EMERGING TECHNOLOGIES FOR SUSTAINABLE IRRIGATION: SELECTED PAPERS FROM THE 2015 ASABE AND IA IRRIGATION SYMPOSIUM

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A Tribute to the Career of Terry Howell, Sr.

ABSTRACT. *This article is an introduction to the "Emerging Technologies in Sustainable Irrigation: A Tribute to the Career of Terry Howell, Sr." Special Collection in this issue of* Transactions of the ASABE *and the next issue of* Applied Engineering in Agriculture*, consisting of 16 articles selected from 62 papers and presentations at the joint irrigation symposium of ASABE and the Irrigation Association (IA), which was held in November 2015 in Long Beach, California. The joint cooperation on irrigation symposia between ASABE and IA can be traced back to 1970, and this time period roughly coincides with the career of Dr. Howell. The cooperative symposia have offered an important venue for discussion of emerging technologies that can lead to sustainable irrigation. This most recent symposium is another point on the continuum. The articles in this Special Collection address three major topic areas: evapotranspiration measurement and determination, irrigation systems and their associated technologies, and irrigation scheduling and water management. While these 16 articles are not inclusive of all the important advances in irrigation since 1970, they illustrate that continued progress occurs by combining a recognition of the current status with the postulation of new ideas to advance our understanding of irrigation engineering and science. The global food and water challenges will require continued progress from our portion of the scientific community. This article serves to introduce and provide a brief summary of the Special Collection.*

Keywords. *Center-pivot sprinkler irrigation, Deficit irrigation, Evapotranspiration, Irrigation management, Irrigation scheduling, Microirrigation, Sensors, Sustainability, Turf and landscape irrigation, Variable rate irrigation.*

On November 9 through 11, 2015, in Long Beach, California, ASABE and the Irrigation Association (IA) jointly convened a symposium entitled "Emerging Technologies for Sustainable Irrigation: A Tribute to the Career of Terry Howell, Sr." This symposium had some similarities to other joint conferences held by ASABE and IA, such as the decennial national irrigation symposia held in 1990, 2000, and 2010 that were discussed by Dukes et al. (2012), the 1995 Fifth Microirrigation Congress, and the 1996 Evapotranspiration and Irrigation Scheduling International Conference. The conference title seemed fitting, as all along the career of Dr. Howell, which spanned six decades, reliable and robust irrigation technologies (both hardware and management strategies) were emerging and helping irrigation, an alteration of the rural and urban environment, to become more sustainable. The authors believe that these aspects (i.e., emerging technologies and sustainability) continue and will need to continue as we strive to provide the global community with food, fiber, greenspace, and forestry products, while providing stewardship of the earth's natural resources.

The irrigated land area has continued to increase slightly in the U.S., but with a migrating geographic location (fig. l). While irrigation remains most heavily concentrated in the semi-arid and arid western U.S., Arkansas and Mississippi now have the third and ninth largest irrigated land areas, respectively (USDA-NASS, 2012). Irrigated land area in the period 1998 through 2012 increased by only 6.4% in the top ten irrigated states while experiencing a

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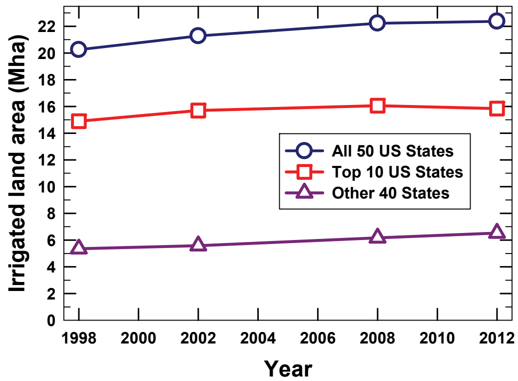

Figure 1. Irrigated land area in the U.S., the top ten irrigated states and the remaining 40 states during the period 1998 to 2012. Data from USDA-ARS Farm and Ranch Irrigation Surveys (USDA-NASS, 1998, 2002, 2008, 2012).

22.0% increase in the remaining 40 states (fig. 1). From 2008 to 2012, irrigated land area actually decreased by 1.3% in the top ten irrigated states and increased by 5.8% in the remaining states. These geographic shifts may be occurring for several reasons, such as increasing competition for water resources in the western U.S. (e.g., rural/urban priorities, extended drought, reservoir management for multiple uses, overdraft of aquifers, etc.) and the increasing desire in the eastern semi-humid and humid regions to mitigate crop production risks due to drought or poor soil water-holding capacities. As crop yields rise due to increasing use of appropriate crop genetics and cultural technologies, it is only logical that irrigation will be desirable to mitigate crop water constraints. Additionally, increases in commodity crop prices periodically spur further irrigation development and technology improvements. These changes in U.S. irrigation emphasize that emerging technologies will continue to be needed in the water-stressed western areas to optimize water productivity (crop per drop), but also in the areas where irrigation is increasing, and may require further adaptation or even newer approaches to irrigation management. Sustainability of irrigation will continue to be important, and its necessity will only grow as we address a growing world population and impending climate change.

Dr. Howell's research career focused on evapotranspiration (ET) determination and measurement to improve water productivity, irrigation systems and their associated technologies, and irrigation scheduling and water management (Howell, 2015). As these are core topics for irrigation engineers and scientists, it should not be surprising that nearly all of the 62 papers presented at the 2015 ASABE and IA symposium dealt with these issues. For the first time within ASABE, the authors of these papers had the option of seeking simultaneous dual publication in the symposium proceedings and through the journal peer-review process. A total of 16 papers were published in both media, and those selected works are summarized in the following sections along with related key highlights from the career of Dr. Howell.

Evapotranspiration Measurement and Determination

Although Dr. Howell's whole career is closely associated with evapotranspiration (ET) measurement and determination, some of his earlier efforts were natural progressions of his early 1980s exposure to the emerging California Irrigation Management Information System (CIMIS) and to his excitement in waking up each morning to alarm clock radio reports of calculated potential ET (Howell, 2015). A desire for better ET measurements for the San Joaquin Valley led to the construction and installation of two large weighing lysimeters in California (Howell et al., 1985), which set the path for future development of the extensive lysimeter facilities at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas (Marek et al., 1988; Schneider et al., 1988; Evett et al., 2016). The lysimeter facilities at Bushland and the associated research efforts are summarized by Evett et al. (2016). Those research accomplishments include development of crop coefficients for the major crops of the Southern High Plain, improvements in determination of reference ET and associated algorithms; field-scale crop simulation modeling; development, testing, and improvement of both ground-based and remote sensing equipment; and methodologies associated with ET determination.

Accurate partitioning of ET into its two components, evaporation (E) and transpiration (T), is important when comparing the effectiveness of different types of irrigation systems and in evaluating strategies aimed at increasing water use efficiency (WUE) or crop water productivity (WP). A two-source energy balance (TSEB) model, initially developed by Norman et al. (1995) and Kustas and Norman (1999), can be used for direct calculations of E and T, which cannot be done with single-source ET models. Recent physically based advances of the TSEB model were tested in field studies on cotton and are reviewed by Colaizzi et al. (2016). The advances were tested using independent measurements of E, T, and ET from microlysimeters, sap-flow gauges, and weighing lysimeters, respectively, at Bushland, Texas. Calculation errors of E and T using the new approach were greatly reduced (>70%) compared to previous TSEB model versions.

Rice is a major U.S. crop, but it currently uses great amounts of freshwater and is considered one of the major crop contributors to greenhouse gas production. Eddy covariance techniques were used by Reba and Counce (2016) to quantify H_2O and CO_2 fluxes for rice at the field scale in the largest rice-growing region in the U.S., the lower Mississippi River basin. The researchers found that the maximum rice crop ET was approximately 6.1 mm d^{-1}, occurring during the later vegetative stages, and that there was a net CO_2 influx to the rice plants during the production season. These findings show that both plant growth stage and management impacted measured H_2O and CO_2 fluxes.

Turfgrasses are an integral part of landscape ecological systems worldwide, and the U.S. land area in turfgrasses, estimated to be approximately 16.4 million ha (Milesi et al., 2005), uses a considerable amount of water resources. A review of turfgrass evapotranspiration (ET_c) and crop coefficients (K_c) for both warm-season and cool-season grasses is provided by Romero and Dukes (2016a) for different locations across the U.S., as well as a discussion of the methods used to determine or estimate these values. A great amount of variability in both ET_c and K_c between and within turfgrass species was reported, as was substantial changes in both that occur during the growing season. The authors conclude that although published ET_c and K_c values may be helpful in irrigation scheduling of turfgrasses, they should be used with caution and with an understanding of the local conditions under which they were developed.

Irrigation Systems and Associated Technologies

Although a change in irrigation systems or associated technologies does not automatically result in improvements in water use and sustainability, improved management capabilities inherent in the technology are often associated with such improvements when coupled with greater human engagement and decision making. In an oral presentation in 2002, Dr. Howell posited that one of the principal reasons that pressurized irrigation systems, such as center-pivot (CP) systems and subsurface drip irrigation (SDI), are considered easier to manage than surface irrigation is because they remove the relatively complex surface water transport phenomena from management considerations.

Center-Pivot Sprinkler Irrigation

In the U.S., the majority of irrigated cropland uses CP sprinkler irrigation. The amount of land irrigated using CP systems has increased by 0.91 million ha while the number of farms using CP systems has increased by 7.5% during the period 2008 through 2012 (USDA-NASS, 2012). Much of this increase has resulted from converting surface and other types of sprinkler systems to medium- and low-pressure CP systems, which can have greater uniformity and application efficiency and thereby increase WUE. Improved designs and management of these CP systems reduces the potential for water losses and other off-target applications that would negatively affect WUE, runoff, and soil erosion.

The effectiveness of sprinkler irrigation in minimizing water losses requires both selection of appropriate sprinkler hardware and implementation of appropriate management for the crop, soil, landscape, and weather conditions. Many types of sprinkler nozzles can be selected for CP and lateral-move sprinkler irrigation systems, and their advantages and disadvantages with regard to water losses were discussed by Howell (2006). Although there is growing interest in lower-pressure sprinkler systems with applications within or near the crop canopy to potentially save energy and reduce evaporative losses, their effectiveness can be greatly affected by their increased runoff potential (Howell and Evett, 2005; Howell, 2006). A soil-independent, quantitative runoff-potential index has been developed by King (2016) to facilitate selection of moving spray-plate sprinklers for CP and lateral-move sprinkler irrigation systems. The methodology was evaluated for a number of commercially available sprinkler packages. The results indicated that substantial differences exist, and several packages can have similar runoff potential. The runoff index provides an effective means for comparing sprinkler choices by identifying sprinklers with large droplets and relatively small wetted diameters.

Management of CP systems through site-specific variable-rate irrigation (VRI) offers potential to further improve and refine WUE within a crop field by more closely managing crop evapotranspiration, which can be affected by numerous factors, including crop type, irrigation method, weather, crop condition, cultural practices, and soil properties (O'Shaughnessy et al., 2016). A discussion of recent advances in site-specific VRI platforms for CP and a description of a conceptual framework for such systems is provided by O'Shaughnessy et al. (2016). In this supervisory control and data acquisition (SCADA) framework, integrated soil and plant sensors within a wireless communication system provide inputs for algorithms to control and manage the VRI system and to improve the spatial WUE. The authors further discuss three topic areas or applications of site-specific VRI that have already successfully improved spatial WUE: optimizing irrigation application depth within the field, managing crop water stress under deficit irrigation, and adjusting irrigation management spatially in relation to the presence of crop disease and its severity.

Although the use of site-specific VRI systems is growing, there is less understanding of how management of these systems should be optimized for wise use of natural resources and increased farm profitability. A traditional statistical analysis using analysis of variance was compared to a Bayesian semiparametric model for assessing the spatial variation in corn yields as affected by site-specific VRI (Stone and Sadler, 2016). Although both statistical methods resulted in similar analysis conclusions, the researchers indicated that the Bayesian model, which was more spatially explicit, preserved more accuracy in the estimations of actual recorded yields and should be considered more robust and scientifically acceptable. Stone and Sadler (2016) conclude that this technique could provide additional insights into the spatial responses of crops to spatially variable irrigation, thus providing irrigation system managers and designers with improved tools for site-specific VRI management.

Microirrigation

Dr. Howell's involvement with microirrigation can be traced back to his graduate school days, with his research using mist irrigation for crop production (Howell et al., 1971; Hiler and Howell, 1973; Howell and Hiler, 1974a, 1974b) and his senior authorship of the microirrigation chapter for ASAE Monograph No. 3 (Howell et al., 1980). Although the U.S. land area in microirrigation is only about 14% of the amount of sprinkler-irrigated land (USDA-NASS, 2012), it continues to grow, and microirrigation still constitutes an emerging technology in some regions. From 2008 to 2012, drip irrigation increased by nearly 0.46 million ha in the U.S. (USDA-NASS, 2012).

Surface drip irrigation (DI) comprises the overwhelming microirrigation land area, but subsurface drip irrigation (SDI) has increased substantially in the past ten years. Over 93% of the SDI land area is concentrated in ten states (USDA-NASS, 2012). In some of these states, SDI is the primary microirrigation method, rather than DI. This is attributed to those states' greater production of lesser-value commodity crops, for which a deeper, multiple-year SDI system, which can be amortized over several years, is often the only economical microirrigation option for a producer (Lamm, 2016). Although SDI has been considered the most appropriate microirrigation system for row-crop applications since the 1970s (Hanson et al., 1970; Mitchell and Tilmon, 1982; Howell, 2015), limitations in SDI materials and in knowledge of SDI initially made any large-scale advances difficult (Zetzsche and Newman, 1966; Mitchell, et al., 1969; Camp, 1998; Howell, 2015). In a review of SDI production of four crops (cotton, tomato, corn, and onion), Lamm (2016) reports moderate or larger yield increases over alternative irrigation systems for cotton, processing tomato, and onion, with the latter two crops obtaining differences particularly in marketable yield and quality. This was not the case for field corn, for which a review of 12 studies averaged little or no differences between SDI and alternative systems. Design parameters such as dripline spacing and installation depth are also discussed for the four crops, along with combined irrigation and nutrient management.

Microirrigation systems can be used with lower-quality water that may contain biological contaminants. Shock et al. (2016) evaluated the potential of using water containing moderate levels of *E. coli* for both subsurface drip-irrigated and furrow-irrigated onion for fresh market consumption. They found that the silt loam soil retained most of the *E. coli* close to the water entry point into the soil for both irrigation systems. However, a small fraction of the *E. coli* was found in the soil immediately adjacent to the onion bulbs, although no *E. coli* uptake was detected within the bulbs. Although more research may be needed, it may be safe and practical to use the soil as a filter for *E. coli* for onion production when using furrow and subsurface drip irrigation.

Traditionally, nutrient fertilization through microirrigation systems is only recommended for systems with a design emission uniformity of 70% or greater, depending on system characteristics (ASAE, 2003). However, spatial variability in the soil can greatly affect the ultimate nutrient distribution in the soil (Wang et al., 2016). Using simulation, the researchers found that spatial variabilities in saturated hydraulic conductivity, saturated water content, and the initial soil water and soil nitrate contents all resulted in significant differences in nitrate leaching. Wang et al. (2016) conclude that microirrigation system uniformities as low as 60%, although lower than the current standards, may be acceptable in terms of nitrate leaching, as the soil spatial variability may dampen the uniformity effects of the microirrigation system.

SMART CONTROLLERS FOR LANDSCAPE IRRIGATION

Although Dr. Howell's career focused on irrigation of agricultural crops, much of his work with establishment of micrometeorological weather stations (Howell et al., 1984), evapotranspiration measurement (Howell et al., 1985, 1995; Marek et al., 1988; Schneider et al., 1988; Howell et al., 2004; Farahani et al., 2007), remote sensing (Gowda et al., 2007), and irrigation management (Howell et al., 1987a, 1987b; Unger and Howell, 1999) is closely related regardless of the type of plant. Irrigation of home lawns and landscapes can greatly impact municipal potable water supplies. In most municipalities, it is difficult to separate indoor and outdoor water use. To get a more accurate estimation of outdoor water use, Romero and Dukes (2016b) tested methods for separating indoor and outdoor water use using municipal potable meter data for single-family homes in Florida. Two methodologies were compared for estimating indoor water use: a method in which the minimum monthly use (presumably winter) was assumed to represent indoor use, and a second method based on a per-capita use of 250 L d^{-1}. While indoor use was overestimated by 140% and underestimated by 34% by the minimum month and per-capita methods, respectively, the corresponding outdoor use (i.e., irrigation) calculated by the per-capita method was underestimated by 5% to 19% for an additional 5% and 15% assumed impervious area, respectively. The authors conclude that the per-capita method will result in the most reliable estimates of indoor and outdoor water use for central Florida conditions.

Davis and Dukes (2016) evaluated how end-user programming in a particular brand of ET controller might affect residual landscape irrigation amounts and performance. The controllers they evaluated (i.e., the original model and a model with updated firmware) did not fully account for rainfall and consequently consistently over-irrigated the landscapes, although there were substantial reductions in over-irrigation with customized programming. The inaccuracy in rainfall accounting might result in over-irrigation of 50% to 100% greater than the gross irrigation requirement in that region of Florida, so the authors conclude that better rainfall accounting would be extremely beneficial to overall water conservation and water use efficiency.

With the increasing demands on freshwater resources, the use of reclaimed water for landscape irrigation has gained considerable interest in many parts of the U.S. Landscape irrigation controllers that incorporate soil moisture sensors (SMS) for feedback control can have improved performance, but there has been concern about using SMS with reclaimed water, which can affect the soil dielectric permittivity and thus affect the SMS values. In a controlled field-plot study, Cardenas and Dukes (2016a) compared time-based irrigation control to control incorporating one of four different SMS as affected by both potable and reclaimed water. Water savings using SMS controllers averaged 63% and 59% for the potable and reclaimed water sources, respectively, compared to irrigation control without SMS. The authors conclude that the small accuracy reduction in SMS when using reclaimed water would be acceptable. This study led them to a second study that implemented one of the SMS controllers in residential landscape settings (Cardenas and Dukes, 2016b) that used reclaimed water. In a study involving 64 homes in Palm Harbor, Florida, that was conducted for a 32-month observation period, the homes that used SMS-based control had statistically significant water savings, averaging 44%, as compared to the homes that were monitored only for water use.

Irrigation Scheduling and Water Management

Dr. Howell is a recognized expert in irrigation scheduling, having written two book chapters on the topic (Howell et al., 1986; Howell and Meron, 2007), and he was asked to give a keynote presentation on the topic at the 1996 ASAE and IA joint conference on evapotranspiration and irrigation scheduling (Howell, 1996). Although modern science-based irrigation scheduling has existed for approximately 60 years, with one of the first reports by Van Bavel (1956), the long-term and consistent adoption of appropriate irrigation scheduling has been dismal (Shearer and Vomacil, 1981; Lamm and Rogers, 2015). To facilitate better adoption rates and improved irrigation scheduling, Migliaccio et al. (2016) developed a software application (i.e., smartphone and tablet app) to provide real-time irrigation schedules for various crops (avocado, citrus, cotton, peanut, strawberry, urban turf, cabbage, squash, tomato, and watermelon) in the southeastern U.S. The application can use real-time weather data from both the Florida Automated Weather Network and the Georgia Environmental Monitoring Network to calculate crop ET using a water balance method for scheduling irrigation. The software inputs vary by crop, but nearly all scenarios require root depth, irrigation rate, and soil type. Similarly, a variety of output information is available to better serve the needs of irrigators.

Many areas of the U.S. are experiencing water shortages, and irrigators often cannot meet the full crop water needs using their current irrigation and cropping system scenarios. As a result, many producers are implementing strategies such as deficit irrigation to address water shortages. The CERES-Maize crop model was used by Kisekka et al. (2016) to examine several deficit-irrigation strategies for corn production in southwest Kansas. Their modeling combined experimental results from field studies and long-term weather data to evaluate management-allowable depletion (MAD) for corn, the optimum level of plant-available soil water at planting, and the irrigation season termination criteria. They found that irrigation scheduling based on a 50% plant-available soil water threshold (MAD) maximized net returns compared to initiating irrigation at a greater soil water content, that it was important to have adequate soil water reserves at planting (<25% depletion from field capacity), and that terminating irrigation at 90 to 95 days after planting maximized net economic returns. Although the simulation results were specific to the region, the authors suggest that the simulation techniques can be applied in other areas with constrained water supplies for irrigation.

Concluding Statements

Dr. Howell's contributions to irrigation engineering and science encompass three major topic areas: evapotranspiration measurement and determination, irrigation systems and their associated technologies, and irrigation scheduling and water management. Some of the articles in this Special Collection present a review of past efforts and the current status in these topic areas, while other articles discuss promising opportunities to advance our knowledge in these topic areas. This scope emphasizes that the status of irrigation engineering and science should be considered a continuum, with emerging technologies building on earlier knowledge and progress, and hopefully leading toward sustainable irrigation that will be necessary to provide food, fiber, greenspace, and forestry products for an increasing world population.

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