State-of-the-Art Review

Smart Irrigation Controllers in Residential Applications and the Potential of Integrated Water Distribution Systems

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Abstract: Drought and population growth, especially in the western United States, are propelling a need for more efficient irrigation. Smart irrigation controllers, which interface with soil moisture, evapotranspiration (ET), or weather sensors, have been promoted as a demand-side management tool for this purpose. This paper reviews the body of research on residential smart irrigation controllers and their effectiveness. We find that smart irrigation controllers consistently reduce water demand by 15% among general users and more than 40% among indulgent users. Gaps in research include studies addressing peak demand reduction, centralized communication, data verifiability, and human factors of landscape management. Future work may develop techniques for coordinating networks of smart irrigation controllers to enable greater shifting and shaving of discretionary irrigation demands, similar to what is already happening in the electric grid, thereby creating an integrated water distribution system (IWDS). An IWDS may utilize smart irrigation controllers as direct load control devices at customer end points and interface with advanced metering infrastructure (AMI) and supervisory control and data acquisition (SCADA) systems at a central location to create more effective demand-side management (DSM) strategies for water conservation. **DOI: 10.1061/JWRMD5.WRENG-5871.**

Practical Applications: Weather-based irrigation controllers (WBICs) have become the prevalent smart controllers used for residential irrigation scheduling. They are easy to install, have smartphone control, are easy to program, utilize local real-time weather data, prevent operating the irrigation system during rain or other adverse weather events, adjust watering schedules and duration seasonally, conserve water, and reduce water billing costs. In addition to the ease of use and benefits at the residential user level, smart irrigation controllers have the potential to provide the water utility with controls to buffer or shift peak irrigation demands. This buffering and shifting of peak demands have the potential to lower energy costs, decrease the carbon footprint, and delay costly infrastructure upgrades. With technological advancements and the proliferation of smart controllers, the future for water utilities will become more similar to the electrical grid industry. The smart controllers and technology will enable the development of the IWDS. The IWDS will allow the water utility to utilize data from AMI meters, SCADA systems, smart irrigation controllers, artificial intelligence, and other smart technology to operate more effectively and efficiently.

Introduction

The current Western United States drought dating back to 2000 is the driest 22-year span since at least 800 CE and will likely continue (Williams et al. 2022). The declining health of the Colorado River (Wheeler et al. 2022) and the Great Salt Lake (Abbott 2023) are two strong indicators of this trend. At the same time, the American West's population and water needs are growing (Hedden-Nicely 2022; Robbins 2022), with implications for both the overall volume and the peak timing of water demand (Arunkumar and Mariappan 2011). The convergence of a changing climate and a growing water demand presents an immediate opportunity for legal reform, efficiency incentives, and significant water resources infrastructure investments (Hedden-Nicely 2022; Sowby 2022). The United States is not alone in experiencing extreme drought—Khan and Gilani (2021) observe that parts of most continents are vulnerable—and solutions may be applied elsewhere.

A particular opportunity in North America is in residential landscape irrigation, a significant end use of water (Coomes et al. 2010; DeOreo et al. 2016; Mayer et al. 2015). The US Geological Survey reports that, on a per capita basis, the Northern and Eastern states use less water and the Mountain and Western states, where outdoor watering is more common, use the greatest (Dieter et al. 2018). More particular studies show that irrigation accounts for 30%–50% or more of residential water use (Devitt et al. 2008; Haley et al. 2007; USEPA 2013, 2022a; Waskom and Neibauer 2014); in the Southwestern United States, the figure is closer to 90% (Cooley and Gleick 2009). Fig. 1 shows the breakdown of residential water use based on the study by DeOreo et al. (2016).

At first, all residential in-ground irrigation systems (sprinkler systems) were manually controlled (and some still are). Under manual control, a homeowner must physically turn the system on and off; the frequency and duration of watering are discretionary. Automatic timers were introduced in the 1960s. Because of the automation they offer, timers are more convenient than manual irrigation, but they often lead to overwatering because they are typically programmed for the peak growing season and are rarely adjusted to reflect seasonal changes or precipitation events. In the

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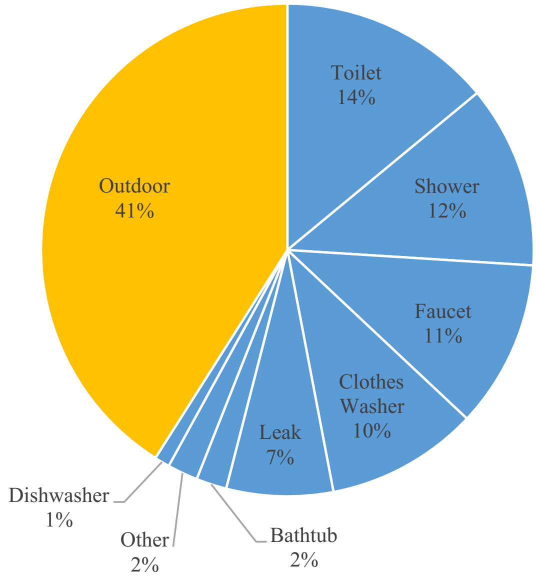

Fig. 1. Residential average water use. (Data from DeOreo et al. 2016.)

United States, for example, a timer-controlled irrigation system applies, on average, 47% more water than manual watering (Mayer et al. 1999).

As the next evolution of irrigation technology, smart irrigation controllers have been promoted since the late 1990s. The devices monitor soil moisture, evapotranspiration, and/or weather and optimize irrigation schedules accordingly. They thus avoid the excess watering associated with timers while still offering benefits of automation over manual watering. For these reasons, a 2016 Water Research Foundation report concluded that water utilities should encourage the use of smart irrigation controllers instead of timers (DeOreo et al. 2016). The USEPA (2022c) estimates that nearly 28 million sprinkler systems are installed across the United States, but despite the availability of the technology, less than 10% of them utilize smart controllers. In the early stages there were just a few commercially available smart controller options. Currently there are nearly 1,000 smart controllers with the WaterSense label available (USEPA 2022b), up from over 700 as reported in 2020 (Dukes 2020).

It is occasionally necessary to compress abundant literature on a specific topic and provide perspective on the state of the research in the form of a review paper (Sowby and Grigg 2022). Reviews on smart irrigation controllers, notably those by Dukes (2012, 2020), have been provided in the past, but they were limited to journal articles and did not include many valuable engineering reports and studies. Given the need to address pressing water conservation issues and learn from advancements in the electric integrated grid and its implications for integrated water distribution systems, we find it prudent to prepare a new review focused on applications of smart irrigation controllers.

To advance the state of the practice, we review here more than 80 studies on residential applications of smart irrigation controllers found through the method described subsequently. We discuss common findings from the studies, including water savings and other benefits, as well as gaps and limitations. We then recommend pathways for future research and the possibilities for integrated water distribution systems to mimic the advancements of the electric grid.

Methods

We began our review by extensively searching Scopus, Web of Science, Google Scholar, the ASCE Library, and American Water Works Association (AWWA) periodicals for relevant sources. Keywords used to query material included "smart controllers," "water demand side management," "water conservation," and "residential landscape irrigation." We then examined the references in the articles to expand our search. Agricultural studies were excluded, and generally only studies in the past 25 years were of interest specifically documenting residential landscape controller applications and not just research describing new controllers or theories. We digitally or physically verified each primary source before including it in the final list [i.e., we did not rely on citations by others, a problem noted by Chini et al. (2021)]. We excluded nearly 10 studies from this review that were not discoverable and verifiable. For each study, we cataloged the location, conditions, controller technology, baseline definition, water savings, and other pertinent information as applicable. We then used the tabulation to develop our discussion, which follows.

Results and Discussion

Summary of the Studies

The Appendix summarizes the reviewed studies. The list contains 51 journal articles, 24 reports, and five conference proceedings (80 total sources) published between 1984 and 2021, reporting on studies in 20 states across the United States and three countries (United States, Australia, Canada) as shown in Fig. 2. Fig. 3 provides a timeline.

Early studies focused on determining water savings potential in controlled university and field applications. Once smart controllers were established, the studies became more complex and considered seasonal variations, specific field conditions, manufacturer comparisons, more complex statistical analyses, and human elements and preferences.

The studies consider a variety of irrigation control technologies (as either the baseline or the project), which we define here and as depicted in Fig. 4:

- Manual: physically turning on a valve to start and stop an irrigation event.
- Timer: automatic controller that starts and stops irrigation based on a set schedule (e.g., day, start time, and duration).
- Rain sensor (RS): on-site device interfaced with a timer or controller that prevents irrigation during or after a rain event. These devices are not controllers but mechanisms that allow the controller to respond to weather conditions.
- Soil moisture sensor (SMS): on-site device installed underground in the root zone that collects soil moisture data and interfaces with a controller. Irrigation can be programmed to be bypassed based on threshold soil moisture conditions.
- Evapotranspiration (ET) controller: controller that adjusts irrigation events (bypass, frequency, or duration) based on preprogrammed historical ET data or on-site ET sensors. ET is the combination of evaporation from the soil plus transpiration from plants and depends on weather factors such as sunlight, temperature, wind, and humidity. ET varies seasonally and daily and is highest in the summer and lowest in the winter. Almost all ET controllers use the ASCE standardized reference evapotranspiration equation (Allen et al. 2005) to calculate ET, which is considered the standard for ET calculations. This method accounts for reference ET, crop ET, and many climate factors.

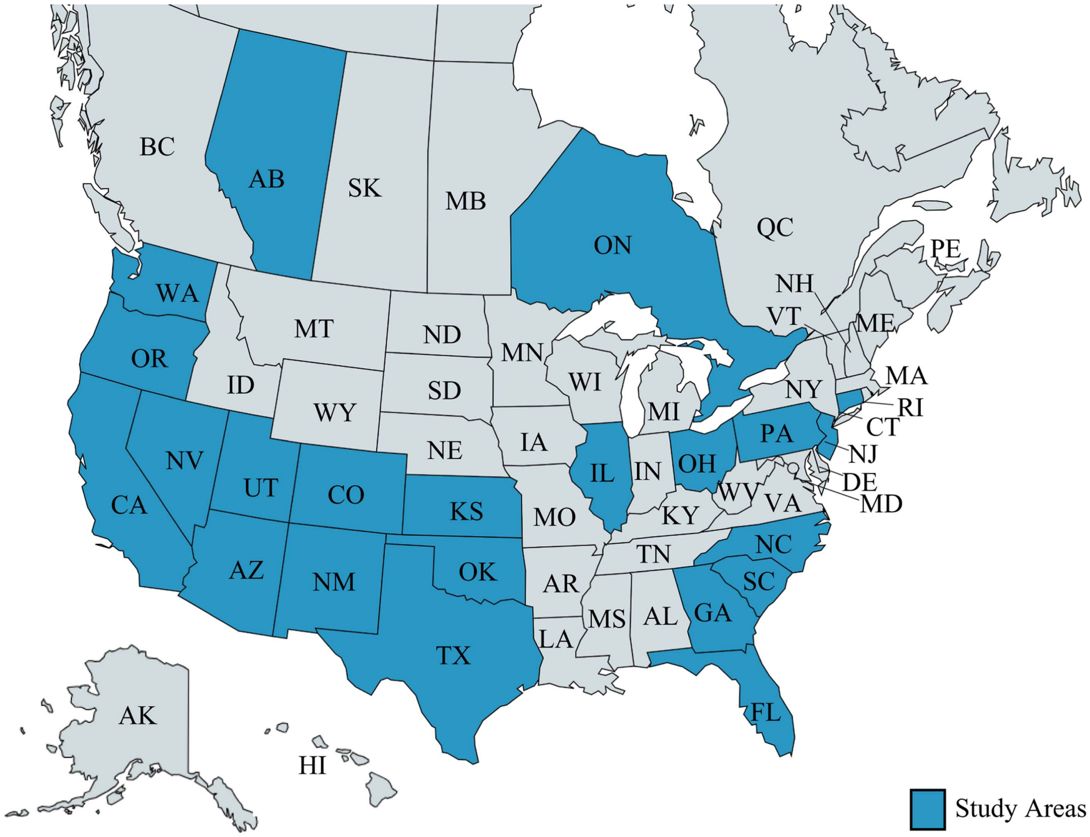

Fig. 2. Locations of North American study areas (Australia not shown).

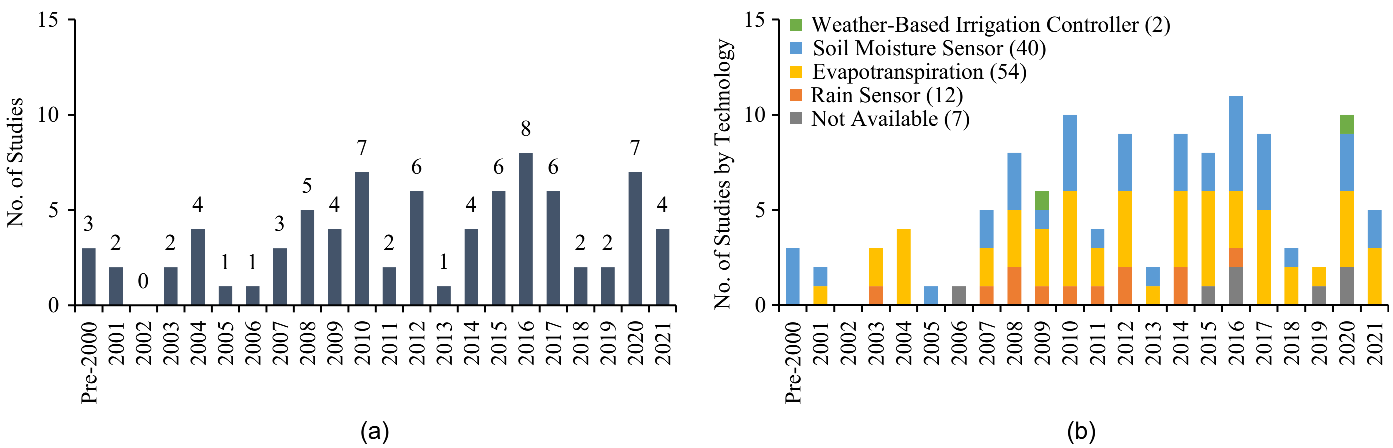

Fig. 3. Timeline of reviewed studies: (a) by year of publication; and (b) by year and technology. Some studies report on multiple technologies.

- Weather-based irrigation controller (WBIC): controller that schedules irrigation to meet the landscaping needs based on current weather data (e.g., precipitation, sunlight, temperature, wind, and humidity) collected on-site or transmitted from off-site weather stations. ET principles are often used to establish and modify irrigation schedules. Conger and Dukes (2020) note that because WBICs often use ET to estimate watering needs, WBICs are commonly called ET controllers.

Plot and field studies consistently demonstrate that SMSs provide greater conservation potential (Cardenas-Lailhacar et al. 2008; Cardenas and Dukes 2016b; Cardenas et al. 2021; Davis and Dukes 2015a; Vick et al. 2017). Studies also demonstrate that SMSs remain reliable and have minimal operation and maintenance costs (DeOreo et al. 1997; Qualls et al. 2001). A major disadvantage of SMSs is the more difficult installation or retrofit by a homeowner because SMSs are required to be buried and typically need one

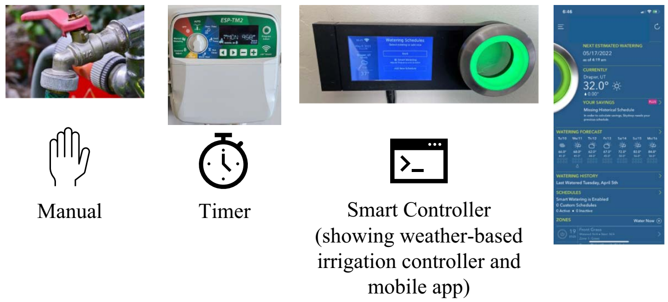

Fig. 4. Evolution of irrigation control technology.

sensor per zone. In addition to the sensor being buried, wires need to be run underground back to the controller. RSs and ET controllers requiring on-site instrumentation will also require greater effort and potential excavation to install wiring between the controller and the instrumentation. Studies have found that an SMS controller with an RS is more effective, saving up to an additional 45% more water (Cárdenas-Lailhacar et al. 2005; Rutland and Dukes 2012). These studies indicate the importance of using SMS and RS together.

In the past, controllers with on-site sensors were favored for being more precise to account for local conditions (Dukes 2020), but due to the complexity of SMSs, this has led to a shift from on-site sensors to signal based (WBIC), which are easier to install and do not require modification to the underground irrigation system other than replacing the old timer controller with the new controller. With the proliferation of publicly and locally available weather stations, the precision of WBICs are gaining equal ground to on-site sensors. Due to the factors listed previously with the greater complexity to SMS and RS installations, WBICs should be the preferred controller alternative for targeted education and outreach programs. Data show that customer WBIC installations are equally or even more effective than contractor-installed controllers at increasing water savings (Aquacraft 2015; Kennedy/Jenks 2010).

As stated previously, only 10% of the estimated 28 million irrigation controllers are smart controllers. This is a low percentage given there are nearly 1,000 smart controller options available (USEPA 2022b). From survey results, the major factor for low adoption rates is the cost of the smart controller (Boyer et al. 2016). Homeowners prefer smart controllers, but water rates and annual savings, water savings potential, and price perception are the most important factors in deciding to upgrade to a smart controller (Khachatryan et al. 2019, 2020; Suh et al. 2017; Zhang and Khachatryan 2019).

To overcome the cost hurdle, Spanish Fork, Utah, took a unique strategy to meet a state 25% reduction goal in water use. Spanish Fork's approach was to provide free, professionally installed smart controllers to residents. As reported in 2019, with approximately 1,400 controllers installed, the customers have a 17% average water use savings. Additional benefits to the city include peak demand reductions enabling them to delay infrastructure upgrades (Paxton et al. 2019). As an update, Spanish Fork has installed 3,250 controllers with 250 remaining to be installed in the summer of 2022 with water savings continuing to be near 17% (Paxton, personal communication, 2022).

Water Savings Performance

The reviewed studies suggest a wide range of water savings (6% to 92%) associated with smart irrigation controllers. The locations of the reviewed studies varied widely with considerable diversity in location and climate. Studies from humid, semiarid, and arid climates demonstrated great effectiveness. While no definitive comparison is possible because the technologies, baselines, and conditions vary across the studies, some general patterns are apparent and are supported by the literature. SMS seemed to perform the best, with savings of 47%, followed by ET controllers, with savings of 30%. This is consistent with Dukes's (2020) ET and SMS combined reported savings of 51% for plot studies and 30% for residential studies.

Negative savings indicate that more water was used because of the smart controller; such cases may be explained by a smart controller being installed on a previous underirrigated landscape. The increased irrigation usage is typically due to the smart controller functioning properly based on controller settings and applying the required theoretical irrigation requirement based on the reference ET (Aquacraft 2015; Davis and Dukes 2014, 2015b).

Another important distinction is the group of water users being targeted. Many studies report savings at 40% or higher, but Dukes (2012), Mayer et al. (2009), and Williams et al. (2014) commented that such results came from studies focusing on excessive irrigators rather than typical applications and hypothesized that a more reasonable expectation would be 10% savings or less. Still, the law of the few should not be overlooked; focusing smart controllers and other water conservation efforts toward a few excessive irrigators can be effective (Davis and Dukes 2015a, b; Mayer and DeOreo 2010; Shurtz et al. 2022). Indeed, DeOreo et al. (2016) found that about 20% of water users applied more than the theoretical ET requirement, but a few indulgent users accounted "for the bulk of excess irrigation for the whole group."

Given the comments by others and the sources we reviewed here, we estimate that smart irrigation controllers reduce water use on the order of 40% or more when targeting excessive irrigators and 15% or less when including typical users, and that SMSs paired with RSs are the most effective devices (Cárdenas-Lailhacar et al. 2005; Rutland and Dukes 2012).

Other Benefits

Beyond saving water and customers benefiting by lowering their water utility bill by using less water for irrigation (Cardenas et al. 2020; Kleinman 2017; USEPA 2021), smart irrigation controllers help limit peak water demand, save energy, improve landscape health, and reduce runoff.

Water conservation from smart irrigation controllers can benefit the water utility in both volume and peak flow rate (Hoyenga and Reaves 2006; Mayer et al. 2018; Mayer and Smith 2017). Because water distribution systems are designed based on peak demand, the peak demand reductions may enable water utilities to modify or delay infrastructure investments (MWDOC&IRWD 2004). Mayer and Smith (2017) estimated a total of 37,850 m^3/day (10 MGD) peak reduction could be achieved based on data from a small study. Hoyenga and Reaves (2006) described how the Eugene Water & Electric Board (EWEB) in Oregon was over capacity in one area of its system but was able to put off emergency capital upgrades by changing only the timing of irrigation, a solution that also reduced maintenance costs and better regulated system pressures.

Because water supply requires energy (Chini and Stillwell 2018; Griffiths-Sattenspiel and Wilson 2009; Sowby and Burian 2017; Sowby and Dicataldo 2022; Zib et al. 2021), water conservation will reduce energy use and the associated carbon emissions. Mutchek and Williams (2010) noted this linkage specifically for smart irrigation controllers. Zib et al. (2021) estimated that the average operational carbon footprint of US water utilities is 0.46 kg

CO_2 per cubic meter of water, so every unit of water saved through smart irrigation controllers reduces carbon emissions accordingly. Because water suppliers are prone to reactively meet peak water demand with pumps (Jones and Sowby 2014), the implications for energy and/or cost savings are particularly relevant in energy markets with dynamic pricing or limited capacity.

There are some environmental benefits too. Several studies have reported that through proper irrigation application, landscapes are healthier and more resilient (Cardenas and Dukes 2016a; MWDOC&IRWD 2004; Mayer et al. 2009; Shurtz et al. 2022). Further, large field studies have documented that when landscapes receive optimum irrigation rates, runoff drops by 49% to 71% (Aquacraft 2003; Berg and Diamond 2004; MWDOC&IRWD 2004; Kennedy/Jenks 2010; Koeller 2004) and downstream water quality improves thanks to lower pollutant loads (MWDOC&IRWD 2004).

Research Gaps and Limitations

The literature review identified several research gaps. The key findings for discussion are peak demand reduction, centralized communication, human factors of landscape management (plant choice, layout, and maintenance), and data verifiability.

A few studies (Hoyenga and Reaves 2006; Kleinman 2017; Mayer and Smith 2017; Paxton et al. 2019) identified potential benefits from peak demand management through smart irrigation controllers, including cost savings from delaying future infrastructure capital facility projects, more efficient operation and maintenance, lower energy costs, and water quality improvements. Few such studies exist, however, and they have been limited in size, number of participants, scope, and objectives. Hydraulic modeling studies and larger, more complex studies are needed to determine the limitations and the maximum potential of smart controllers in peak demand reduction.

Centralized communication is greatly needed in the water sector to harness growing data streams from smart irrigation controllers, advanced metering infrastructure (AMI), and supervisory control and data acquisition (SCADA) systems. Current limitations in data synchronization do not allow for optimization of peak demand reduction and facilitation of artificial intelligence (AI) capabilities in operation and management decisions. The electric grid system uses centralized communications (Abrahamsen et al. 2021; Panda et al. 2022) to create an integrated electric grid for accurate demand forecasting and peak demand reduction management. The water sector needs to follow the lead of the electrical sector and start implementing centralized communication. Several studies describe the inaccuracies of outdoor water usage and provide methodologies for making this estimate (Boyer et al. 2014; Davis and Dukes 2015b; Devitt et al. 2008; Romero and Dukes 2016; Torbert et al. 2016). The synchronization of smart controllers and meters will allow for accurate measurement of indoor and outdoor water usage per connection and ultimately for the entire water system.

The human factor continues to be an area of study lacking sufficient evidence to establish connections between user preferences, long-term conservation, and landscape management. Dukes (2020) noted that in his 2012 review paper (Dukes 2012) there had been no studies including the human factor, but studies in the following decade started to include customer feedback and customer interaction with the controller and smartphone apps. The Spanish Fork approach (Paxton et al. 2019) of supplying free smart controllers to opt into the program needs additional follow-up to determine long-term effectiveness and whether cost and social benefits outweigh the controller costs.

Additionally, in reviewing the body of research, we could not locate some sources cited by others or could not verify some results cited by others. We had to exclude nearly 10 reports from the Appendix because we could not find the original source online, through library requests, or through direct requests to the authors. Although other researchers have cited a primary source and may have had access, we too sought the primary source and a secondary reference was not adequate. We also encountered a few inconsistencies in referenced data that could not be verified from the original source. These were cases where data from the primary source were misquoted, miscalculated, or misunderstood when presented in a secondary source. Data availability, verifiability, and reproducibility (Rosenberg and Watkins 2018) are important to ensure smart controller research can advance.

Toward Integrated Water Distribution Systems

Integrated water resource management (IWRM), as defined by the Global Water Partnership, is a process that "promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global Water Partnership 2022). IWRM is based on the principles of social equity, economic efficiency, and environmental sustainability (de Oliveira Vieira et al. 2020). Integrated urban water management (IUWM) is a subset of IWRM with a narrower focus on water supply, drinking water, wastewater, and stormwater (Bahri 2012). The natural next step is an integrated water distribution system (IWDS) as depicted in Fig. 5.

Mayer and Smith (2017) propose to do in the water sector what the electrical utility industry has been doing since the 1950s with direct load control demand-side management (DSM) strategies. Direct load control, through an agreement between the utility and customer, allows the utility to remotely control the customer's appliances, which are most typically an air conditioner or water heater. The utility installs a remote-control switch on the customer's appliance for this purpose. The DSM strategy, applied across many customers, reduces stress on the grid to avoid blackouts or brownouts. DSM strategies now affect over a million water heaters and nearly a million central air conditioners (Gellings 2017). The electrical utility sector has continued to make enhancements to DSM strategies and demand forecasting to become an integrated grid.

The integrated electric grid is more than just AMI and direct load control strategies; it is the utilization of two-way electricity and communication flow of data (Judge et al. 2022). The integrated electric grid involves self-healing, congestion management, real-time pricing, reliability, security, advanced analytics with artificial intelligence, machine learning, AMI, integration of renewable energy sources, electric vehicles, and energy storage systems, making the electric grid far more complex than a water distribution system (Judge et al. 2022; Panda et al. 2022). AMI enables the two-way communication of data, but the full capabilities of smart grid infrastructure is made possible through a centralized command center controlling the communication and facilitating analysis and decisions (Abrahamsen et al. 2021).

We encourage water utilities to follow the same path as electrical utilities and develop an integrated water distribution system that can better stay within its capacity by dynamically controlling some portion of the customer demand. Similar to benefits seen in the electric grid, IWDS will help water utilities become more efficient, reduce operation and maintenance costs, and reduce peak demand. Additional benefits can be achieved from an IWDS by enhancing

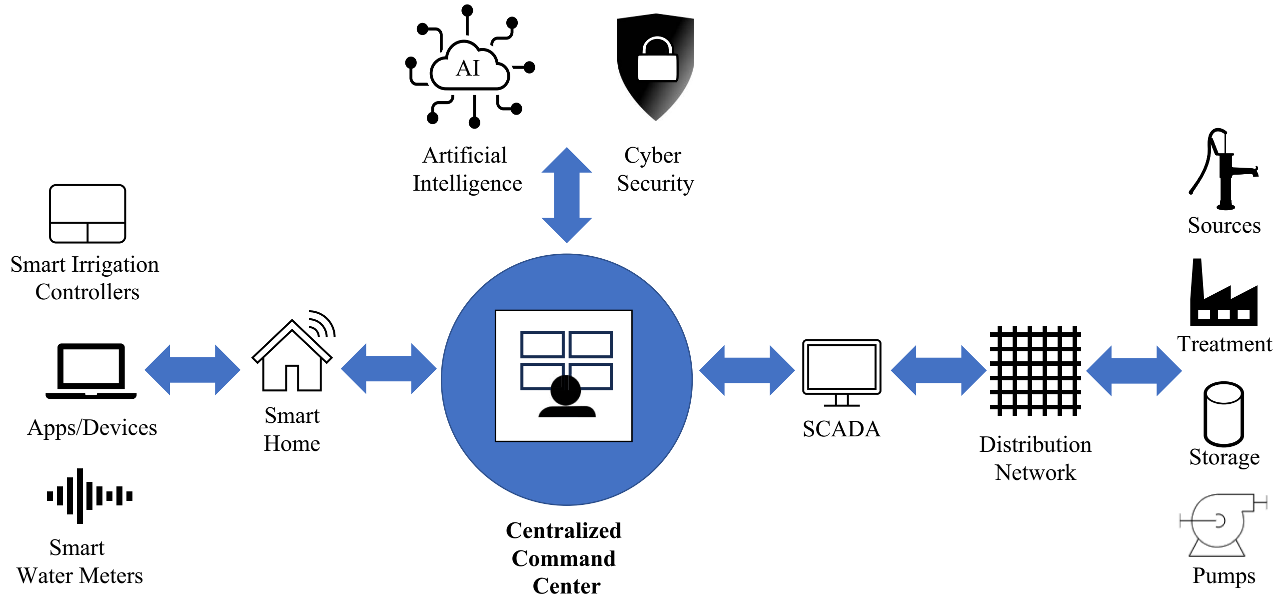

Fig. 5. Integrated water distribution system schematic.

water conservation potential and better drought restriction enforcement and monitoring (when in effect).

We discuss the possibility of IWDS in the context of smart irrigation controllers because they are the enabling technology. Residential irrigation, unlike the public health function of indoor water supply, is a nonessential water use and has the potential for greater DSM optimization to ensure drinking water is available for indoor use. Landscape irrigation is discretionary and can occur at any time during a relatively large window (or not at all, if capacity is unavailable). For example, in a given week, depending on weather, a typical customer's watering cycle may need to run for 1 h during a 10-h overnight window on two separate days, so there are then 35 possible 1-h slots in which it may run. Coordinated across thousands of customers with smart irrigation controllers, water demand could be spread out to best manage peak flows, storage, and pressure. The concept is analogous to what Khatami et al. (2018) described for scheduling the charging of electric vehicles to avoid spikes in power demand.

The next application phase for smart irrigation controllers is to become integrated along with AMI and SCADA systems. Smart irrigation controllers are the water utilities' direct load control devices. Demand forecasting and machine learning capabilities (Doorn 2021; Hadjimichael et al. 2016) will be greatly enhanced in an integrated water distribution system benefiting water utilities with increased conservation potential and peak demand management strategies. A recent survey of US water utilities indicated that about 24% have experimented with AI and that automation and water conservation are among the top motivations for more water utilities to do so (Rapp et al. 2023). The integrated water distribution system can become one of the tools to reform values and ensure a cooperative future as water becomes more scarce (Hedden-Nicely 2022).

Conclusion

Motivated by the Western US drought, developments in irrigation technology, and successful concepts from the electric grid, we reviewed 80 studies on residential applications of smart irrigation controllers. We found typical savings of 15% among general users and more than 40% among indulgent users. Soil moisture sensors paired with rain sensors have demonstrated the highest water savings potential when connected with smart irrigation controllers. However, the complexity of modifying the underground irrigation system with these devices has led to a preference for weather-based irrigation controllers, which only require replacing the old timer controller with the new smart controller. We recommend that WBICs should be the preferred controller alternative for targeted education and outreach programs. Even the most efficient and top-of-the-line controller cannot compensate for improper controller setup, lack of operation and maintenance, leaks, and poor irrigation design and management (Nautiyal et al. 2015). Overall, smart irrigation controllers are an effective demand-side management tool to conserve outdoor water use and provide extensive benefits to both the residential customer and the water utility.

The literature is sparse in its coverage of how smart irrigation controllers reduce peak water demand, how centralized communication should be handled, and how to address the human elements of landscape management informed by smart controllers. We suggest these topics for further study. An important limitation in our review was the inability to verify (or even locate) certain sources or reproduce results, an aspect that should be considered in future studies.

We recommend that water utilities build on the advances of the smart integrated electric grid and more fully mimic practices that have become standard for electrical utilities. Integrated electric grids have long been using direct load control devices for demand-side management of peak power loads. Smart irrigation controllers have the potential to provide similar benefits to water utilities. As many parts of North America and other urbanized locations around the globe are dealing with water scarcity and population growth, IWDSs built on smart irrigation controllers may open the way to DSM capabilities that are better suited to the challenges of a modern sustainable water supply.

Appendix. Summary of Reviewed Studies on Residential Smart Irrigation Controllers

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Augustin and Snyder (1984)	Journal	SMS	Study period December 1979 through June 1983 on test plots in sandy soil	Florida	26%	Timer	Benefit during frequent but unpredictable rainfall
Allen (1997)	Report	SMS	Field study with 37 homes during 1996 irrigation season	Providence and Salt Lake City, Utah	10%	Control group	Small town versus metro comparison
DeOreo et al. (1997)	Report	SMS	1997 field study with 23 sensors	Boulder, Colorado	76%	Theoretical requirements	Sensors remained reliable for 5 years
Hunt et al. (2001)	Report	ET	Field study with 33 homes	Orange County, California	16%	Control group	Used postal mailings advising of irrigation schedules
Qualls et al. (2001)	Journal	SMS	Field study with 23 test sites (21 residential, two public)	Boulder, Colorado	73%	Theoretical requirements	Minimal operations and maintenance costs over the 3- to 5-year period
Aquacraft (2003)	Report	ET	3-year field study with nine homes during drought conditions	Colorado	21%	Theoretical requirements	Average of $190 water bill savings
Saving Water Partnership (2003)	Report	ET and RS	Field study with 106 homes during drought conditions (53% of historical average)	Puget Sound area, Washington	78,491 L/year (20,735 gal./year)	N/A	Study coalition included 24 water utilities
Berg and Diamond (2004)	Journal	ET	18-month study	Irvine, California	10%	Control group	Larger landscape = better savings; 49% reduction in stormwater runoff
Koeller (2004)	Report	ET	Review report	California	N/A	N/A	Summary of ET controller water savings and potential to reduce runoff
MWDOC&IRWD (2004)	Report	ET	18-month field study with 112 homes and 26 nonresidential controllers, 417 in control group, 225 in education group	Irvine, California	Residential 10%; Nonresidential 16%	Control group	Targeted education programs; 50%–71% reduction in runoff
Pittenger et al. (2004)	Report	ET	University plots in sandy loam soil	Riverside, California	Variable	Timer	Setup of WBIC is most important factor in performance
Cárdenas-Lailhacar et al. (2005)	Conference	SMS	University plots in fine sand	Gainesville, Florida	Average 72%	Control group	SMS increased efficiency; SMS without RS used 45% more water
Hoyenga and Reaves (2006)	Journal	N/A	Overview of SWAT and need for partnerships between utilities and builders	Eugene, Oregon	N/A	N/A	Example of peak demand reduction to delay capital project
Davis et al. (2007)	Conference	ET	20 university plots in fine sand	Florida	Controller 1 & 2 = 11% − 40%; Controller 3 = −63%	Timer	Comparison study of 3 different controllers
Pathan et al. (2007)	Journal	SMS	Six university plots in sandy soil	Perth, Australia	25%	Timer	Water savings with little loss to turfgrass health; decreased risk of nitrogen leaching

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Shedd et al. (2007)	Conference	ET, RS, and SMS	72 university plots in sand and fine sand	Florida	SMS = 0%–63%; RS = 7%–33%; ET = 36%–59%	Timer	Two dry seasons during test period (<historical rainfall)
Cárdenas-Lailhacar and Dukes (2008)	Journal	RS	University plots during rainy period (62% days had rainfall)	Gainesville, Florida	3%–44%	Timer	Test to determine effectiveness of rain sensors; payback period less than a year
Cárdenas-Lailhacar et al. (2008)	Journal	RS, SMS	72 university plots in fine sand	Gainesville, Florida	RS = 34%; SMS = 69%–92%	Timer	SMS-based treatments more efficient than timer
Devitt et al. (2008)	Journal	ET	18-month field study with 27 homes	Las Vegas	20%	Control group	17 sites with ET controllers and 10 sites with non-ET controllers
Grabow et al. (2008)	Conference	ET and SMS	20-week university plot study in sandy loam during warmer and dryer than normal conditions	Raleigh, North Carolina	11%	Timer	Important to use representative weather station
USBR (2008)	Report	ET and SMS	Review report	Various	Various	Various	Summary of research and studies related to smart irrigation controllers
Davis et al. (2009)	Journal	ET	15-month study in 20 university plots in sandy soil	Florida	43%	Timer	ET controller twice as effective compared to RS alone
Mayer et al. (2009)	Report	WBIC	3,112 smart controllers across more than 20 water agencies	California	6%	Weather-normalized change in irrigation volume	High users not targeted; not all reductions statistically significant; 41.8% increased water use in first year; decrease of 16.4% in Year 3 versus. preinstall year
McCready et al. (2009)	Journal	ET, RS, and SMS	72 university plots in sandy and fine sand during drought conditions	Citra, Florida	ET = 25%–62%; SMS = 0%–74%; RS = 7%–30%	Timer	Four treatment periods with three relatively dry periods
Shober et al. (2009)	Journal	ET	16 university plots in fine sand	Wimauma, Florida	Variable	Timer	No negative effect on plant health; ET controllers did not result in savings over the reduced time treatment
Cárdenas-Lailhacar and Dukes (2010)	Journal	SMS	University plots in sandy soil during warm season	Gainesville, Florida	40%–88%	Timer	Savings were percentage of scheduled irrigation cycles bypassed
Cárdenas-Lailhacar et al. (2010)	Journal	RS, SMS	64 university plots in fine sand during drought conditions	Gainesville, Florida	RS = 13%–24%; SMS = 16%–83%	Timer	SMS saves water and maintains turf quality
Davis and Dukes (2010)	Journal	ET	20 university plots in fine sand	Wimauma, Florida	42% (previous research)	Timer	Proper ET controller programming is important; potential to be more efficient than manual irrigation
Kennedy/Jenks (2010)	Report	ET	Field study with 1,222 homes	Orange County, California	Household = 7.1%; residential outdoor = 9.7%	Control group	Eight controller brands tested; excessive users not targeted; runoff reduction was significant; smart timers installed by homeowners performed better than those installed professionally

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Mayer and DeOreo (2010)	Journal	ET	3,112 smart controllers in residential and commercial landscapes	California	6%	Weather-normalized change in irrigation volume	Savings include sites with both decreased and increased use
Mutchek and Williams (2010)	Journal	ET and SMS	Carbon footprint analysis of smart controllers	N/A	N/A	N/A	A need to lower controller prices and increase water savings to make controllers more widely used in the Southwest
Swanson and Fipps (2010)	Report	ET and SMS	2-year study with virtual landscapes using six controllers in 2008 and 10 controllers in 2009	College Station, Texas	N/A	N/A	Improvement in controller performance and reduction in excessive irrigation
Dukes and Davis (2011)	Report	ET	University test plots	Gainesville, Florida	N/A	N/A	Ability of the controller to handle rainfall has the most influence over SWAT scores
McCready and Dukes (2011)	Journal	ET, RS, and SMS	72 university test plots	Citra, Florida	N/A	N/A	Evaluation of only one 30-day SWAT test period may not completely capture controller performance
Al-Ajlouni et al. (2012)	Journal	ET	University plots in clay loam during cool season	Las Cruces, New Mexico	−53% to 259% of control	Timer	Control set to 80% of ET; two of five ET controllers saved significant water, two increased irrigation, and one had no change
Cárdenas-Lailhacar and Dukes (2012)	Journal	SMS	56 university plots in Gainesville, 36 university plots in Citra, 58 homes in Pinellas; sandy soils during warm season	Citra, Gainesville, and Pinellas, Florida	42%–72%	Timer	Savings reported for conditions where turf quality remained good; field application rates appear to be lower than plot experiments
Davis and Dukes (2012)	Journal	ET	Three field studies in southwestern and central Florida; 36 homes in southwestern Florida study	Florida	63%	Timer	Users already irrigating less than well-watered conditions and accepting declines in landscape quality will not benefit
Dukes (2012)	Journal	ET and SMS	Review paper	Various	10%–70%	Various	Excellent summary of pilot- and plot-scale scientific studies
Haley and Dukes (2012)	Journal	RS and SMS	26-month field study with 58 homes in sandy soil	Palm Harbor, Florida	65%	Nonintervention residential landscapes	SMS controllers showed significant irrigation savings
Rutland and Dukes (2012)	Journal	RS and ET	14 months, 20 university plots in sand during warm season	Wimauma, Florida	25%–41%	Timer	Adding RS increased water savings
Grabow et al. (2013)	Journal	ET and SMS	3-year study of 40 university plots during cool season	Raleigh, North Carolina	ET = −11%; SMS = 24%–39%	Timer	ET excessive watering due to overestimation of reference ET
Davis and Dukes (2014)	Journal	ET	2-year field study with 36 homes	Apollo Beach, Riverview, and Valrico, Florida	23%–41%	Timer	Users already irrigating less than well-watered conditions and accept declines in landscape quality will not benefit

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Dobbs et al. (2014)	Journal	ET and SMS	16 university plots in gravelly loam during warm season	Homestead, Florida	RS = 17%–49%; ET = 66%–70%; SMS = 64%–75%	Timer	Leaching coincided with rainfall events and excessive irrigation
Melody et al. (2014)	Report	ET, RS, and SMS	Various	Various	Various	Various	Summary of research on smart irrigation controllers
Williams et al. (2014)	Report	ET, RS, and SMS	Meta-analysis of water savings of 42 data points	Various	WBIC = 15%; SMS = 38%; RS = 21%	Various	Eliminated duplicative and secondary results along with studies of high-water users
Aquacraft (2015)	Report	ET	Evaluation of 1,365 smart controllers	Santa Clarita Valley, California	Not uniform	Control group	Programs should target excessive irrigators; water use increased among underirrigators and reduced among overirrigators; homeowner versus contractor installed had same results
Davis and Dukes (2015b)	Journal	ET	Two independent field studies; 36 Hillsborough and 139 Orange County homes	Hillsborough and Orange Counties, Florida	Reduction	N/A	Programs should target excessive irrigators to increase water conservation potential
Davis and Dukes (2015a)	Journal	ET and SMS	22-month field study with 167 homes in sandy soil	Orange County, Florida	21%–52%	Nonintervention residential landscapes	SMS controllers perform better under test conditions; proper programming important; additional savings from education and detailed programming
Mayer et al. (2015)	Journal	N/A	N/A	N/A	N/A	N/A	Outdoor water savings are achievable and can be significant; outdoor conservation programs and measures are challenging, cost savings are rarely documented, and standardization of methods and measures are needed
Migliaccio et al. (2015)	Journal	ET	Smartphone app developed and tested in university plot during warm season	Homestead, Florida	42%–57%	Timer	Smartphone app was comparable to ET controllers; limitation is that app is not directly connected to controller
Nautiyal et al. (2015)	Journal	ET and SMS	20-week field study with 24 homes	Wake County, North Carolina	ET = 22%; SMS = 42%	Standard irrigation controller with no intervention	Variable rainfall and weather made it difficult to discern changes in behavior due to smart technology; smart controller cannot overcome poor irrigation system design, installation, and maintenance
Boyer et al. (2016)	Journal	SMS	Survey of 3,000 commercial customers	Oklahoma City	N/A	N/A	At current water rates, commercial users unlikely to install smart controllers
Cárdenasand Dukes (2016a)	Journal	SMS	64 university plots in fine sand during warm season	Gainesville, Florida	RS = 21%; SMS = 61%	Timer	All water savings were achieved without a decline in the landscape quality
Cárdenasand Dukes (2016b)	Journal	SMS	32-month field study with 64 homes using reclaimed water	Palm Harbor, Florida	44%	Nonintervention residential landscapes	SMS treatment effective at conserving water

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Davis and Dukes (2016)	Journal	ET and SMS	31-month study, three independent studies; smart controller study; two virtual tests	Gainesville, Florida	−51%	Timer	Virtual testing with controllers not physically connected to irrigation systems and unable to fully account for rainfall
DeOreo et al. (2016)	Report	N/A	4,643 customer survey responses; 2 weeks of potable meter usage from 762 customers	Arizona, California, Colorado, Connecticut, Georgia, North Carolina, Oregon, Pennsylvania, Florida, New Mexico, Nevada, Illinois, Texas, Washington, Alberta, and Ontario	N/A	N/A	In-ground irrigation systems were present in 53% of respondents, with smart controllers in 1%–8%; approximately 20% of homes overirrigated; outdoor irrigation accounted for the largest peak flows
Mayer (2016)	Journal	N/A	4,643 customer survey responses; 2 weeks of potable meter usage from 762 customers	Arizona, Californi, Colorado, Connecticut, Georgia, North Carolina, Oregon, Pennsylvania, Florida, New Mexico, Nevada, Illinois, Texas, Washington, Alberta, and Ontario	N/A	N/A	Irrigation use highly variable; follows consistent pattern with majority of homes applying at or below the theoretical irrigation requirement; small group of overirrigators accounted for bulk of excess irrigation
Tess (2016)	Report	ET and RS	12-month field study at three city test locations	Urbana, Illinois	Inconclusive	Timer	Inconclusive because high precipitation precluded need to irrigate for most of the study period
Torbert et al. (2016)	Report	ET and SMS	Field study of 167 homes and four commercial properties in sandy soils	Orange County, Florida	ET = 18%–32% (non-edu. and edu.); ET = 28% (commercial); SMS = 30%–42% (non-edu. and edu.)	Control group	Educational groups irrigate less due to optimized controller settings; post survey, majority satisfied; greater dissatisfaction with SMS versus ET
Chabon et al. (2017)	Journal	SMS	2-year field study in silty clay during cool season	Manhattan, Kansas	31%–70%	Timer	Larger savings in a wetter year
Kleinman (2017)	Conference	ET	Field study with 30 homes	Delaware, Ohio	12%	Control group	Peak day demand study found 43%–45% peak reduction
Mayer and Smith (2017)	Report	ET	Field study with 15 homes	New Jersey	N/A	N/A	Pilot-scale peak shifting experiment with remote interruption on two separate dates; estimated total of 318,000 L/day (84,000 gal./day) peak demand reduction
Morera et al. (2017)	Journal	ET and SMS	Survey of 167 customers, with 143 responding (86% response rate)	Florida	N/A	N/A	Controller satisfaction tied to satisfaction with appearance of landscape and perceived water-saving effectiveness

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Suh et al. (2017)	Journal	ET and SMS	Survey responses of 2,641 homeowners (88% response rate)	California, Florida, Texas	N/A	N/A	Study on perception and knowledge correlated with smart controller purchases; perceptions of conservation, restrictions, neighbors' habits, and sociodemographic variables influenced decisions to purchase
Vick et al. (2017)	Journal	ET and SMS	3-year field study with 36 homes	Catawba-Wateree River basin, North Carolina and South Carolina	ET increase; SMS = 30%; average = 21%	Timer	Savings largely negative, but SMS provided savings compared to baseline; water savings in highly controlled settings may not achieve equal benefits in residential applications
Mayer et al. (2018)	Journal	ET	Field study with 15 homes	New Jersey	N/A	N/A	Peak shifting experiment with remote interruption on two separate dates; estimated total of 318,000 L/day (84,000 gal./day) peak demand reduction
USBR (2018)	Report	ET and SMS	Review report	N/A	N/A	N/A	Smart controller overview and product features
Paxton et al. (2019)	Report	ET	1,400 free controllers installed	Spanish Fork, Utah	17%	Control group	Effective in peak demand reduction; update: 3,500 controllers installed through summer 2022
Zhang and Khachatryan (2019)	Journal	N/A	N/A	California, Florida, and Texas	N/A	N/A	Survey ($n = 3{,}000$); technology features focusing on the ease of use, reliability, and failure notifications are important and could increase adoption of controllers
Cárdenas et al. (2020)	Journal	SMS, ET	2-year university plots in fine sand	Gainesville, Florida	ET = 28%–64%; SMS = 51%–63%; app = 47%–56%	Timer	Compared ET and SMS control to smartphone app; to encourage adoption, need to highlight water-saving features
Conger and Dukes (2020)	Journal	WBIC	Virtual tests and 16 university plots	Citra, Florida (virtual), Balm, Florida (test plots)	43% average based on previous findings	N/A	Summary of SWAT and EPA WaterSense programs; water savings for high users but increased irrigation for underirrigators; unable to recreate the SWAT test using just the protocol documentation
Dukes (2020)	Journal	ET and SMS	Review paper	Various	Plot studies average = 51%; residential studies average = 30%	Various	Studies have expanded to multiple climates and various soil and plant types; 17 identified studies in the past decade, five reported negative savings, typically due to ET controllers improperly set up or maintained
Khachatryan et al. (2020)	Journal	N/A	Survey ($n = 3{,}000$) assessing consumer perceptions of smart irrigation technologies	California, Florida, Texas	N/A	N/A	Results indicate consumers value smart irrigation technology
Khachatryan et al. (2019)	Journal	N/A	Survey ($n = 3{,}000$) assessing consumer perceptions of smart irrigation technologies	California, Florida, and Teaxas	N/A	N/A	Findings suggest that sensor-based controllers are preferred over the alternatives

Appendix. (*Continued.*)

Study (listed chronologically)	Type	Technology	Conditions	Location	Savings	Savings comparison	Comments
Serena et al. (2020)	Journal	ET and SMS	2-year university plots in sandy loam	Las Cruces, New Mexico	29%–45%	Timer	Demonstrated that smart controllers can be effectively used in arid environments in both cool and warm seasons without negatively affecting landscape quality
Swanson and Fipps (2020)	Conference	ET	Virtual landscape over three seasons (summer, fall, winter) in various soil types	Texas	N/A	N/A	Nine controllers evaluated; inconsistent performance; each controller showed water savings compared to a standard timer; controller performance was better during summer
Cárdenas et al. (2021)	Journal	SMS, ET	5-year field study with 167 homes in sandy and flatwoods soils	Orange County, Florida	17% to 31% (ET); 18% to 42% (SMS)	—	Review of past studies; SMS more efficient; demonstrated long-term ability of SMS and ET controllers to be effective
Haghverdi et al. (2021a)	Journal	ET	3 years, 36 university plots in fine sandy loam soil	Parlier, California	39% to 103% of theoretical ET	N/A	75% theoretical ET irrigation application could maintain hybrid bermudagrass quality; deficit irrigation could sustain quality for shorter durations before falling below minimum acceptable threshold
Haghverdi et al. (2021b)	Journal	ET	2 years, 36 university plots in fine sandy loam soil	Parlier, California	N/A	N/A	Limiting watering to specific days each week (common strategy of California drought response) did not provide substantial water savings
USEPA (2021)	Report	SMS	N/A	N/A	N/A	N/A	Potential SMS performance based on system being properly designed, installed, and maintained; controller being properly programmed; and user monitoring water use and landscape healthier for periodic adjustments; nationally, potential for 1.77 trillion L (390 billion gal.) of water savings

Note: SWAT = smart water application technologies; and edu. = educational.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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