Yang et al., 2022). The system requires: ○ Regular assessment of soil moisture levels and water balances (Champaneri et al., 2024) ○ Integration with weather data and ET measurements (English & Hillyer, 2015) ○ Evaluation of crop growth stages (Champaneri et al., 2024) ○ Analysis of water stress sensitivity ○ Implementation of precise water application control (Champaneri et al., 2024. **Material Specifications** • The system must incorporate specific materials meeting stringent performance criteria such as Polyethene pipes with 16mm diameter; in-line labyrinth design drippers; flow rates maintained at 2-4 L/h; operating pressure of 101.2 kPa; and a minimum 90% Emission Uniformity coefficient (Capra et al., 2008). • Proper system operation requires comprehensive monitoring capabilities through calibrated soil moisture sensors; weather monitoring stations; gravimetric water analysis equipment; and other water application control systems (Capra et al., 2008). **Structural Components** • Essential infrastructure elements include main and submain pipeline networks; control valves and pressure regulators; filtration system; backflow prevention devices; system monitoring and control equipment; and water efficiency measurement tools.

Category	Implementation Considerations for Deficit Drip Irrigation
Operational and Maintenance Requirements	• The successful operation and maintenance of deficit drip irrigation systems require careful attention to multiple system components and parameters. These systems must operate based on crop evapotranspiration (ETc) calculations, with total irrigation not exceeding 70% ETc. For non-sheltered planting, rainfall amount must be factored into irrigation calculations, though there is no specific consensus on irrigation amounts for different growth periods. **System Organization and Rotation Management** • Efficient operation requires strategic organization of the irrigation system. The area must be divided into small management units, with each unit organized into multiple irrigation groups. This organization facilitates easy operational control, reduced transmission pipeline flow, stable pump conditions, efficient flow supply within design specifications. **Water Application Management** • Water application requires precise forward scheduling with specific dates and times. System operators must consider several critical factors: o Key Management Parameters include irrigation adequacy across the field; management allowed depletion (MAD); targeted root zone soil moisture levels; application efficiency goals; and critical growth stage timing (English & Hillyer, 2015). o Distribution requirements include uniform water distribution; proper hole spacing aligned with plant spacing; and consistent hole diameter maintenance (English & Hillyer, 2015). **System Monitoring and Performance Assessment** • Monitoring protocols to ensure optimal system performance include the following considerations (Capra et al., 2008): o System performance metrics include maintenance of 101.2 kPa system pressure; emission uniformity exceeding 90%; regular calibration and error detection; and continuous flow rate verification.

Category	Implementation Considerations for Deficit Drip Irrigation
	o Field monitoring requirements include regular soil moisture assessment; water use tracking; crop stress evaluation; and environmental condition monitoring through integration of multiple data sources such as soil moisture measurements, neutron probe readings, and stem water potential measurements. **Water Use Efficiency and Performance Evaluation** • Application efficiency seeks to ensure enhanced performance with sub-ET water application; minimized deep percolation losses; and improved soil moisture utilization (Capra et al., 2008). • System performance considerations include distribution uniformity requirements, pressure variation tolerances, and evaluation of system response time (Capra et al., 2008). **Management Planning and Risk Assessment** • Water allocation planning considers seasonal water use forecasting; growth stage water availability balance; identification of stress sensitive periods; and understanding of crop-water relationships. • Risk management protocols encompass system uniformity monitoring; clogging prevention; equipment failure detection; crop stress assessments; strategic timing of water application; split fertilizer application; crop selection based on water availability; and quality impact evaluations. **Maintenance Requirements** • Regular maintenance is essential for sustained system performance and incorporates performance verification checks; application uniformity monitoring; flow rate calibration; efficiency assessment; sensor calibration; filter cleaning; and system flushing.
Resources	• Washington State University Extension offers research-based guidance on deficit irrigation strategies for regional crops, particularly addressing water stress management; crop-specific irrigation scheduling; soil moisture monitoring protocols; and system design specifications

Category	Implementation Considerations for Deficit Drip Irrigation
	• Irrigation Scheduler Mobile Tool[16] helps track soil water content; calculate water application rates; monitor crop water stress; provide irrigation scheduling guidance; and is compatible with regional weather networks (Yorgey et al., 2018). • Enterprise budgets for irrigation system analysis is available through Washington State University, University of Idaho, and Oregon State University, • Financial assistance programs through NRCS Conservation Stewardship Program provide cost-share opportunities for system implementation; supports irrigation efficiency improvements; and offers technical assistance for system design.

[16] https://treefruit.wsu.edu/article/irrigation-scheduling-tool-available-online-and-as-a-new-phone-ap/#:~:text=Irrigation%20Scheduling%20Tool%20Available%20Online%20and%20as%20a,Adjust%20your%20irrigation%20sets%20over%20the%20season.%20

Direct Root Zone (DRZ) Irrigation

Direct root zone irrigation is a specialized irrigation system that delivers water directly to specific soil depths through vertical tubes installed in the root zone, utilizing PVC pipes placed at depths ranging from 30-90 cm with pressure compensating emitters controlling water delivery (Jacoby & Ma, 2018a).

Use Cases

Currently most prevalent in viticulture, with ongoing research exploring applications in other perennial crops. Particularly valuable in areas with limited water availability or challenging soil conditions, showing specific success in areas with deep sandy soils and varying topographical conditions (Ma et al., 2019a). Regional implementation has driven the development of specialized protocols and adaptations. Washington researchers and growers have established specific installation procedures for various soil types common in vineyards, created monitoring systems tailored to regional conditions, and developed precise irrigation scheduling protocols based on local climate patterns. These innovations have been validated through extensive trials across multiple vineyard sites with varying soil types and topographical conditions (Ma et al., 2019b).

Benefits

- The system demonstrates substantial improvements in water use efficiency, achieving 30-45% water savings compared to conventional irrigation methods.
- Key benefits include enhanced root distribution throughout the soil profile and improved nutrient uptake efficiency.
- The technology's precision in water placement enables management at multiple soil depths simultaneously, offering superior control over water distribution patterns and root development (Jacoby & Ma, 2018a).

While DRZ irrigation shows significant promise, implementation requires careful consideration of certain factors. These include higher initial installation costs, the need for precise installation procedures, and currently limited long-term durability data (Jacoby & Ma, 2018a). Despite these challenges, the technology continues to evolve with ongoing research exploring applications beyond viticulture to other perennial crop systems.

Table 10. Implementation Considerations for DRZ Irrigation Systems

Category	Implementation Considerations for Direct Root Zone Irrigation
Lifespan	The lifespan of a direct root zone irrigation system depends on the quality of the components, maintenance, water quality, and environmental conditions. Components can last between 7-25 years depending on maintenance, water condition, pressure and root intrusion.
Land Area Requirements	• DRZ irrigation systems require specific site conditions and technical specifications to ensure optimal performance. The system design and implementation requirements are based on research conducted in established vineyards under semi-arid conditions, demonstrating successful adaptation to various environmental and topographical settings. **Site Selection and Soil Requirements** • Successful implementation of direct root zone irrigation systems has been demonstrated primarily in loam fine sand soils (Jacoby & Ma, 2018b). • The system performs optimally in areas with low annual rainfall, approximately 200-224 mm (Ma et al., 2019b). • Research indicates specific soil composition requirements at 0-40 cm depth, comprising 80% sand, 17% silt, 3% clay, with total carbon of 0.56% and total nitrogen of 0.056% (Ma et al., 2019a). • The system has proven adaptable to both flat and sloped vineyard conditions and can be integrated with existing trellis systems in established vineyards.
Associated Costs	The primary costs associated with direct root zone irrigation are material, installation and operating cost. Common materials include emitters, drip tubing/PVC piping, delivery tubing, filters and pressure regulators. Emitters range for $2-$10 each and tube ranges from 0.25 - $1.50 per foot. Filters and pressure regulators vary by size and manufacturer and range from $20-$100 or more. Labor cost will vary by the size and complexity of the system.
Technical Requirements	**Environmental Considerations and System Performance** • System efficiency and operation can be affected by various environmental factors as documented by Ma et al. (2019). These include cloud cover variations, smoke from regional wildfires, diurnal temperature fluctuations, spring rainfall patterns, and winter temperature extremes.

Category	Implementation Considerations for Direct Root Zone Irrigation

	System Components and Technical Specifications
	• The primary irrigation system consists of vertical PVC delivery tubes (Schedule 40) with 20mm inner diameter and 25.4mm bore holes. These tubes are pre-cut to specified lengths and split approximately 15cm from the lower end to facilitate water distribution (Jacoby & Ma, 2018a).
	• Essential system components consist of:
	  ○ Water delivery infrastructure such as a 0.25-inch diameter water supply lines; 6.35 mm diameter feeder lines; pressure compensating drip emitters (CETA, Antelco); and flow rate capacity of 2L/hour per compensating emitter.
	  ○ Control and monitoring equipment comprise battery powered controllers for automated operation; mechanical water meters for flow measurement; suspended irrigation lines; and support and trellis integration systems.
	Installation Requirements
	• Installation specifications have been developed through field testing and implementation (Jacoby & Ma, 2018a). The system requires vertical bore holes of 35.4mm diameter at depths ranging from 30-90cm.
	• Tubes must be placed approximately 40cm on either side of the vine trunk, with specific vertical spacing requirements including 60cm between drip line and soil surface, and 40cm between drip line and bottom trellis wire. The system delivers 4L/hour total per vine through two delivery tubes.

Operational and Maintenance Requirements	• Direct root zone irrigation (DRZ) systems integrate with existing irrigation infrastructure while offering unique operational advantages. The system operates through a pipeline network that can be integrated with existing sprinkler systems, featuring dual surface drip lines per row - one dedicated to surface fertigation and another as part of the DRZ system. **Irrigation Scheduling and Management** • Irrigation timing aligns with commercial crop practices, with operations typically beginning before bud break. The system offers flexible irrigation options based on specific requirements. • For example, in a study investigating DRZ system on grape quality and water efficiency (Jacoby & Ma, 2018b), the system provides flexibility in irrigation rates and delivery depths without requiring installation or removal of buried drip

Category	Implementation Considerations for Direct Root Zone Irrigation
	lines, allowing adjustments based on grape quality, climate conditions, and soil types across growth stages of grapevines: ○ Water Application Protocols: ▪ Full irrigation (24 hours at 4L h^{-1} $vine^{-1}$) implemented: ▪ At bud break ▪ Two rounds post-harvest for soil moisture replenishment ▪ During winter/early spring for frost damage prevention ▪ Deficit irrigation applied from fruit set until harvest (Jacoby & Ma, 2018b) ▪ Irrigation intervals of 3-6 days, adjusted for weather conditions (Ma et al., 2019b) ▪ 20-hour irrigation sets typically delivered during nighttime periods ○ Soil Moisture Thresholds: Irrigation is triggered when water content falls below (Ma et al., 2019b): ▪ 4 ± 1mm at 20cm depth ▪ 11 ± 1mm at 40cm depth ▪ 12 ± 1mm at 60cm depth **Monitoring Requirements** • The system requires comprehensive monitoring protocols: ○ Equipment and Parameters: ▪ EnviroSCAN Probes (Sentek technologies, Australia) for soil moisture monitoring ▪ Electronic capacitance sensors for soil moisture tracking (Jacoby & Ma, 2018a) ▪ Regular stem water potential measurements (Ma et al., 2019b) ▪ Integration capability with remote sensing systems (Ma et al., 2019b) ▪ Monitoring of vine response and fruit development ▪ Root development tracking

Category	Implementation Considerations for Direct Root Zone Irrigation
	▪ Quality parameters (brix, acidity, etc.). ▪ Automated weather station data tracks temperature patterns, rainfall events, and evapotranspiration calculations (Ma et al., 2019a). **Maintenance Protocols** • Regular maintenance tasks include monitoring water delivery rates, maintaining battery powered controllers, checking mechanical meters, installing protective caps to prevent airborne debris from fouling emitter, seasonal removal of water meters before winter and reinstallation in spring, proper meter positioning (face up) for optimal accuracy, monitoring of soil moisture content, and considerations of seasonal variations and weather patterns (Jacoby & Ma, 2018b). • The DRZ system offers easier access for maintenance compared to other buried drip systems due to reduced susceptibility to clogging and rodent damage.
Resources	Consult your local land grant university extension office or the Natural Resource Conservation Service for information about direct root zone irrigation systems. Agricultural trade organization may also provide information for specific crops.

Micro-irrigation

According to the NRCS Washington Irrigation Guide (2022), micro-irrigation involves the "frequent, low volume, low pressure application of water on or beneath the soil surface by drippers, drip emitters, spaghetti tub, subsurface or surface drip tube, basin bubblers, and spray or mini sprinkler systems". The NRCS Field Office Technical Guide (FOTG) indicates that micro-irrigation is used to support the following:

- Efficiently and uniformly apply irrigation water and maintain soil moisture for plant growth.
- Prevent contamination of ground and surface water by efficiently and uniformly applying chemicals or nutrients.
- Establish vegetation (e.g., windbreaks and buffers).
- Improve poor plant productivity and health.

Drip Irrigation

Drip irrigation delivers water to crops at a slower rate, without wetting plants. Water is pumped in pipes or carried to a field in tanks. Water in a drip irrigation system is then supplied through small diameter pipelines and applied to the root zone through low pressure, low volume devices (e.g., drip emitters, drip tape, micro spray, and bubblers) (NRCS, 2022). Drip irrigation provides farmers with the ability to precisely water crops wherever and whenever necessary. Drip irrigation can achieve greater precision with the implementation of flow meters and soil moisture sensors (U.S. Department of Agriculture, n.d.). The system may use valves to separate fields in zones. This allows for a limited water source to provide water to a large area by watering one part at a time (U.S. Department of Agriculture, 2023).

Mobile Drip Irrigation

Mobile drip irrigation (MDI) drags drip tubing with in-line emitters behind a center pivot. Landowners should consider MDI if they have an inadequate water supply for unstressed crop production and field runoff problems that make it difficult to use low elevation spray application or low energy precision application (WSU Extension, 2022). MDI combines the high efficiency of surface drip irrigation with the flexibility and convenience of center pivot irrigation. Engineers can provide technical support by conducting topographic surveys and designing site-specific irrigation systems.

Benefits

According to guidance from Snohomish County, drip irrigation provides several advantages over sprinklers or hand watering. Drip irrigation (1) delivers water close to the plant roots, where they need it; (2) reduces water loss from evaporation and overspray; and (3) is healthy for plants because it keeps foliage dry, which reduces fungal diseases (Snohomish County Public Works, n.d.). Oregon State University described that well designed drip irrigation systems lose minimal water to runoff, deep percolation, or evaporation. Additionally, since the crop root zone is only irrigated, nitrogen in the soil is less likely to leach during the growing season.

In most cases, MDI can decrease plant disease pressure, minimize salt damage to the foliage, or both (WSU Extension, 2022). In previous studies, MDI resulted in energy savings of up to 70%. MDI uses much less water and needs lower pressure than sprinklers to operate, which contributes to significant energy savings. Since MDI emitters deliver water directly to the soil surface, wind drift and evaporation losses are minimal. MDI can help eliminate overwatering under the inside spans of center pivots, which can save up to 10% of total water distributed to the system (WSU Extension, 2022).

Oregon State University also noted the following advantages of drip irrigation:

- Systems can be adapted to oddly shaped fields or fields with uneven topography and/or soil texture.
- Drip irrigation is helpful when water is scarce or costly. Landowners may not need to "over-water" parts of their field to adequality irrigate more difficult areas.
- Drip irrigation allows for precise application of nutrients and can consequently reduce fertilizer costs and nitrate losses.
- Improved yield and quality of crops under drip irrigation have been observed in onion, broccoli, cauliflower, lettuce, melon, tomato, and cotton.

Table 11. Implementation Considerations for Drip Irrigation

Category	Implementation Considerations for Drip Irrigation
Lifespan	The lifespan of a drip irrigation system depends on the quality of the components, maintenance, water quality, and environmental conditions. Drip lines can last approximately 1-3 seasons. Components such as emitters, filters, mainlines and fittings can last between 5-15 years depending on maintenance, water conditions and UV exposure.

Land Area Requirements	• Microirrigation applies on sites where soils and topography are suitable for irrigation and there is enough quality water for irrigation.
	  ○ Test and assess water supply and quality for irrigation. Test the water for physical, chemical, and biological contaminants that are commonly found in the area that could cause clogging in the microirrigation system's emitters. Water testing results should inform whether or not irrigation is suitable to the land and any water quality treatment requirements.
	  ○ These systems can be used on steeply sloping fields by using pressure compensating emitters or by placing lines across the slope (NRCS, 2022).
	  ○ Field shape and slope often dictate the most economical lateral direction. Laying laterals downslope can allow for longer lateral run lengths and lateral size reduction. However, the designer must ensure pressure stays in an acceptable range. Uneven topography may require the use of pressure-compensating emitters (NRCS, 2020).
	• Keep your layout simple and map it if it will be buried under mulch (Snohomish County Public Works, n.d.).
	• Irrigation zones are impacted by topography, field length, soil texture, optimal tape run length, and filter capacity.
	  ○ If you are installing drip irrigation on a slope, follow the contours of the slope.
	  ○ The design of the drip irrigation system should account for the effect of the land's contour on pressure and flow requirements.
	  ○ For larger areas, use more than one zone. Otherwise, there will not be enough pressure (and no drip) at the end of the line.
	• If drip irrigation is installed **before** plants are in, then use parallel lines that are appropriately spaced to provide enough water while allowing for growth in the plant root zone.

Category	Implementation Considerations for Drip Irrigation
	• Drip irrigation should be installed after plants are in. If drip irrigation is installed **after** plants are in, then try to encircle the root zones of trees and shrubs to allow for increase in size. There is no need to encircle perennials, they are fine with a line on one or both sides.

Associated Costs	• Drip irrigation is a low-cost option in comparison to other irrigation systems.
	    ○ Smaller systems that are operated by manual labor and gravity flow can be less expensive.
	• Irrigation systems will generally cost time and money to operate and manage.
	• Costs of irrigation systems can vary based on water availability and size of the system.
	    ○ Drip irrigation systems are costly and typically cost $2,000 to $4,000 per acre per acre (NRCS, 2022). This cost estimate includes a capital investment for several years and annual costs.
	    ○ Accessing water may be costly if a farm needs to construct a well or pond.
	• Drip tape can contribute to additional cleanup costs after harvest since growers need to plan for drip tape disposal, recycling, or reuse.
	• The Washington State Conservation Commission (WSCC) Irrigation Efficiencies Grant Program (IEGP)[17] is a water savings program that works with conservation districts to provide financial support to landowners who install efficient irrigation systems.

Technical Requirements	**Design Considerations**
	• High-level considerations
	    ○ Growers who are new to drip irrigation may want to begin with a simple system on a small acreage.
	    ○ Consider power and water source limitations since water quality may create challenges and increase irrigation system costs.
	• The following design considerations are provided by NRCS (NRCS, 2020):

[17] https://www.scc.wa.gov/programs/irrigation-efficiencies-grant-program-iegp

Category	Implementation Considerations for Drip Irrigation
	○ Design the system with capacity to provide supplemental water at a rate that will ensure establishment and survival of planned vegetation. ○ Design the system to uniformly apply water and chemicals without excessive water loss, erosion, reduction in water quality, or salt accumulation. ○ There should be sufficient system capacity to meet water application requirements during critical crop growth periods. ○ Include an allowance for reasonable water losses (e.g., evaporation, runoff, deep percolation, and system deterioration over time) and auxiliary water needs. ○ Size and position each appurtenance in accordance with sound engineering principles and site-specific requirements. • Operating pressure guidance provided by NRCS (NRCS, 2020[18]): ○ Select the design operating pressure that is in accordance with the manufacturer's recommendations. ○ Account for pressure losses and gains and field elevation. ○ Design lines to supply water to all manifold and lateral lines at a flow rate and pressure not less than the minimum design requirements of each subunit. ○ Do not exceed manufacturer recommendations for maximum pressure in any lateral or manifold during any phase of the operation. • Weed control ○ Growers may need to redesign their weed control system since drip irrigation might be unsatisfactory if herbicides need sprinkler irrigation for activation (Oregon State University, n.d.). ▪ Drip irrigation can enhance weed control in arid climates by keeping the soil surface dry. ▪ The tape depth should be compatible with cultivation and weeding operations.

[18] https://www.nrcs.usda.gov/sites/default/files/2022-09/Irrigation_System_Microirrigation_441_NHCP_CPS_2020.pdf

Category	Implementation Considerations for Drip Irrigation
	• Tubing depth and spacing for drip irrigation depend on soil and crop conditions. ○ Consider burying the lines at least 6 inches deep so settling and soil loss do not expose the lines and so lines don't freeze. Avoid burying them deeper because you may not be able to tell whether or not they are working. ○ The emitter line depth should be selected based on the auxiliary irrigation methods used for leaching, germination, and initial development. ○ The maximum later line distance from the crop row is 24 inches for annual row crops (NRCS, 2020). ○ Use a pressure reducer at the water source or the lines may come apart at junctions. • WSU Extension provided the following considerations for implementing an MDI system (see here[19] for detailed information): ○ Installing an MDI system onto the center pivot can be done by most landowners after a short training. ○ The required spacing between the driplines depends on soil and crop types. Sandier soils and shallow-rooted crops need closer dripline spacing to avoid water stress in between driplines. • According to OSU guidance, to determine drip irrigation application rates, use measurements of soil water and crop water use (Oregon State University, n.d.). ○ For shallow rooted crops, irrigate to only replace the soil moisture deficit in the top 12 inches of soil. **Materials** • Include both injectors for chemigation and flow meters to confirm the irrigation system's performance. • Drip irrigation uses the following materials (Snohomish Public Works, n.d.): Flexible plastic tubing with tiny holes (emitters), that can be placed around individual plants or spaced regularly to soak entire beds. Drip tape, which offers a simple and inexpensive way to water closely planted beds and rows.

[19] https://pubs.extension.wsu.edu/mobile-drip-irrigation-mdi

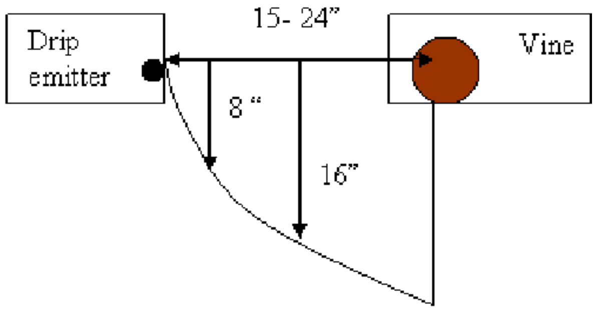
Category	Implementation Considerations for Drip Irrigation

	Micro-sprays, which are low-volume spray heads that water closely planted groundcovers and plants that prefer moist foliage.
	• Other materials that may be needed for drip irrigation include:
	  ○ Backflow preventer, which keeps dirty water or fertilizers from entering drinking water.
	  ○ Filter, which prevents clogging from within your plumbing system.
	  ○ Provide a filtration system at the system inlet.
	  ○ Size the filtration system to prevent the passage of solids in sizes or quantities that might obstruct emitter openings.
	  ○ Design the filtration system to remove solids based on the emitter manufacturer's recommendations.
	  ○ Pressure regulator, since drip irrigation is designed to operate within a certain range of pressure.
	  ○ Timer, to manage watering intervals. Snohomish County Public Works[20] provides detailed guidance on determining how often and how much to water with a drip irrigation system.
	• Design and install air and vacuum relief valves to prevent introduction of soil particles into the irrigation system. additionally, use pressure regulators where topography and the type of applicator dictate their use.
	• Install appropriate fittings above ground at the end of mains, submains, and lateral flush manifolds to facilitate flushing.
	• Anchor the lines with stakes. They can be purchased with the drip line.
	• Buy "splicing" supplies for breakers, female connectors are easier to install.
	• Use a deep layer of mulch in planting beds to help retain moisture, slow weed growth, and prevent erosion.
	  ○ Mulch on sloped areas along with terracing and plantings can prevent runoff and erosion.
	  ○ Materials for organic mulch include: shredded bark, wood chips, pine needles, straw, pecan hulls, cotton seed hull, composted leaves, and shredded cedar.

[20] https://snohomishcountywa.gov/DocumentCenter/View/7261/Smart-Watering?bidId=

Category	Implementation Considerations for Drip Irrigation
	○ The depth of mulch needed depends on mulch type. If the mulch is coarser, then the deeper it should be applied. A 3–4-inch layer of bark mulch should be sufficient. ○ Cover over soaker and drip systems with 2 inches or more of mulch (leaves, woodchips, or straw) to prevent evaporation and spread water flow (Snohomish County Public Works, n.d.). ○ Mulch will need to be reapplied as it decomposes. • Drip emitters are best suited for vineyards, micro sprays for orchards, and dip tape for vegetables (NRCS, 2022). ○ Size mains, submains, and laterals to maintain subunit emission uniformity. Emitter uniformity for microirrigation systems equipped for chemigation must be at least 85 percent. • If you are using soil moisture monitors to inform irrigation scheduling, WSU Extension[21] provided the following considerations: ○ Place the device between 8-16’’ from the drip line in a triangular pattern between the vine and an emitter (see the diagram below). ○ Do not place the soil moisture monitor directly under the drip line. ○ Monitor on both sides of the vine.

[21] https://s3-us-west-2.amazonaws.com/sites.cahnrs.wsu.edu/wp-content/uploads/sites/66/2010/07/2012-Monitoring-Drip-Irrigation.pdf

Category	Implementation Considerations for Drip Irrigation
	 **Figure 2. Diagram of recommended placement of soil moisture monitors for drip-irrigated vineyards. Place sensors 8–16 inches from the drip line in a triangular pattern between the vine and emitter, avoiding direct placement under the drip line and ensuring monitoring on both sides of the vine.**
Operation and Maintenance	• Develop an irrigation management plan that meets the requirements of the NRCS CPS Irrigation Water Management (Code 449). • According to NRCS guidance, the operation and maintenance plan should include the following: ○ Inspecting the flow meter at least monthly. ○ Monitoring water application. ○ Cleaning or back flushing filters as needed. ○ Flushing lateral lines at least annually. ○ Visually inspecting crop performance and emission device flows if visible. ○ Replacing applicators as necessary. ○ Measuring pressure on installed gauges. ○ Checking pressure gauges to ensure proper operation. And repairing or replacing damaged gauges. ○ Following maintenance and water treatment to prevent clogging. ○ Injecting chemicals to prevent precipitate buildup and algae growth.

Category	Implementation Considerations for Drip Irrigation
	▪ Consider adding chlorine or other chemicals to the drip line periodically to kill bacteria and algae. Acid may be needed to dissolve calcium carbonates. ○ Checking chemical or nutrient injection equipment regularly. ○ Checking and assuring proper operation of backflow protection devices. ○ Removing water from the pipeline by gravity or other means when there are (1) freezing temperatures; (2) pipe manufacturer requires draining; or (3) draining the pipeline is otherwise needed. • Filters should be changed as needed and drip trap should be regularly flushed. • Drip irrigation systems also have to be blown out in the fall. (University of Washington, n.d.). MDI does not get leaves wet and instead directly applies water to the soil. • Stagger the watering schedule (a short watering period followed by a long one) and remember that the water has to be left on for a long time (i.e., 1-2 hours for a long session). • Mulch will need to be reapplied as it decomposes. • Filters in the irrigation system need to be regularly cleaned. A method for flushing the lines should be included at the lower end of the irrigation system (NRCS, 2022). ○ Drip tape or tubing must be managed to prevent leaking or plugging. Drip emitters can be plugged by (1) silt or other particles not filtered from the irrigation water; (2) algae growing in the tape; or (3) chemical deposits at the emitter. ○ Emitters and drip tape have small discharge openings that can be easily clogged; therefore, a filter is always required in drip irrigation systems. If a well is used for the water supply, then a fine mesh screen filter is sufficient. ○ If the well produces a large amount of sand, then consider using a centrifugal sand separator. ○ If the water supply comes from a pond or stream, then use a sand filter to remove sediment, algae, and other impurities that can clog emitters. ○ Lastly, drip systems that use surface water may have algae and bacteria growth in the lines which could clog emitters over time. Landowners can manage clogging by periodically injecting chlorine into the system. Additionally, injections of a mild acid solution could be used if there is build-up of mineral deposits. • Root intrusion may need to be controlled for some crops. Rodents should also be controlled wherever drip tape is buried.

Category	Implementation Considerations for Drip Irrigation

Resources	**Resources for further information on irrigation practices**
	• OSU Listing of Manufacturers and Specifications of Drip Irrigation Systems[22]
	• University of Washington - Drip Irrigation[23]
	• NRCS - Selecting an Irrigation System[24]
	• WSU Drip Irrigation[25]
	Washington-specific training, workshops, or educational opportunities
	• WSU Master Gardener Demonstration Gardens at:
	  ○ McCollum Park, WSU Office, 600 128th St SE, Everett
	  ○ Jennings Park, 6915 Armar Rd, Marysville
	  ○ Evergreen Arboretum & Gardens, 145 Alverson Blvd, Everett
	• Woodinville Water District's Waterwise Garden, 17238 NE Woodinville-Duvall Rd, Woodinville
	• Waterwise Garden at Bellevue Botanical Garden, 12001 Main St, Bellevue (www.bellevuebotanical.org[26])

[22] https://agsci.oregonstate.edu/mes/irrigation/introduction-drip-irrigation
[23] https://depts.washington.edu/hortlib/pal/drip_irrigation/
[24] https://www.nrcs.usda.gov/sites/default/files/2022-09/stelprdb1167474-selecting-irrigation-system.pdf
[25] https://foodsystems.wsu.edu/crops/irrigation/
[26] https://bellevuebotanical.org/

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