Chapter 8
Actionable Science for Irrigation

Hui Fang

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H. Fang (✉)
Fairfax County Public School, Fairfax, VA, USA

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1 Introduction

Irrigation, which involves the controlled application of water to plants for agricultural purposes, delivers water to the soil to infiltrate and percolate through the soil profile (Bos and Nugteren 1990). The physical properties of the soil, such as texture, structure, and hydraulic conductivity, will determine the movement patterns of water (Rawls et al. 1998). As water moves through the soil, plant roots absorb it through a process called transpiration which is driven by the difference in water potential between the soil and the plant, creating a water uptake pathway that sustains crop growth (Hopmans and Bristow 2002). Irrigation water can also carry dissolved nutrients, such as nitrogen, phosphorus, and potassium, which are essential for plant growth (Haynes 1985). As water infiltrates the soil, it dissolves nutrients present in the soil matrix and makes them available for plant uptake to ensure that crops have access to the necessary nutrients for their growth and development (Clothier and Green 1994). By providing water to the root zone, irrigation replenishes the soil moisture lost through evaporation and transpiration, and adequate soil moisture is essential for sufficient nutrient uptake, enzymatic processes, and overall plant health (Gan et al. 2013). It also helps regulate soil moisture, preventing water stress and promoting optimal crop performance. In certain regions, the irrigation water may contain dissolved salts and with repeated irrigation, these salts can accumulate in the soil, leading to soil salinization (Rengasamy 2006). Proper irrigation management involves applying water in quantities that exceed the plant's evapotranspiration rate, allowing excess water to leach the accumulated salts below the root zone. This process, known as leaching, helps prevent salt buildup and maintains a favorable soil environment for crop growth (Tukey Jr 1970).

Irrigation has been in practice for thousands of years, and it enables farmers to grow crops in areas that would otherwise be unsuitable for agriculture, increasing crop yields and helping to meet the growing demand for food (Tilman et al. 2002). According to the Food and Agriculture Organization (FAO), irrigation accounts for approximately 70% of global freshwater withdrawals every year (Siebert et al. 2010). With climate change affecting rainfall patterns and freshwater availability, efficient and effective irrigation practices are a high priority for ensuring global food security (Misra 2014). Science is the key to improve irrigation practices, from selecting appropriate crops, to designing efficient irrigation systems, to optimizing water usage. With the help of advanced technologies and data analysis, actionable science can provide farmers with valuable insights into soil moisture levels, crop water requirements, and other critical parameters, enabling them to make more informed decisions and manage their resources more sustainably (Evans and Sadler 2008). The increasing global population results in a growing demand for food, and irrigation is a critical factor in meeting this demand (Mancosu et al. 2015). However, improper irrigation practices can lead to water wastage, soil degradation, and decreased crop yield, resulting in significant economic losses for farmers and food shortages for the population (Pimentel et al. 1995). Science can help address these challenges by providing innovative solutions and strategies to optimize irrigation practices, for example, precision agriculture (Dobermann et al. 2004).

In this chapter, we will explore the various ways actionable science can improve irrigation practices, including case studies and examples of successful implementation. We will also discuss the challenges and limitations of actually applying these techniques in the fields and explore future research directions. This chapter also provides an overview of the current state of the art in actionable science for irrigation and point out the promising directions for further research and innovation to realize sustainable agriculture and protect global food security.

2 Current Irrigation Practice

2.1 Types of Irrigation Systems

Flood Irrigation

In flood irrigation, water is applied to the fields by flooding the entire surface of the soil (Mitchell and Van Genuchten 1993). Water is delivered to the fields via canals, ditches, or pipes and is allowed to flow across the fields, covering the soil surface and infiltrating into the soil. This method is typically used for crops such as rice (Westcott and Vines 1986) that require large amounts of water. However, it can be less efficient than other methods of irrigation and can result in soil erosion, as the water may cause soil to be washed away or deposited in other areas of the field (Patel et al. 2010).

For example, Fresno County in San Joaquin Valley, California, occasionally adopts flood irrigation in its history to fight with the semi-arid climate with hot and dry summers and mild winters (Alexander et al. 1990; Griffith et al. 2016; Schmidt and Sherman 1987). The primary water source for flood irrigation in this region is the Central Valley Project (Becker et al. 1976; De Roos 2000), which collects water from the Sierra Nevada mountains and stores it in reservoirs like the San Luis Reservoir (Carle 2015). Then, the water is delivered to Fresno County through a network of canals and distribution systems managed by the Fresno Irrigation District (FID) (Hopkins and Stretch 2009). Before flooding, the fields are prepared by leveling the land and constructing borders or bunds around the field perimeter to contain the water (Bachand et al. 2014). The borders help prevent water from flowing outside the intended area. The FID also coordinates with farmers to schedule water releases based on their water rights and the crop water requirements (Stretch and Mowry 2010). When it is time to irrigate, water is allowed to flow into the field by opening gates or using other irrigation structures. The water spreads across the field, covering it evenly and saturating the soil. In common practice, the level of flooding is carefully monitored to avoid over-irrigation and minimize water loss due to deep percolation (Bouman 2007). After the flooding, a soaking period is provided to allow the water to infiltrate the soil and reach the root zone of the crops (Bouman and Tuong 2001). This period can vary depending on factors such as soil type, crop water requirements, and evaporation rates. Once the desired soaking period is completed, excess water is drained or allowed to percolate back into the groundwater table. Drainage channels or outlets are strategically placed to remove excess water from the fields and prevent waterlogging (Robinson and Rycroft 1999). If everything goes well, the flooded fields will provide a favorable environment for crop growth, as the water helps nourish the plants and replenish the soil moisture (Shaxson and Barber 2003).

Sprinkler Irrigation

Sprinkler irrigation (Pair 1969) distributes water over the field in the form of a spray or sprinkler, simulating rainfall. It uses sprinkler heads that are connected to a network of pipes and valves and rotate them or have a fixed position and release water in a controlled manner, distributing it over the crops (Lyle and Bordovsky 1983).

Let us take a look at Maricopa County, Arizona, which is known for its arid climate and extensive agricultural activities. Due to the desert climate with hot summers and mild winters, the primary water sources for sprinkler irrigation in Maricopa County include surface water from the Central Arizona Project (CAP) canal system (Hanemann 2002), which delivers water from the Colorado River, and groundwater extracted from aquifers through wells. Before installing the sprinkler system, farmers usually prepare the fields by clearing debris, leveling the land, and installing necessary infrastructure such as pumps, filters, and irrigation lines. Sprinkler heads are strategically placed throughout the field, considering factors like crop spacing and water distribution uniformity requirements (Hargreaves and Merkley 1998). It operates based on a predetermined schedule and can be controlled manually or automated using timers and sensors. It can be adjusted to deliver the required amount of water based on crop type, growth stage, and environmental conditions. When the sprinkler system is activated, pressurized water is distributed through the sprinkler heads and the water is sprayed into the air in a controlled pattern and falls onto the crop canopy, providing irrigation (Zazueta et al. 1994). Also, the sprinkler system is designed to deliver water at a specific application rate, typically measured in inches per hour. This rate is determined based on factors such as soil infiltration rate, evapotranspiration rates, and crop water requirements (Amosson et al. 2002). Farmers in Maricopa County follow irrigation scheduling techniques based on factors like crop type, soil moisture monitoring, weather conditions, and plant growth stage (Eakin et al. 2016) to provide adequate water to the crops while avoiding over-irrigation and water wastage. Besides, regular maintenance of the sprinkler system is required to ensure its proper functioning, which includes checking for leaks, clogs, and damaged components, as well as adjusting the system to account for changes in crop needs and environmental conditions (Mutchek and Williams 2014).

Sprinkler irrigation allows for efficient and uniform water distribution, reducing water loss due to evaporation and minimizing runoff. It is suitable for a variety of crops, including grains, vegetables, and fruits. The flexibility of sprinkler heads allows farmers to adjust the irrigation patterns based on the crop's water requirements and growth stage. However, it is worth noting that sprinkler irrigation requires careful system design and maintenance (Louie and Selker 2000). Factors such as wind conditions, nozzle selection, and water pressure need to be considered to ensure optimal water distribution and minimize water waste.

Drip Irrigation

Drip irrigation directly delivers water to the plant's root zone in a slow, steady, and precise manner via a network of tubes or pipes with emitters or drippers that release water drop by drop at or near the plant's base (Camp 1998). Drip irrigation is highly efficient because it delivers water directly to the plants, minimizing evaporation and reducing water loss through runoff. It allows for precise control of water application, ensuring that each plant receives the right amount of water. Drip irrigation is commonly used for various crops, including tomatoes, fruits, vegetables, and even in landscaping applications. It is especially beneficial in arid regions with limited water availability. While drip irrigation requires careful planning and maintenance to avoid clogging of emitters and ensure proper water distribution, it is known for its water efficiency and ability to conserve resources. It also helps reduce weed growth and minimize soil erosion compared to other irrigation methods.

For example, Yolo County, California, uses drip irrigation (Johnstone et al. 2005; Mehta et al. 2013) and diverted waters from the close-by rivers into canals, which are managed by irrigation districts such as the Yolo County Flood Control and Water Conservation District (http://www.ycfcwcd.org). Farmers work with irrigation experts to design the drip irrigation system based on factors such as crop water requirements, soil characteristics, and field layout (Shock 2006). The design includes the selection and placement of drip lines, emitters, filters, and pressure regulators. Before installing the drip irrigation system, farmers prepare the fields by clearing vegetation, leveling the land, and ensuring proper soil drainage. Filtration systems are also installed in advance to prevent clogging of the drip emitters (Capra and Scicolone 2004). Then, drip lines are laid out along the rows or beds where the crops are planted. The drip lines consist of flexible tubes with evenly spaced emitters or drippers that deliver water directly to the root zone of the plants. Also, pressure regulators and filters are installed to ensure uniform water distribution and prevent damage to the emitters. The system is configured with control valves and tubing connectors to create zones that allow for precise control of water delivery.

When the drip irrigation system is activated, water flows from the water source through the main supply line and into the drip lines. Emitters release water slowly and directly to the base of each plant, delivering water at a controlled rate. Farmers can determine the appropriate irrigation schedule based on factors such as crop water requirements, weather conditions, and soil moisture monitoring (Thompson et al. 2007). This helps ensure that plants receive adequate water while avoiding over-irrigation. On the other hand, regular maintenance is necessary to keep the drip irrigation system functioning optimally. Farmers have to monitor the system for leaks, clogs, or damaged emitters, and replace or clean them as needed. They also monitor soil moisture levels to fine-tune irrigation schedules. Some drip irrigation systems also incorporate fertigation to allow the simultaneous application of water and fertilizers (Singandhupe et al. 2003).

Deficit Irrigation

Deficit irrigation reduces the amount of water applied to crops below the full crop water requirement (Fereres and Soriano 2007). Deficit irrigation involves intentionally applying less water than the crop's full water requirement. This approach introduces a certain level of risk, as water stress can potentially impact crop yield and quality for the return of more efficient water use. For example, in California's wine grape production, deficit irrigation is often employed during certain growth stages, such as berry development, to optimize grape quality and concentrate flavors (Permanhani et al. 2016). By carefully managing water inputs, growers can influence vine growth and grape composition, achieving desired characteristics in the final wine product. Scientific research and field trials have provided insights into the appropriate timing and extent of deficit irrigation for different grape varieties, helping wineries produce high-quality wines with less water.

However, there are several challenges associated with implementing it in the real world. Different crops have varying sensitivity to water stress during different growth stages. Determining the optimal timing and extent of deficit irrigation requires a deep understanding of the crop's water requirements, growth patterns, and response to water stress. It can be challenging to accurately assess the crop's tolerance to water deficit and ensure that yield and quality are not compromised. Also, implementing deficit irrigation practices requires precise water management decisions. Determining the appropriate deficit level, irrigation timing, and duration requires accurate monitoring of soil moisture, weather conditions, and crop development stages. Meantime, deficit irrigation practices need to be adapted to the specific agro-climatic conditions, soil types, and crop varieties of each region. Factors such as evapotranspiration rates, rainfall patterns, and soil characteristics vary across locations, making it challenging to generalize deficit irrigation strategies. Site-specific adaptation is also necessary to optimize the benefits of deficit irrigation in different agricultural settings. Lack of awareness, training, and access to technical expertise may hinder the adoption and proper implementation of deficit irrigation techniques. The economic viability of deficit irrigation practices depends on various factors, including crop value, market conditions, and production costs. Assessing the economic implications and ensuring a favorable cost-benefit ratio is difficult for widespread adoption. In some regions, water rights and regulatory frameworks may pose constraints on implementing deficit irrigation (Linker et al. 2016). Water allocation policies, permits, and restrictions may limit the flexibility of farmers to adopt deficit irrigation practices. Addressing policy barriers and establishing supportive frameworks can encourage the adoption of deficit irrigation and incentivize water-efficient practices.

2.2 Parties Involved in Irrigation Decisions and Activities in the United States

There are several parties and activities involved in a typical irrigation decision and practice in the United States. Farmers of course are the primary party responsible for making irrigation decisions and implementing irrigation practices on their land. There are also irrigation companies who manage the water distribution system, including canals, pipelines, and water delivery infrastructure (Shah and Bhattacharya 1993). They allocate water resources to farmers based on water rights and contracts. Water management agencies like EPA (Environment Protection Agency) (Solley et al. 1998) oversee water allocation and usage regulations, ensuring compliance with local, state, and federal laws. They may set water usage limits and promote water conservation practices. Local organizations or committee boards (Caponera and Nanni 2019) working for water conservation and promoting water-saving practices will also provide education on efficient irrigation techniques, and offer incentives for implementing water conservation measures.

Meanwhile, research institutions will conduct studies and research on irrigation techniques, crop water requirements, and water-use efficiency and their findings contribute to the development of best practices and guidelines for irrigation decision-making. Also, farmers often need to involve agricultural consultants who are independent professionals who offer expertise on irrigation practices, system design, and water management strategies tailored to specific crops and farming operations. Within the local government, especially those states with a large portion of agriculture in their GDP (Gross Domestic Product), there will be irrigation monitoring and enforcement departments to ensure compliance with water usage regulations, conduct inspections, and monitor water diversion and distribution systems (Ma and Ortolano 2000). For those water conservation districts, special districts will be established to manage and conserve water resources within a specific geographical area. They may also provide funding, technical support, and educational resources to farmers for implementing efficient irrigation practices. These parties and activities will be weaved together and collectively contribute to effective irrigation decision-making and practices in the United States, to optimize water usage, sustain crop productivity, and conserve water resources.

2.3 What Does a Day of Farmers Look Like During the Irrigation Season?

Farmers often start their day very early to make the most of daylight hours. They may begin by checking weather forecasts and monitoring irrigation schedules, and typically visit their fields to assess crop health, soil moisture levels, and overall irrigation needs (Wang and Cai 2009). They may walk or drive through the fields, observing plant growth, checking for signs of pests or diseases, and evaluating the effectiveness of previous irrigation applications. Farmers also allocate time for maintaining and inspecting their irrigation systems. This includes checking irrigation equipment, such as pumps, pipes, valves, and sprinklers, to ensure they are functioning properly. Repairs or adjustments may be made as necessary. Based on the data collected from soil moisture sensors, weather information, and field observations, farmers make decisions about irrigation scheduling and application rates. They calculate the water requirements of the crops, taking into account factors like evapotranspiration rates and soil moisture levels. If the farm operates under a water allocation system, farmers may need to manage their water resources efficiently. They allocate water to different fields of crops based on priority and water availability. This involves monitoring water usage, tracking water levels in reservoirs or canals, and complying with any regulations or restrictions in place.

They will operate the irrigation equipment by starting and stopping pumps, adjusting sprinkler settings, or managing automated irrigation systems to ensure that water is distributed evenly across the fields (Mermoud et al. 2005). Farmers usually maintain their detailed records of irrigation activities, such as the amount of water applied, irrigation start and stop times, and any observations or adjustments made. These records help in monitoring water usage, evaluating irrigation effectiveness, and planning for future irrigation cycles. In addition, farmers need to conduct other tasks such as crop planting, pest control, fertilization, harvesting, equipment maintenance, and managing farm personnel. Throughout the day, farmers keep an eye on weather conditions, soil moisture levels, and any changes in crop health. They may utilize technology, such as remote monitoring systems or mobile applications, to stay updated on real-time data and receive alerts if any irrigation issues arise. Towards the end of the day, farmers will review the day's activities, assess the effectiveness of irrigation, and plan for the next day's tasks.

2.4 How Does the Government Manage Irrigation? How Do Water Managers Allocate Water?

The governments establish regulatory frameworks, policies, and institutions to oversee water management practices. In many regions, the government allocates water rights and permits to users, including agricultural entities. These rights grant users the legal entitlement to a certain volume or flow of water for specific purposes, such as irrigation. Water rights may be based on seniority, beneficial use, or other allocation principles. Water managers, often operating under the authority of government agencies, develop water allocation plans (Molden 2013). These plans outline the distribution of available water resources among different user groups, including farmers. Allocation decisions consider factors such as water availability, demand, environmental considerations, and social priorities. Water managers employ various methods to allocate water among users. These methods can include predetermined allocations, proportional sharing based on water rights, rotational schedules, priority systems, or market-based mechanisms. The specific method used depends on local circumstances and water management goals. Water managers implement monitoring systems to track water usage, measure water flows, and assess water availability. This involves installing water meters, monitoring river/stream flows, and collecting data on groundwater levels. Accurate measurement helps in enforcing water rights, managing water allocations, and detecting unauthorized or excessive water use.

Governments may establish pricing mechanisms and incentives to encourage efficient water use (Dinar et al. 1997). This can include tiered pricing structures that charge higher rates for excessive water use or offering incentives for implementing water-efficient technologies and practices. The aim is to promote responsible water use and discourage wasteful practices. Governments often implement water conservation programs and initiatives to promote efficient irrigation practices. These programs may include educational campaigns, subsidies for water-saving technologies, funding for irrigation system upgrades, and support for research and development of water-efficient farming techniques. Government agencies engage with stakeholders, including farmers, water user associations, and environmental groups, to ensure a participatory approach to water management (Jonsson 2005). Consultation processes allow for input from various stakeholders, consideration of diverse perspectives, and the development of collaborative solutions. Governments enforce water regulations and allocate resources to monitor compliance with water allocation rules and regulations. Penalties may be imposed on those who violate water rights, exceed allocations, or engage in unauthorized water use. Enforcement actions are aimed at ensuring fairness, equity, and sustainability in water allocation practices.

3 Cutting-Edge Research for Irrigation and Struggles to Be Actionable

3.1 Artificial Intelligence (AI) and Machine Learning

AI and machine learning algorithms can analyze vast amounts of data collected from various sources (Sun et al. 2020), such as soil moisture sensors, weather forecasts, and crop characteristics. By processing this information, the algorithms can identify patterns, correlations, and trends to develop optimized irrigation strategies.

AI has great potential to enable precision irrigation by integrating real-time data with irrigation systems (Vianny et al. 2022). AI systems can continuously monitor and adjust irrigation based on dynamic factors, such as soil moisture levels, plant water stress, and weather conditions (Abioye et al. 2020). AI-based decision support systems also provide farmers with actionable insights and recommendations for irrigation management. By analyzing data from multiple sources and employing machine learning algorithms (Sun et al. 2019a, b), these systems can suggest optimal irrigation schedules, water application rates, and irrigation techniques tailored to specific crop types, soil conditions, and weather patterns. For instance, a study conducted in Spain demonstrated the application of AI algorithms for optimizing irrigation scheduling in olive orchards (Linaza et al. 2021). The researchers employed machine learning techniques to analyze data from soil moisture sensors and weather forecasts and automatically recommend irrigation schedules that optimized water use and maintained crop yield. The study showed significant water savings while improving olive tree growth and productivity. However, AI faces challenges in becoming actionable for irrigation in the United States due to several factors. AI models require high-quality data for accurate predictions and recommendations. In the case of irrigation, data on soil moisture, weather conditions, crop types, and land management practices must be reliable and readily available. In some regions, data may be scarce, inconsistent, or of low quality, making it challenging to develop AI models that can provide actionable insights. AI tools need to be compatible with existing irrigation infrastructure and technologies, which can vary widely. Ensuring that AI systems can integrate with different hardware and software platforms is still work in progress for practical implementation. Meanwhile, the adoption of AI technologies for irrigation may involve initial costs for hardware, software, and training. Ensuring affordability and accessibility for a broad range of farmers, including smallholders, is also crucial for widespread adoption. AI recommendations must consider environmental sustainability and water conservation goals. Striking a balance between maximizing crop yields and minimizing water usage and environmental impact can be a complex task for AI too.

3.2 Unmanned Aerial Vehicles (UAVs)

UAVs, commonly known as drones, have gained significant attention in agriculture, particularly for monitoring crop health, detecting water stress, and optimizing irrigation practices (Matese et al. 2018). UAVs equipped with various remote sensing technologies (Sun et al. 2014), such as multispectral or thermal cameras, LiDAR (Light Detection and Ranging) (Christiansen et al. 2017), or hyperspectral sensors, can capture high-resolution imagery and collect data on crop health parameters, including water stress indicators. These sensors capture reflected or emitted energy from crops, providing valuable information on vegetation vigor, leaf temperature, and water content. UAVs also enable farmers to gather detailed field information quickly and accurately and create irrigation prescriptions tailored to specific field conditions.

For example, researchers at the University of California, Davis conducted a study using UAVs to monitor crop water stress and guide precision irrigation in vineyards (Tang et al. 2022). The study utilized multispectral and thermal cameras mounted on UAVs to capture high-resolution imagery. The imagery was processed to derive vegetation indices and crop water stress indicators. This information helped identify areas of the vineyard experiencing water stress and guided irrigation interventions to target those areas specifically. The study demonstrated the potential of UAVs for optimizing irrigation practices and improving water management in vineyards. However, the operation of UAVs is subject to strict regulations by the federal aviation administration (FAA). Obtaining the necessary licenses and permissions for agricultural drone use can be a time-consuming and bureaucratic process in some states. Farmers and service providers must adhere to safety and airspace regulations, which can limit the flexibility and immediacy of drone-based irrigation monitoring. Most agricultural drones have limited flight endurance, typically ranging from 30 minutes to a few hours, depending on the model. This limited flight time may not cover the entire field or growing season, requiring multiple flights and battery changes, which can be inconvenient and time-consuming. Meanwhile, the costs could be a problem. The initial cost of purchasing drones and associated sensors, as well as ongoing maintenance and repair expenses, can be a significant financial burden for farmers, particularly smallholders. Additionally, training personnel to operate and maintain UAVs adds to the overall cost.

3.3 Nanotechnology for Water Delivery

Nanotechnology holds potential for precise water delivery to plant roots through nanoscale channels or coatings (Agrawal and Rathore 2014). Nanotechnology enables the design and fabrication of materials with nanoscale structures, such as carbon nanotubes or nanoscale coatings, that can facilitate water transport (Noy et al. 2007). These structures can create channels or coatings that effectively control the movement of water, allowing precise delivery to plant roots. For example, researchers at the Massachusetts Institute of Technology (MIT) have explored the use of carbon nanotubes as water transporters within the plant xylem, the tissue responsible for water transport from roots to leaves (Lew et al. 2020). They investigated the potential of carbon nanotubes to facilitate more efficient water uptake by plant roots, leading to reduced irrigation needs. But nanotechnology is a relatively new field, and there is still much to learn about the long-term effects and environmental impacts of nanomaterials in agricultural settings. Farmers and regulators may have concerns about the safety and potential risks associated with the use of nanotechnology in irrigation. The introduction of nanotechnology into agriculture is subject to regulatory approval in many countries. Ensuring that nanomaterials meet safety and environmental standards can be a lengthy and rigorous process, delaying their adoption for agricultural use. Nanoscale materials are typically designed for specific and targeted applications, making it difficult to apply them uniformly across extensive farmland. More importantly, nanomaterials can potentially accumulate in soil and water systems, raising environmental concerns. Understanding the ecological impact of nanotechnology in agriculture is essential for responsible adoption.

3.4 Soil Amendments

Soil amendments are the materials added to the soil to enhance its properties (Park et al. 2011). In the context of water retention, researchers have focused on incorporating hydrogels or superabsorbent polymers into the soil. These materials have the ability to absorb and retain large amounts of water, forming gel-like structures that hold moisture within the soil profile. This improves the soil's water holding capacity, reducing the frequency and volume of irrigation required. The retained water becomes available to plant roots, enhancing plant water availability, especially during periods of drought or limited water supply. By enhancing the water holding capacity of the soil, hydrogels or superabsorbent polymers can also minimize water losses through evaporation. The retained water remains within the soil, reducing the rate at which moisture is lost to the atmosphere. This allows for more efficient water use, as a larger proportion of applied water is utilized by the plants rather than being lost to evaporation. For example, a study conducted by Saha et al. (2020) investigated the effects of hydrogel amendment on water retention and plant growth in sandy soils. The research demonstrated that the addition of hydrogels significantly improved soil water holding capacity, resulting in enhanced plant growth and reduced irrigation requirements. The study highlights the potential of soil amendments like hydrogels in improving water availability and plant performance.

3.5 Nanostructured Materials

Nanotechnology involves manipulating materials and structures at the nanoscale (typically at the size of one billionth of a meter) to create new properties and functionalities (Nasrollahzadeh et al. 2019). In the context of irrigation, nanotechnology offers opportunities to develop materials with enhanced water-related characteristics, such as improved water retention, reduced evaporation, and controlled water movement (Lowry et al. 2019). Nanoscale particles can be incorporated into soil or coatings to modify the behavior of water in the irrigation system. These materials can alter the physical properties of the soil or create barriers that regulate water movement, leading to improved water management and increased water-use efficiency (Mauter et al. 2018). By adjusting the flow and distribution of water, nanotechnology can help maintain optimal soil moisture levels for plant growth and reduce water losses due to deep percolation or surface runoff. Nanomaterials can also be used to develop coatings or films that reduce evaporation from soil or water surfaces. These coatings create a barrier that limits the escape of water vapor, thereby reducing water losses and improving overall water-use efficiency. For instance, a study by Dimkpa and Bindraban (2017) explored the use of nanoscale hydroxyapatite particles to modify the properties of sandy soil and demonstrated that incorporating hydroxyapatite nanoparticles can increase the water holding capacity and improved soil water retention, leading to enhanced plant growth and water-use efficiency.

3.6 Desalination Technologies

Desalination is the process of removing salts and other impurities from saline water, making it suitable for irrigation purposes. Desalination technologies have seen significant advancements, driven by progress in physics and chemistry, allowing for the production of freshwater from seawater or brackish water sources. Reverse osmosis is a widely used desalination technology that utilizes a semi-permeable membrane to separate salts and impurities from water. Under pressure, water is forced through the membrane, leaving behind the dissolved salts and contaminants. The resulting freshwater can be used for various applications, including irrigation. Membrane distillation is an emerging desalination process that utilizes a hydrophobic membrane to separate water from saline solutions. The membrane allows water vapor to pass through while preventing the passage of salts and impurities. By creating a vapor-pressure difference, freshwater is generated through condensation, leaving behind concentrated brine. Advancements in physics and chemistry have enabled the development of more efficient and cost-effective desalination processes. These technologies have witnessed improvements in energy efficiency, membrane durability, and overall system performance, making desalination a viable option for providing irrigation water in regions facing water scarcity. Zein et al. (2023) investigated the performance of a solar-powered reverse osmosis desalination system for irrigation water supply in a remote agricultural area. The research proved the feasibility and effectiveness of using renewable energy sources to power desalination processes, providing a sustainable solution for irrigation water production.

3.7 Water Treatment and Recycling

Innovative approaches in water treatment and recycling have been developed to minimize water waste and improve the quality of irrigation water. Physicochemical processes, including coagulation, filtration, and advanced oxidation, are commonly employed to remove contaminants and pathogens from water sources. Coagulation (Palta et al. 2014) is a process in which chemicals called coagulants are added to water to destabilize and aggregate suspended particles, such as clay, silt, and organic matter. The formed aggregates, called flocs, can be easily removed through sedimentation or filtration processes. Coagulation is an effective method for reducing turbidity and removing particulate matter from water. Filtration involves passing water through a porous medium, such as sand, activated carbon, or membranes, to remove suspended particles, microorganisms, and other contaminants. Different types of filters, including rapid sand filters, multimedia filters, and membrane filters, are used in water treatment systems. Filtration helps improve water clarity and removes a wide range of impurities. Advanced oxidation processes utilize powerful oxidants, such as ozone, ultraviolet (UV) light, and hydrogen peroxide, to break down and remove organic pollutants, pesticides, and pathogens from water. These processes generate highly reactive hydroxyl radicals that can effectively degrade and transform organic compounds into harmless byproducts. Norton-Brandão et al. (2013) investigated the use of coagulation, filtration, and UV disinfection for treating wastewater to be used for agricultural irrigation. The research demonstrated the effectiveness of these physicochemical processes in removing suspended solids, pathogens, and contaminants, ensuring the safety and quality of the irrigation water.

3.8 Vertical Farming

Vertical farming is an innovative approach to agriculture that involves growing crops in vertically stacked layers or on vertically inclined surfaces using artificial lighting. Vertical farming systems create controlled environments where temperature, humidity, lighting, and nutrient levels can be precisely regulated. This allows for optimal growing conditions and maximizes crop productivity throughout the year, independent of external climate variations. Vertical farming methods, such as hydroponics and aeroponics, utilize water in a highly efficient manner. Hydroponic systems circulate a nutrient-rich solution to provide plants with the necessary nutrients, while aeroponic systems mist the plant roots with a nutrient solution. These systems typically use significantly less water compared to traditional soil-based farming methods, as water is recirculated within the system, reducing water waste and evaporation. Vertical farming relies on artificial lighting systems, such as LED lights, to provide the necessary light energy for plant growth (Wong et al. 2020). LED lights can be tailored to emit specific wavelengths of light that are optimal for plant photosynthesis, resulting in energy-efficient lighting and targeted crop growth. For example, AeroFarms and Plenty are two prominent companies that have implemented vertical farming systems (O'sullivan et al. 2019). Both operate indoor vertical farms that utilize aeroponic systems and LED lighting to grow leafy greens and herbs in densely stacked trays.

3.9 Aquaponics

Aquaponics is a sustainable farming method that combines aquaculture (fish farming) with hydroponics (soilless plant cultivation) (Savidov et al. 2005). The system utilizes the waste produced by fish to provide nutrients for plants, while the plants filter the water, creating a symbiotic relationship. Aquaponics systems can be implemented in urban areas and are known for their high water and land use efficiency. Companies like Growing Power (Proksch et al. 2019) have pioneered the use of aquaponics in farming. The main hurdle for its actionableness is the initial cost. Setting up an aquaponics system can require a significant initial investment in infrastructure, including tanks, pumps, filtration systems, and grow beds. The costs associated with building and maintaining the system can be a barrier for many farmers, particularly small-scale or resource-constrained operations.

3.10 Genetic Engineering and Biotechnology

Advances in genetic engineering and biotechnology offer opportunities to develop crop varieties with enhanced traits, such as drought tolerance, disease resistance, and increased nutrient content (Bhalla 2006). These technologies aim to develop climate-resilient crops that can thrive under changing environmental conditions with limited irrigation. For example, genetically modified (GM) crops like drought-tolerant maize (corn) have been developed to withstand water scarcity (Kumar et al. 2020). Organizations like the International Maize and Wheat Improvement Center (CIMMYT) (Singh 1988) have been actively involved in research on climate-resilient crop varieties. These genetic modifications can raise regulatory and safety concerns, both in terms of environmental impact and potential health risks. Navigating complex regulatory frameworks can be a significant barrier to the adoption of genetically modified crops for irrigation. Importantly, genetically modified organisms (GMOs) can face resistance from the public and consumer groups who have concerns about the safety of such crops. Negative public perception can lead to market rejection and reluctance among farmers to adopt genetically engineered crops for irrigation. In addition, over time, pests and pathogens may develop resistance to genetically modified crops, reducing their effectiveness and requiring ongoing research and development efforts to stay ahead of evolving threats.

4 Successful Use Cases of Science with High Actionableness

4.1 Improving Irrigation Efficiency Using Remote Sensing and Soil Moisture Data

By combining remote sensing and soil moisture data, stakeholders can better understand crop water requirements and make informed decisions about when and how much to irrigate (Deines et al. 2021). The Yakima Basin Agricultural Water Enhancement Program in Washington State (Vano et al. 2010) is a collaborative effort between the Natural Resources Conservation Service (NRCS) (Schaefer et al. 2007), the Washington State Department of Ecology, and local farmers, and aims to improve water-use efficiency and agricultural sustainability in the Yakima Basin region (Fig. 8.1).

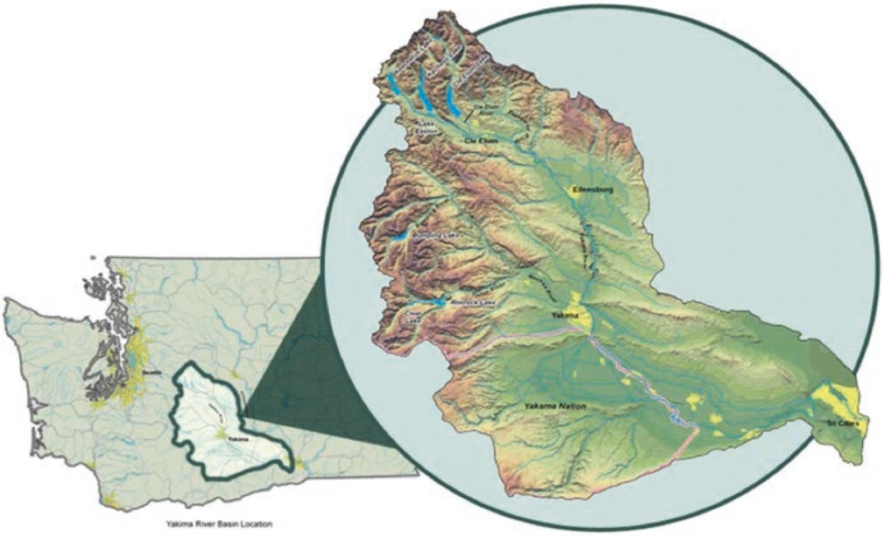

Fig. 8.1 Yakima River Basin. (Image courtesy: https://apps.ecology.wa.gov/publications/documents/1512003.pdf)

By analyzing the satellite imagery and aerial survey data, the program assessed the health of the crops, such as examining vegetation indices, which indicate the overall health and vigor of the plants. Unhealthy or stressed areas can be identified, enabling targeted interventions. Satellite imagery and aerial surveys also help in monitoring water stress levels in the crops (Sheffield et al. 2018). By analyzing indicators like canopy temperature and infrared reflectance, the program identified areas experiencing water stress, which require additional irrigation or water management strategies (Vano et al. 2010). Soil moisture measurements provide quantitative data on the amount of moisture present in the soil at different depths. The sensors continuously monitor and collect soil moisture data over time. The measurements can be logged manually or transmitted wirelessly to a central data management system. Then, the collected soil moisture data is analyzed and interpreted to understand the moisture distribution within the soil profile. This information helps in determining the overall water availability and moisture status in different soil layers. Irrigation scheduling recommendations, generated based on the collected data, are customized to each farmer's specific needs and take into account factors like crop water requirements, spatial variability in soil moisture, and other relevant parameters. Web-based platforms or mobile applications serve as decision support tools in the program. Farmers can access these tools, typically through their devices or computers, to receive the tailored irrigation scheduling recommendations. The decision support tools provide real-time updates on crop health, soil moisture conditions, and irrigation recommendations. The farmers can align their irrigation activities with the specific needs of their crops and the moisture conditions in the soil, thus improving irrigation efficiency and conserving water resources.

4.2 Managing Irrigation During Drought Using Climate Forecasting and Soil Moisture Monitoring

Managing irrigation during drought using climate forecasting and soil moisture monitoring involves using weather forecasts and soil moisture data to make informed decisions about irrigation during periods of drought. This can help to conserve water resources and maintain crop yields. For example, the Murray-Darling Basin in Australia, one of the country's largest agricultural regions, has experienced prolonged drought periods in the past (Leblanc et al. 2012). To manage irrigation during such drought conditions, the Murray-Darling Basin Authority (MDBA) implemented a program that combines climate forecasting and soil moisture monitoring (Grafton 2017). The program utilizes climate forecasting model results which take into account various factors such as atmospheric pressure, temperature, humidity, and oceanic conditions to generate forecasts. It also gathers data from meteorological stations strategically located throughout the Murray-Darling Basin. By analyzing these data together, the program can predict rainfall patterns and estimate future weather conditions. Relying on climate forecasting and soil moisture monitoring data, water managers and farmers can gain valuable information to guide their decision-making process. If forecasts indicate periods of increased rainfall, they can delay or reduce irrigation to avoid overwatering. Or, if dry conditions are anticipated or soil moisture levels are low, they can schedule irrigation to supplement the water needs of the crops. These informed decisions can lead to improved crop health and yield. Crops will receive the right amount of water at the right time, minimizing water stress and maximizing productivity.

4.3 Precision Irrigation for Water and Energy Savings

Precision irrigation is a water management approach that uses technology to apply water only where and when it is needed. This approach can help to conserve water resources, reduce energy use, and improve crop yields. For example, the FieldNET Precision Irrigation system can enable farmers to optimize water and energy usage while improving crop yields (Saiz-Rubio and Rovira-Más 2020; Cohen et al. 2021). One successful implementation of this system can be found in the cornfields of Nebraska, USA. Similarly in the fields, soil moisture sensors are strategically placed in the fields to gather accurate and representative data. They are typically distributed across various locations within the fields to capture the spatial variability of moisture content.

Besides soil moisture, ET (evapotranspiration) monitoring technology is integrated into the precision irrigation system (Abioye et al. 2020). It measures the rate of water loss from the soil through evaporation and the transpiration of plants. This technology provides valuable information on the water needs of crops and typically involves advanced irrigation methods such as drip irrigation or center pivot systems

Fig. 8.2 Standard central pivot facilities in the soybean and wheat fields in Nebraska

(Fig. 8.2). In Lindsay precision irrigation system (Bhatti et al. 2020), ET technology is integrated to enhance irrigation management. With the information obtained from ET monitoring and weather data, farmers can make informed decisions to adjust their irrigation practices accordingly. They can optimize the timing, duration, and application rates of irrigation to match the actual water requirements of the crops.

Precision irrigation system incorporates Variable Rate Irrigation (VRI) technology, which allows for the application of different amounts of water across the field based on crop variability, soil conditions, and water requirements. VRI takes into account factors like crop evapotranspiration rates, plant water stress levels, and desired moisture levels in the root zone to deliver water precisely where and when it is needed. It eliminates the irrigation of non-cropped areas or areas with excess moisture, reducing unnecessary water usage and potential environmental impacts.

5 Suggestions for Improving Actionableness

5.1 Suggestions for Scientists

Agricultural scientists should actively engage and collaborate with farmers, irrigation practitioners, water managers, and policymakers throughout the research process (Gonsalves 2005). Involving stakeholders in study design, data collection, and interpretation helps ensure that research findings are relevant, practical, and applicable to real-world irrigation challenges. Conduct field validation trials to assess the performance and feasibility of research outcomes in real agricultural settings (Jones et al. 1998). Demonstrating the effectiveness of new irrigation technologies, practices, or management approaches under practical conditions can enhance their adoption and implementation. Also, conduct long-term studies to capture the effects and sustainability of irrigation interventions over extended periods as longitudinal research provides valuable insights into the long-term impacts. Assess the potential benefits, such as increased crop yield, water savings, and reduced energy costs, in relation to the investment required. This analysis can help stakeholders evaluate the investment of new irrigation technologies or practices. Try to develop practical guidelines and protocols based on research findings and convert scientific knowledge into actionable recommendations that can be easily understood and implemented by farmers, irrigation practitioners, and policymakers. Also, scientists need to provide clear step-by-step instructions, decision-support tools, or software platforms to facilitate the practical application of research outcomes. Educational resources, workshops, and training programs will be very helpful to increase awareness and knowledge among farmers and irrigation professionals. Meanwhile, stay engaged with policymakers and relevant institutions to advocate for policies that support sustainable irrigation practices, and share research findings, data, and evidence-based recommendations to influence policy development and encourage the adoption of water-efficient irrigation technologies and management strategies. It is part of scientists' obligation to establish mechanisms for continuous monitoring, evaluation, and feedback on the implementation of research outcomes. After the research is in practice, scientists need to pay attention to collect data on the adoption, performance, and challenges faced by stakeholders when applying recommended irrigation practices. This feedback loop helps refine and improve research interventions, ensuring ongoing actionability.

5.2 Suggestions for Farmers

Farmers should actively seek out education and training programs related to irrigation management. By increasing their knowledge and understanding of irrigation principles, technologies, and best practices, farmers can make informed decisions and implement effective irrigation strategies on their farms. Participate in on-farm demonstrations organized by agricultural extension services, research institutions, or industry experts. These demonstrations provide an opportunity to witness and learn firsthand about the practical implementation of irrigation technologies and management techniques. They should consider investing in soil moisture monitoring tools and sensors, as regularly monitoring soil moisture helps farmers make informed decisions regarding irrigation scheduling, ensuring that water is applied when and where it is needed, leading to improved water use efficiency and crop performance. Develop and follow a well-defined irrigation schedule based on crop water requirements, weather conditions, and soil characteristics. Consult with irrigation experts or use available online tools and mobile applications that provide customized irrigation recommendations based on local conditions and crop type. Also, consider the adoption of efficient irrigation technologies such as drip irrigation, micro-sprinklers, or precision irrigation systems. These technologies help deliver water directly to the root zone, reducing water losses due to evaporation or runoff and maximizing water use efficiency. Farmers usually need to inspect and maintain irrigation equipment to ensure optimal performance, and meantime check for leaks, clogs, or damaged components that can affect the distribution of water. Proper maintenance helps prevent water wastage and ensures the longevity of irrigation infrastructure. Stay engaged with fellow farmers, participate in farmer networks, and attend community meetings or workshops focused on irrigation management. Utilize available data and information sources from the science communities and government, and access weather forecasts, soil moisture data, and crop water requirement calculators to make data-driven decisions on irrigation timing and application rates.

5.3 Suggestions for Government and Water Managers

It is recommended to adopt an integrated approach to water management that considers various stakeholders, including farmers, industries, and environmental concerns. Implement fair and transparent water allocation and pricing policies that encourage efficient water use and incentivize conservation practices. Use tools such as water rights systems, water trading mechanisms, and tiered pricing structures to promote responsible irrigation practices and encourage farmers to adopt water-saving technologies. Governments can improve or expand their financial incentives, grants, or subsidies to farmers for adopting efficient irrigation technologies and practices. These incentives can help offset the initial investment costs and encourage farmers to upgrade their irrigation systems, thereby improving water use efficiency and reducing water losses. Also, it is important to offer technical assistance, training programs, and capacity-building initiatives to farmers and irrigation professionals. Establish clear regulatory frameworks for irrigation management, including water usage limits, reporting requirements, and enforcement mechanisms. Government agencies are obligated to invest in research and development initiatives that focus on irrigation technologies, water management strategies, and climate adaptation measures, and support research institutions, universities, and agricultural extension services to develop innovative solutions and provide evidence-based recommendations for irrigation management. Make public data platforms accessible to farmers and water managers, allowing them to make informed decisions regarding irrigation planning and water allocation. Establish fundamental monitoring systems to assess the effectiveness of irrigation management strategies and programs and regularly evaluate the impact of interventions, identify areas for improvement, and adapt policies and practices accordingly.

6 Conclusion

This chapter overviewed the current practice of irrigation and the existing challenges. For example, the availability of reliable and accurate data is essential for implementing effective irrigation management practices, which can be challenging to get especially in developing countries or remote areas. Also, different data sources may not be compatible with each other, making integration and analysis difficult. Meanwhile, the irrigation management practices often require the use of advanced technology, such as sensors, remote sensing tools, and modeling software, which are inaccessible to many farmers, or they may lack the technical expertise to use effectively. It can also be unaffordable, especially for small-scale farmers. To address these challenges, various strategies should be employed, such as making data accessible, reliable, and compatible across different sources, providing support to make technology more usable to farmers via subsidies, free training, and technical assistance, developing affordable technology options, or providing financing or incentives for farmers to adopt these practices without breaking the bank or worrying about the invest-return issues.

Future directions are focused on addressing the challenges of water scarcity, increasing agricultural productivity, and reducing environmental impacts. Smart irrigation systems (Sun and Di 2021) use real-time data to determine irrigation needs and apply water precisely, reducing water waste and increasing efficiency. The integration of artificial intelligence, machine learning (Sun et al. 2019a, b), and the Internet of Things (IoT) technologies can further optimize irrigation management. Climate change is expected to increase the frequency and intensity of extreme weather events like droughts and floods (Kumar et al. 2018). As water scarcity becomes increasingly severe, finding alternative water sources for irrigation like treated wastewater or desalinated water will become more important (DeNicola et al. 2015). Developing technologies that can treat and use alternative water sources effectively is a promising area of research. Also, precision agriculture will continue to be a popular research topic in the coming years. There are many other promising directions in the fundamental research of the soil, seed, water, and environment which could greatly enhance our ability to produce adequate food while controlling the water use in irrigation to sustainably secure food supply without damaging the environment and climate. This chapter aims to establish the groundwork for the ongoing research and hope to facilitate a seamless transition from laboratory concepts to practical field solutions, making it easier to implement advanced irrigation practices in the future .

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