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Protecting Groundwater Quality

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Editor's Note: This paper was presented during the 2014 USCID Water Management Conference in Sacramento, and is included in the Conference Proceedings.

Nitrate pollution of groundwater is a common problem in agriculture resulting from nitrate applied as fertilizer or animal waste being transported by deep percolation losses from irrigation and rainfall (Bouwer, 1989). In humid areas deep percolation results primarily from rainfall, while in arid and semi-arid areas deep percolation is the result of the application of excess irrigation water or poor distribution uniformity. Other sources of nitrate include municipal wastewater and sludge (Artiola, 1991), food processing waste and leachate from septic systems.

The hypoxic zone in the Gulf of Mexico created at the mouth of the Mississippi River was caused in part by nitrate drained from areas in the upper mid-west (Rabalais et al., 2007; Burkart and James, 1999). This area is a primary production area for field crops, e.g., corn and soybeans and is heavily fertilized. The uncontrolled drainage discharge into the Mississippi River is the primary source of agricultural nitrate being

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Canal Automation

Program Set for Phoenix Conference

New advances in canal automation will be the focus of the **USCID Fall Conference**, to be held December 2-5, 2014, in Phoenix, Arizona. The theme is *Planning, Operation and Automation of Irrigation Delivery Systems*. The Conference will feature the work of the EWRI Task Committee on Recent Advances in Canal Automation, and participants will receive the just-published *ASCE Manual of Practice 131: Canal Automation for Irrigation Systems*.

Several noted U.S. and international experts in the field will speak during the Conference. The Opening Plenary Session will feature presentations by

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New USCID Secretary, Board Members

During its annual meeting in May, the USCID Board elected **Brian T. Wahlin**, WEST Consultants, Inc., as Secretary. **Bryan P. Thoreson** continues as President.

In recent balloting, **Steven C. Macaulay**, **Samuel L. Schaefer** and **Delbert M. Smith** were elected to three-year terms on the USCID Board of Directors. Each was elected to his first term. A Tellers Committee of Thomas E. Mitchell, Tony L. Wahl and Larry D.

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President's Message

During the upcoming USCID Conference in Phoenix in December, it will be my privilege to present the *USCID Merriam Improved Irrigation Award* and the *USCID Service to the Profession Award* to two outstanding professionals nominated by our members. If you haven't already, please send your nominations to USCID Executive Vice President **Larry Stephens**. I'm also looking forward to presenting the $1,000 *USCID/Summers Engineering Scholarship* to an outstanding university student soon to become one of our future leaders. For more information, see page 20.

By the time this newsletter is in your mailbox, the technical program for the **Conference on Planning, Operation and Automation of Irrigation Delivery Systems** will be available at www.uscid.org. The technical program will include a panel on irrigation district modernization, featuring district managers from throughout the West. As described in the accompanying article, this Conference is in cooperation with the Task Committee on Recent Advances in Canal Automation, Environmental and Water Resources Institute, ASCE. Conference attendees will be the first to receive, hot off the press, the Canal Automation Manual prepared by the EWRI Task Committee.

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Inside . . .

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Mission Statement

The Mission of USCID is to promote progressive and sustainable irrigation, drainage and flood control practices in support of food and fiber production and public safety, recognizing that sustainability embodies economic, social and environmental goals.

USCID Newsletter and Membership

The *USCID Newsletter* is published in Winter, Spring and Fall for USCID Members. News items and technical articles of interest to the irrigation community are invited. Membership information is available on the USCID website.

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ICID News and Activities

ICID·CIID

ICID Annual Report Issued

The 2013-2014 ICID Annual Report was recently published, and may be downloaded from the ICID website: http://www.icid.org/annualreport.html. The following timeline events were taken from the Report:

1950-1960

Established on June 24, 1950, with 11 founding member countries

First IEC meeting in India, 1950

ICID Bulletin started, 1952

1961-1970

Central Office building dedicated by vice president of India, 1966

Multilingual Technical Dictionary released, 1967

1971-1980

First Irrigation and Drainage Workshop, Wageningen, The Netherlands, 1978

Silver Jubilee celebrated, 1975

1981-1990

N.D. Gulhati Lecture Series started, 1981

Received UN Peace Messenger Award, 1987

IPTRID started, 1990

1991-2000

New logo debuts, 1992

Young Professional Forum established, 1994

Start of WATSAVE Awards, 1998

Launch of website, 1999

International Micro Irrigation Congress taken over by ICID, 2000

2001-2010

ICID Journal renamed *Irrigation and Drainage*, 2001

Released Multilingual Technical Dictionary on CD-ROM, 2001; 2nd Edition, 2010

Established Awards for Best Performing National Committee and Work Body, 2003

2011- 2014

ICID e-Bulletin started (English and French), 2012

Established World Irrigation and Drainage Prize, 2012

Established Scholarships for Young Professionals, 2013

Organized First World Irrigation Forum, 2013¤


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Oakdale Irrigation District, California

Protecting Groundwater Quality (continued)

transported to the Gulf of Mexico. Efforts to control this source will require modifications in drainage system design (Burchell et al., 2005) and management of drainage systems (Bjorneberg et al., 1996; Greenan et al. 2009; Luo et al., 2010; Lalonde et al., 1996). It will also require changes in fertilizer management.

Groundwater in the San Joaquin Valley is affected by nitrate pollution from agricultural sources including perennial crop (Nightingale, 1972; Pratt et al., 1972; Dasberg et al., 1984), animal manure from dairy operations, and food processing wastes. Deep percolation losses from irrigation are the transport mechanism that moves the nitrate to the groundwater.

Furrow irrigation is the predominate method of irrigation throughout the world and in the San Joaquin Valley. Furrow irrigation is an inefficient method if not properly designed and operated. Proper design and operation would include having the correct furrow length, a uniform slope across the field, and adequate flow for the field size. It would include proper timing and duration of the irrigation. However, these conditions are not routinely met; and, as a result, there is poor distribution uniformity and excess application of water. Often, the irrigation duration is set by water availability (rotation within district) rather than actual need. The end result is that deep percolation losses are common.

Irrigation with water from lagoons containing animal and food processing waste high in nitrate is another problem, because the supply may exceed the demand for water and nitrogen. This may result in excess water being applied just for disposal resulting in deep percolation and nitrogen movement to the groundwater.

In the San Joaquin Valley, as result of extended periods of drought and limitations on the available water supply, there has been a gradual shift in irrigation from gravity driven methods (surface irrigation) to pressurized systems, sprinkler and microirrigation (drip and microsprinklers). Pressurized systems have the advantage of better control on the depth of applied water and better control on the uniformity of applied water. The initial shift was to high value crops that supported the additional cost of the systems. As the technology has improved, drip irrigation has been implemented on high value vegetable crops (lettuce, peppers, processing tomato) as well as perennial crops, trees and vines.

Drip irrigation has proved to be a very efficient irrigation method that allows good control on the depth and timing of irrigation as well as controlling fertilizer applications. It also allows for high frequency irrigation from daily to several times a day (Phene et al., 1989). This compares to weekly irrigation or longer intervals using surface irrigation. The increased frequency of irrigation allows smaller depths of applied water reducing the potential for deep percolation losses. Frequent irrigation also allows for the application of small amounts of fertilizer during irrigation which reduces the potential for nutrient loss.

Research has demonstrated enhanced plant growth, improved yields and crop quality using drip irrigation (Bryla et al., 2003; Ayars, 2007; Ayars et al., 1999; Hanson et al., 2006; McNiesh et al., 1985). Other advantages of drip irrigation include improved pest management, better weed control, automation (Ayars and Phene, 2007, Phene et al., 1989), and improved farm operations. Disadvantages include higher cost, filtration requirements, a fixed row spacing that may limit crops that may be grown, and installation and removal for annual crops.

Drip irrigation has been further categorized as either surface or subsurface drip. As the names imply, surface drip is laid on the ground surface in a variety of configurations depending on the crop. It may be positioned half way between two rows so water is supplied to two plant rows with one line or simply adjacent to each row. Surface drip systems require annual installation and removal which adds an additional cost to the system. It does allow for variable row spacing and field length.

Subsurface drip irrigation **(SDI)** is the installation of drip tubing at depths below the soil surface ranging from 2 to 15 inches depending on the crop (Phene et al., 1987). The shallow depths are used for vegetable crops grown on beds (Zotarelli et al., 2008; Zotarelli et al. 2009; Stork et al. 2003), so that the tubing can be removed easily after harvest. Deeper installations are used for perennial crops and field crops (Hutmacher et al., 1996; Lamm et al. 1995; Hanson et al., 2006) and will remain in place for several years (Ayars et al., 1999). Permanent installation of the drip tubing restricts the cropping to a fixed row spacing for future crops. It does however protect it from damage by machinery and animals. Subsurface drip also limits the amount of water applied during a single application. Excessive water application results in water moving to the surface which defeats the purpose of burial of the drip line (Lamm and Camp, 2007).

One major advantage of SDI is that both water and nutrients are applied directly to the crop root zone, which facilitates uptake of both water and nutrients (Phene et al., 1991; Phene et al., 1987; Phene et al., 1993; Tarkalson and Payero, 2008; Stork et al., 2003). High frequency application water enables good control of the soil matric potential which will minimize deep percolation losses (Phene et al., 1989). Effective control of **SDI** has been demonstrated using soil matric potential sensors particularly in light textured soils (Zotarelli et al., 2008; Zotarelli et al., 2009).

Deep percolation losses result when the hydraulic gradient is dominated by gravity and not the soil matric potential. This requires that the soil water content be maintained at a level less than field capacity. Soil matric potential sensors can be used to provide feedback to automate a SDI system to maintain water content at a level to prevent deep percolation (Ayars and Phene, 2007).

This paper describes a field project determining the nitrogen requirements for a developing pomegranate orchard that is being irrigated by both surface and subsurface drip using high frequency applications.

Materials and Methods

This project is located on the Kearney Agricultural Research and Extension Center (KARE) and uses a 3.54-acre pomegranate orchard (*Punica granatum, L* var. Wonderful) that includes a large weighing lysimeter (Phene et al., 1991, Ayars et al., 2003). This lysimeter is used to determine the water use for the fully irrigated (100 percent) subsurface drip irrigation with adequate nitrogen (N_2) treatment and to automatically manage the hourly irrigation scheduling of both the DI and SDI systems. Irrigation is initiated when 0.04 inches of water is lost as measured by the lysimeter. The lysimeter is equipped with a drainage management system capable of measuring 0.002 inches of drainage water for sampling for nutrient analysis. Water applied to the DI treatments is increased by 10 percent to account for evaporation from the soil surface and water used by weeds. The lysimeter tree is irrigated using a SDI system with the same number of emitters per tree as the rest of the orchard. Trees were planted with rows spaced 16 feet apart and trees in the rows spaced 12 feet along the row. The orchard is laid out in a complete randomized block with sub-treatments and 5 replicates. The main irrigation treatments are DI and SDI (installed at 20-22-inches depth) systems with dual drip irrigation laterals, each 3.5 feet from the tree row. The fertility sub treatments are 3 N treatments (50 percent of adequate N, adequate N, based on biweekly tissue analysis and 150 percent of adequate N, all applied by variable injection of N-pHURIC (10 percent N as urea, 18 percent S), AN-20 (10 percent NH_4-N and 10 percent NO_3-N). Potassium thiosulfate (K_2T, 25 percent K from K_2O and 17 percent S) and phosphorus (from H_3PO_4, PO_4-P) are supplied by variable injection of P=15-20 ppm and K=50 ppm to maintain adequate uptake levels. The pH of the irrigation water is automatically maintained at 6.5+/-0.5 and both pH and EC_w are measured by the control system. Tree and fruit responses are determined by canopy measurements, bimonthly plant tissue analyses and fruit yield and quality. Soil samples are collected three times a year in 6 inch increments from the surface to 48 inches in depth to determine nutrient distribution. Analysis of variance (ANOVA) for the Randomized Complete Block Design (RCBD) with sub-samples will be used to determine the treatment significance.

Table 1. Components of the pomegranate water balance.

Year	ET_o	Precipitation	SDI Irrigation	DI Irrigation	ET_c**	Drainage	Runoff
2010	49.73	17.34	1.00	1.0	2.10	No data	0
2011*	50.9	10.42	8.49	8.49	9.8	0	0
2012	54.6	8.97	16.8	18.6	19.7	0	0
2013***	54.0	2.98	26.3	28.9	28.5	0	0

Notes: All units are inches.
*2011 ET_c values from May 1 to December 8 only.
**Lysimeter ET_c adjusted for orchard spacing.
***2013 values until December 14.

Results and Discussion

Pomegranate Water Balance

Table 1 shows the components of the water balance from May 1, 2010, until July 30, 2013. Reference evapotranspiration (ET_0) was taken from CIMIS weather station located on KARE. The crop water use (ET_c) came from the lysimeter and was adjusted for tree spacing. Precipitation came from the CIMIS station while drainage was measured in the lysimeter and there was no runoff. We matched the crop water requirement with the high frequency irrigation. No drainage was measured from the lysimeter when 10 inches of rain was recorded in 2011, 8.97 inches 2012, and 2.36 inches 2013. This means that most of the rain was stored in the profile and used by the pomegranate tree.

Yields, Water Use Efficiency and Nitrogen Use Efficiency from 2012 Pomegranate Harvest.

Pomegranate prime fruits were harvested by a local packer on 10/30/12 and for juice on 11/8/12. Sub-samples were harvested from the five center trees of each of the five yield rows and measured for total weight and quality. Results from harvests are shown in Table 2 and indicate a significant yield increase due to the SDI system but none from the nitrogen treatments. Much of the yield increase was due to the larger size fruit in the SDI treatment.

Effects of irrigation and nitrogen treatments on WUE and NUE of pomegranate are shown in Table 3. The SDI treatment increased the WUE for the "Prime" pomegranate but not for the "Juice" fruits. Even though there was no statistical difference the NUE was improved for the SDI compared to DI. Also, the NUE was reduced as the applied N increased from N1 to N3. There was a large decrease in NUE from N1 to N2. The difference in applied nitrogen was a reduction of 102 pounds per acre, which only resulted in a loss of 300 pounds of fruit per acre.

Soil Matric Potential Measurements and Hydraulic Gradient Calculations in the SDI Irrigated Lysimeter

With the concern for transport of nitrate to the groundwater, it is essential to quantify the movement of NO_3 through and below the crop root zone. To do this we used heat dissipation soil matric potential (SMP) sensors installed in two columns of 4 SMP sensors each at depths of 24, 36, 48, and 60 inches from the soil surface. These SMP's provide the SMP status in the lysimeter and are used to calculate the hydraulic (SMP) gradient (HG) to infer the leaching potential under high frequency SDI (Phene et al., 1989). If needed to obtain the HG subtract 1 from the SMP values. Figure 1 shows the calculated daily averaged SMP gradient (HG) from March 26, 2013 to August 10, 2013

Table 2. Effects of irrigation and nitrogen treatments on pomegranate yields.

Total Marketable Yield 10/30 – 11-/08/12	Harvest #1 Prime Fruit 10/30/12		Harvest #2 Juice Fruit 11/08/12		Harvest #2 Non-Marketable 11/08/12	
Main Effects Irrigation Method: **(lb/ac)**	Yield (lb/ac)	Fruit Wt. (lb)	**Yield** (lb/ac)	Fruit Wt. (lb)	Cracked (lb/ac)	Undersized (lb/ac)
Surface Drip (DI) 18,738 b	9967	1.18 b	8771	0.80 b	698	299
Subsurface Drip (SDI) 20,631 a	11561	1.29 a	9070	0.86 a	598	399
Prob > "F" value 0.0548	0.067[y]	0.0002	NS	0.032	NS	NS
Nitrogen Level						
N1 - 46 (lb/ac) 19,036 (lb/ac)	10,365	1.19	8671	0.79	897	199
N2 - 148 lb/ac) 19,335 (lb/ac)	10,963	1.27	8,372	0.82	698	299
N3 - 249 lb/ac) 20,432 (lb/ac)	10,864	1.25	9,568	0.83	399	399
Prob > "F" value **NS**	NS[z]	NS	NS	NS	NS	NS
Contrast						
1 vs 2 and 3	NS	0.006	NS	0.045	NS	0.025
Polynomial Fit	-	L*SD	-	L 0.09SD	-	L*D

Table 3. Effects of irrigation and nitrogen treatments on WUE and NUE of pomegranate.

Treatments	WUE-Prime lb/ac/in	WUE-Juice lb/ac/in	NUE-N1 lb fruit/lb N/ac	NUE-N2 lb fruit/lb Nac	NUE-N3 lb fruit/lb N/ac
DI SDI	554 a 680 b	487 a 534 a	217 251	67 78	40 46
% SDI Increase	23	9	15.7	16.4	15.0

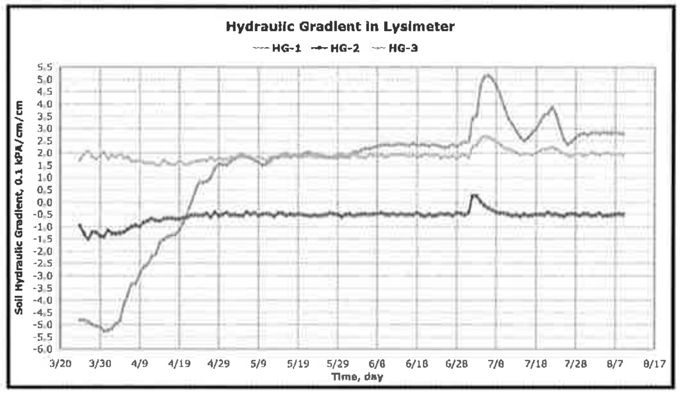

Figure 1. Average hourly hydraulic gradients calculated using soil water matric potential sensors in the lysimeter.

(HG>0 indicates upward flux and HG<0 indicate downward flux). HG-1 is the SMP gradient from 24 to 36 inches. HG-2 is the SMP gradient from 36 to 48 inches and SMP HG-3 is the SMP gradient for 48 to 60 inches. Results in Figure 1 indicate that HG-1 and HG-3 are positive with upward flow while the zone from 36 to 48 inches has water moving to deep depths due to uptake by the root system. However, the gradient from 48 to 60 inches is upward thus preventing drainage and nitrate leaching. This would be expected to occur in the DI and SDI systems as well in the orchard.

The rise in hydraulic gradient starting on 7/4/13 resulted from a relay failure causing the irrigation pump to stay on for several hours (Murphy's Law) longer than required and resulted in excess irrigation. Despite the excess irrigation, there was still no drainage.

Soil Nitrate Profiles Measured in 2012

Using SDI places nitrate below the soil surface and within the crop root zone. It also changes the availability and the potential for nitrous oxide emissions. We monitored the effect of irrigation system on nitrate using soil sampling. Soil nitrate (NO_3) was measured every 6-in. from the soil surface down to 48-in depth on 4/12, 8/12 and 12/12. Figure 2 shows nitrate values for the DI and SDI measurements averaged for all the N treatments. In nearly every case, the NO_3 in the SDI treatment were lower than those measured in the DI treatments. We measured N_2O emissions and found that use of SDI nearly eliminated all N_2O emissions for all N levels compared to the DI (data not shown).

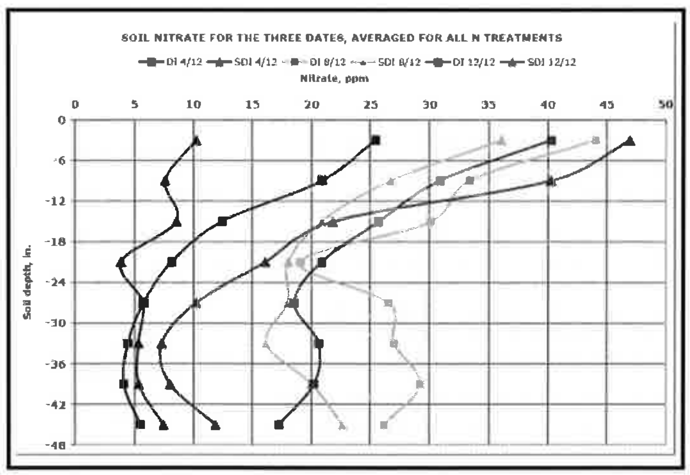

Figure 2. Soil nitrate (NO_3) measured every 6-in. from the soil surface down to 48-in depth on 4/12, 8/12 and 12/12. In this graph, these measurements were averaged for all N treatments.

Conclusion

1. High frequency drip irrigation with subsurface drip irrigation was effective in eliminating deep percolation losses.
2. SDI produced high yields and WUE compared to DI.
3. SDI eliminated nitrous oxide losses at all levels of nitrogen application.

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Student Conference Attendance, Presentation and Networking Opportunity

Planning, Operation and Automation of Irrigation Delivery Systems

A USCID Water Management Conference

Phoenix, Arizona December 2-5, 2014

Cooperating Organization:
Task Committee on Recent Advances in Canal Automation
Environmental and Water Resources Institute, ASCE

www.uscid.org/14azconf.html

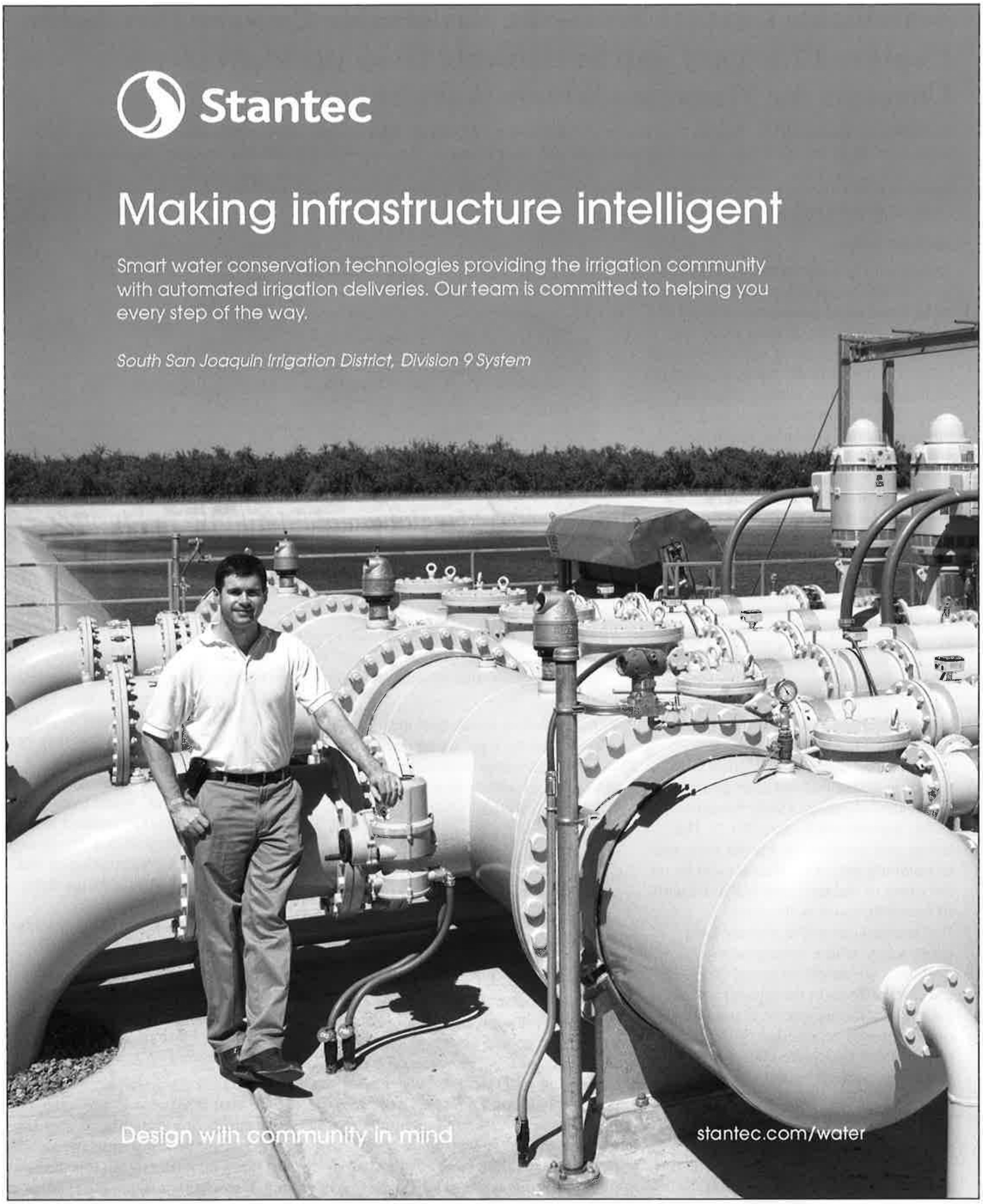
Six college or university students will receive a free registration and an opportunity to present their work to an international audience during the upcoming USCID Phoenix Conference. The free registration, funded by USCID's endowment from the American Water Foundation, includes all Conference activities including field tours on Tuesday and Friday, all technical sessions, an exhibition, coffee breaks, proceedings, and many meals during the four-day Conference — an excellent educational and networking opportunity!

The first six USCID student members who submit a brief abstract of a Poster Presentation for the Conference Poster Session on Thursday, December 4, will receive the Conference Registrations. Students may join USCID online (www.uscid.org/uscid_m.html). The first year of Student Membership is free.

To participate, send a 250-word summary of the proposed presentation by e-mail to stephens@uscid.org. The abstract should include the title of the presentation and contact information for the author and co-authors.

Students may also attend the Conference for a nominal registration fee of $25. This registration includes attendance at the technical sessions but does not include proceedings, tours, meals nor coffee breaks.

To register for either student program, go to the conference website above and take the link to the online registration form. For the AWF scholarship, put AWF in the Total Registration Fee; or enter $25 for the basic registration.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Sustainable Capture Fractions, Sustainable Capture Thresholds, Capture Efficiency and Sustainable Groundwater Storage: Concepts for Managing Stream-Aquifer Systems

by Jeffrey C. Davids, P.E., Davids Engineering | CSU Chico | H2oTech, Chico, California (jeff@davidsengineering.com); Steffen W. Mehl, Ph.D., CSU Chico, Chico, California; and Grant G. Davids, P.E., Davids Engineering, Davis, California

Editor's Note: This paper was presented during the 2014 USCID Water Management Conference in Sacramento, and is included in the Conference Proceedings.

Introduction

Traditionally, water resource managers have tended to address surface water and groundwater systems as distinct and separate. However, in most cases, as development and use of water resources intensify, it eventually becomes evident that changes in one system affect the other. The goal of this paper is to introduce a few emerging concepts within the field of hydrogeology, specifically pertaining to the management of interacting surface and groundwater systems.

Conceptual Framework

Management of interacting surface and groundwater systems is challenging for two main reasons:

1. The timescale of an aquifer's reaction to stress depends in part on the spatial scale and the diffusivity of the aquifer: the larger the aquifer and the lower the diffusivity, the longer the timescale. Thus peak impacts of pumping can occur significantly after pumping starts, or even after pumping has ceased (Jenkins, 1968; Bredehoeft, 2010; Barlow and Leake, 2012). The timescales involved in aquifer responses to pumping and other stresses can be on the order of decades, making it difficult to associate cause with effect. Furthermore, adaptive management approaches, where management decisions are modified based on observed effects in the aquifer system, do not necessarily ensure that adverse outcomes will be avoided. Instead, it is necessary to anticipate management outcomes, such as by numerical modeling.

2. Many of the interactions among streams, aquifers, and ecosystems are nonlinear, posing challenges to creating adequate representations of such physical relationships in numerical models.

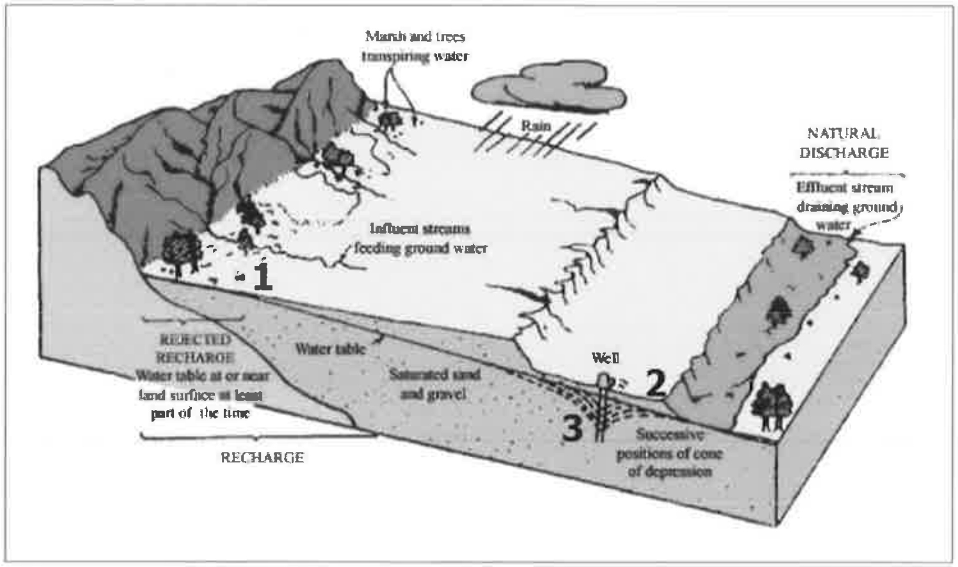

Figure 1. Theis Capture Concept adapted from Theis (1940)

These technical challenges are exacerbated by legal frameworks for water rights administration that do not always align with hydrologic reality (Glennon, 2009).

Groundwater extraction can cause reduction of streamflow, affecting both human uses and ecosystems (Barlow and Leake, 2012). When a groundwater system is pumped, the water table near the production well (or wells) declines. Initially the decline is accounted for by a change in aquifer storage surrounding the well. As pumping continues, and the cone of depression expands, impacts to both recharge and discharge can occur. In a recharge area, the cone of depression will lower the water table, potentially inducing recharge in areas that historically rejected recharge because of high groundwater levels. In a discharge area, the cone of depression will reduce the water table gradient with a consequent reduction in discharge to streams, springs, or evapotranspiration (ET) of shallow groundwater. These relationships are expressed in Theis' (1940) concept of capture which, briefly summarized, states that when a groundwater aquifer is pumped, the pumping 'captures' water from (1) induced recharge, (2) reduced discharge, and/or (3) a change in aquifer storage (generally some combination of the three). Figure 1 illustrates the three sources of water captured by groundwater pumping. With reference to Figure 1:

1. Induced recharge is caused by a lowering of the water table in an area that historically would have rejected recharge because of saturation (illustrated near '1').

2. Reduced discharge occurs when water that otherwise would have discharged to a stream or to a spring, or as ET of shallow groundwater, is captured by pumping. In this case, water that historically discharged to a stream is being captured (illustrated near '2').

3. Finally, a change in storage is caused by a lowering of the water table near the pumping well; this lower of the water table is often referred to as a 'cone of depression' (illustrated near '3').

In close proximity to a stream, a decrease in surrounding groundwater levels either flattens the gradient of flow toward the stream, thereby reducing discharge to it, or steepens the flow gradient away from the stream, thereby inducing additional recharge from it (i.e., stream depletion). Glover and Balmer (1954) and Hantush (1965) later derived a mathematical solution to quantify stream depletion, including a complementary error function. Later, Jenkins (1968a, 1968b and 1968c) popularized this analytic approach by presenting the stream depletion factor (SDF) shown in the equations below. SDFs can calculate, based on aquifer diffusivity and proximity to the pumping well, the change in streamflow caused by pumping groundwater. Miller et al. (2007) investigated the use of the SDF method in characterizing stream depletion due to groundwater pumping in a narrow alluvial aquifer. Utilizing SDFs, Bredehoeft (2010) investigated the impacts of seasonal pumping from a well (or series of wells) located at various distances from a stream. Regulatory agencies frequently use SDFs (Miller and Dunford, 2007), including the state of Colorado for the management of conjunctive use programs along the South Platte and Arkansas rivers (Bredehoeft and Kendy, 2007).

$$SDF = \frac{a^2 S}{T}$$

$$q_s = Q_w * \text{erfc} * [SDF/(4t)]^{1/2}$$

Where the variables are defined as:

- q_s = instantaneous stream depletion
- Q_w = pumping rate of the well
- erfc = complementary error function
- a = distance from the stream to the well
- T = aquifer transmissivity
- S = aquifer storage coefficient
- t = time since pumping started

Over time, if groundwater discharge (both natural and anthropogenic) exceeds groundwater recharge, there will be a change in storage and a corresponding decline in the water table. If the water table is lowered below the elevation of a streambed, stream-aquifer interaction is reduced to a one-way leakage from the stream into the aquifer. In this case, the stream is characterized as being "decoupled" from the aquifer, and water flows from the stream into the aquifer at a rate that is independent of the water table elevation. Also as groundwater elevations decline, spring discharges are inevitably reduced and might completely stop. In cases where groundwater discharge comprised all of streamflow for certain stream reaches and/or periods of time prior to development, excessive pumping can lead to artificially ephemeral streams (Davids, 2011).

While SDFs can be used to simulate the effects of pumping on streamflow, they are based on certain assumptions that limit their usefulness for analyzing interacting surface water and groundwater systems. The most critical limitations are the assumptions that: 1) streamflow is continuous, 2) the stream can be treated as a constant-head boundary, and 3) other discharge paths potentially affected by pumping, such as evapotranspiration from phreatophytes, can be neglected. Thus, SDFs cannot be applied to the analysis of streams where discharge is significantly diminished by pumping, a serious limitation in cases where the objective is to understand the nature of stream-aquifer interaction. And, in many systems, understanding the effects of pumping on other discharge flow paths is critical for developing sustainable management regimes for interconnected systems.

Managing Stream-Aquifer Interactions

Groundwater management approaches have evolved over time, beginning with the concept of safe yield from the 1920s, progressing through the 1940s with the concept of capture, transitioning in the 1980s to sustainability based approaches, and most recently to the utilization of groundwater flow models and sustainability goal setting and backcasting (Alley and Leake, 2004; Gleeson et al., 2012; Kalf and Woolley, 2005). Through this nearly century long evolution, the general consensus is that a comprehensive, integrated approach (one that considers surface water, ecosystems, water quality, etc.) is needed to achieve sustainable development of groundwater resources. However, comparatively little has been done to establish practical (easy to implement and interpret) metrics that can be used by modelers and managers alike.

Here we offer a conceptual framework for establishing the sustainability of groundwater pumping from an aquifer that interacts with surface streams. The key principles relate to the concept of capture (Theis, 1940) and the water budget with respect to all discharge flow paths before and after pumping. This is done through the quantification of the Sustainable Capture Thresholds further defined below. The efficacy of a proposed groundwater pumping scenario can be evaluated based on its modeled Capture Efficiency.

Four concepts are described here as the basis for developing metrics for sustainable management of stream-aquifer systems:

- Sustainable Capture Fraction (SCF), and is defined as the acceptable limit of the effects of pumping on each discharge flow path, and lies between 0 and 1.
- Sustainable Capture Threshold (SCT), defined as the amount of total outflow from a stream-aquifer system (e.g., stream outflow, groundwater outflow, riparian evapotranspiration (ET), etc.) that can be sustainably captured.
- Capture Efficiency (CE), a metric derived through numerical modeling that indicates how close various management alternatives come to actually capturing the SCT for each flow path.
- Sustainable Groundwater Storage (SGS), the portion of groundwater storage that can be sustainably exercised.

SGS is determined from SCTs and CEs and is often only a small fraction of the total water stored in an aquifer because it is typically the uppermost portion of the aquifer (only a few feet or tens of feet in many cases) that dictates the magnitude and direction of interaction between groundwater and surface water systems.

The original concept of capture (Theis, 1940) applied only to defining impacts to an aquifer caused by increased pumping. Impacts to surface water were imbedded in the induced recharge and reduced discharge terms. Explicitly applying these terms to individual discharge flow paths is important for sustainable management of stream-aquifer systems, and forms the basis of the approach proposed here.

An *upper* bound on sustainable capture can be estimated based on the total outflow from a system, including both surface water and groundwater outflows. The total outflow is the potential capture threshold (PCT). While it is theoretically possible to achieve a steady-state while pumping at a rate equal to the PCT, this is usually not desired because of adverse consequences, such dry stream reaches and springs, complete extinction of phreatophytes, and/or cessation of groundwater outflow from the basin. The SCT is the portion of the PCT that can be captured while avoiding such unacceptable effects.

Analysis of the surface water and groundwater outflows from a hydrologic system is needed to define these thresholds, such as by applying an adequately conceived, developed, and calibrated numerical model of the system. Such a model can be used to define the portion of each discharge flow path that theoretically could be sustainably captured, representing the Sustainable Capture Fraction (SCF). Defining acceptable limits of the effects of pumping is unavoidably subjective and would ideally be addressed through a process involving all stakeholders. The SCF lies between 0 and 1 and needs to be established for all discharge flow paths. For example, if the natural flow in a stream was 10 cubic feet per second and a minimum flow rate of 5.7 cfs was determined to be acceptable (for downstream water rights, fishery, or other purposes), then the SCF would be 0.57. SCFs for each flow path can be either constant or varying over space and time. SCFs are used to determine the SCT for each discharge flow path.

$$SCT_X = SCF_X * \text{Natural Discharge for Flow Path X}$$

This is done for each discharge flow path in the system, and the sum is the SCT. [Authors' note: A modeling example with multiple discharge paths (i.e., stream outflow and evapotranspiration) illustrating the concepts of SCTs, CEs, and SGS has been completed and the results will be included in subsequent papers on this subject.]

Lake Tahoe Analogy

Despite the differences between managing surface water storage and groundwater storage, the two are alike in one way, revealed through the following analogy. Lake Tahoe holds approximately 120 million acre-feet of water (UC, Davis 2013), yet only the upper few feet are exercised for water storage because of the requirement to maintain flow into the Truckee River (Tahoe's only outlet), to preserve the shoreline, and for other purposes. The key point is that the lake level is easily observed and actions taken to prevent adverse consequences have immediate effect. Furthermore, no one contemplates tapping into the huge stock of water stored below the river's outlet elevation simply because it's there.

Sacramento Valley

The Sacramento Valley, and other similar basins where groundwater continues to sustain streamflow, is analogous to Lake Tahoe in that groundwater storage and levels can be drawn down below the "outlets" to surface streams. The difference and challenge is that groundwater levels are not readily observable, and the complicated relationships between groundwater levels and streams are not adequately defined. Additionally, groundwater levels do not respond immediately to changes in recharge and pumping, but are damped over space and time, so that cause and effect are not easily discernable. Moreover, because the connections between aquifers and streams are not directly observable, they can be overlooked or easily disputed, or it can be argued that they don't really exist. These factors put the Sacramento Valley's aquatic environment at risk as California's water demands increase, both within and outside the Sacramento Valley.

This simple analogy illustrates the important concept of SGS, as opposed to Total Groundwater Storage (TGS). As previously discussed, in the case of Lake Tahoe, sustainable storage is limited by minimum flow requirements in the Truckee River. At best, discussions about groundwater management that focus solely on TGS are missing an important part of the story. At worst, completely ignoring the concept of SGS can lead to policy decisions that have severe unintended consequences to streams and springs. Clearly, there are a host of issues with developing adequate numerical models of stream-aquifer systems. Nevertheless, a stakeholder driven process utilizing the concepts discussed herein of SCT, and CE can be applied to stream-aquifer systems to at least obtain a first cut at the possible range of SGS.

Conclusion

The methods proposed here provide a framework for analyzing sustainable pumping rates for interconnected stream-aquifer systems. The framework is based on the Theis (1940) concepts of capture, analyzing each discharge path independently. This is useful for developing meaningful SCFs for each discharge flow path via a stakeholder driven process. The sum of the product of the natural discharge and the SCF for all discharge flow paths yields the total SCT. The effects of pumping at a rate equal to the total SCT can be analyzed in terms of each discharge flow path to calculate flow path specific CEs. This readily identifies the limiting constraint (the discharge flow path with the Capture Efficiency that first exceeds 100percent), and can be integrated into an optimization approach for determining pumping rate, schedule, and well placement that maximizes extraction without exceeding defined SCTs. Finally, any exercising of groundwater storage must ensure that SCTs are not violated. The total amount of storage within the aquifer that can be exercised without exceeding SCTs is considered Sustainable Groundwater Storage.

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USCID Newsletter Advertisers, Spring 2014

President's Message (continued)

Former Commissioner of the Bureau of Reclamation, and current Executive Vice President of NWRA, Bob Johnson will make a dinner presentation on water issues in Congress that affect irrigation districts. To hear a first-hand account of the outstanding technical presentations and networking opportunities at USCID conferences, talk with a colleague who attended the recent USCID Conference in Sacramento. I am sure that after hearing about the Sacramento conference you will be eager to experience the Phoenix conference first hand. Sign up early and bring your colleagues.

To encourage student involvement, the USCID Board continues to make available American Water Foundation Scholarships for full registration at the Phoenix conference for students who submit a poster abstract. Low cost registration is also available for students who want to attend, but are unable to prepare a poster. Another excellent opportunity for students is the **USCID/Summers Engineering Scholarship**. Applications for the $1,000 scholarship will be solicited and accepted this summer.

Another event not to miss this fall is the **22nd International Congress on Irrigation and Drainage**, September 14-20, in Gwangju Metropolitan City, Republic of Korea. The Congress theme is *Securing Water for Food and Rural Community under Climate Change.* USCID members are encouraged to attend.

During the spring Board meeting, we welcomed three new Board members. With the election of **Steve Macaulay**, **Sam Schaefer** and **Delbert Smith** (see story on page 19) USCID will be in capable hands for the future. While we welcome the new Board members, it is with sadness that we say good bye to retiring Board members **Luis Garcia**, **Laura Schroeder** and **John Sweigard**. We thank them for their years of service and leadership and welcome Laura in her new role as a Board Advisor.

One notable action at the recent Board meeting was the approval of minor revisions to the USCID mission statement to more clearly state our mission:

The Mission of USCID is to promote progressive and sustainable irrigation, drainage and flood control practices in support of food and fiber production and public safety, recognizing that sustainability embodies economic, social and environmental goals.

In closing, I want to again invite you to get involved with USCID — present a paper at a conference, join a conference planning committee, and share your ideas and experiences with others. Although it is a cliché, in the case of USCID it is true that the organization is only as strong as its members.

Bryan Thoreson
President, USCID¤

Phoenix (continued)

Peter-Jules van Overloop, Delft University of Technology; **Darell D. Zimbelman**, Water Systems Operations & Management LLC; **Charles M. Burt**, ITRC, California Polytechnic State University. Following a coffee break, presenters will include **Pierre-Olivier Malaterre**, IRSTEA; **Robert Strand**, Agricultural Research Service, USDA, and **Sumith Choy**, Rubicon Pty Ltd; and **Albert J. Clemmens**, WEST Consultants, Inc. On Wednesday morning, the Plenary Session continues with a Panel Discussion on Irrigation District Modernization.

The technical program continues on Wednesday afternoon and Thursday with concurrent technical sessions.

Meal speakers include Consultant **Herve L. Plusquellec**, Washington, DC; **Sheryl Sweeney** and **Samuel Lofland**, Ryley Carlock & Applewhite, Phoenix, AZ; **Robert Johnson**, Executive Vice President, NWRA, Scottsdale, AZ; and **Michael J. Lacey**, Director, Arizona Department of Water Resources, Phoenix, AZ.

Charles Burt will present a pre-Conference Workshop on Variable Speed Pumps will take place on Monday afternoon. Tuesday morning will feature a field tour to Ameron and Pueblo Grande.

The Conference will conclude with a full-day field tour to the Central Arizona Project. An Exhibition and several networking events round out the Conference program. Complete Conference information is online at www.uscid.org/14azconf.html.¤

Water Management Certificate Program Offered in Arizona

A Water Management Certificate Program, sponsored by Arizona State University and the Agribusiness & Water Council of Arizona is accepting applications for the 2014/15 year. This year marks the second year of the program. USCID Member **Nelson W. Plummer** currently serves as President of the Council.

The purpose of the program is to assist in preparing water professionals with the skills needed to become water industry leaders, particularly those involved in the management of irrigation and conservation districts and other water user organizations in Arizona and the West. The program courses will be taught by seasoned water industry practitioners.

The program will focus on training future leaders in all aspects of water resources management, including financing and budgeting, operations and maintenance, land use issues, energy resource management, water resources management, inter-governmental relationships, communication, the role of consultants and attorneys, and the many political demands that must be navigated by managers.

Classes will be held on Friday afternoon and all day Saturday once each month, beginning September 26, and ending June 26, 2015 (no class in December). Classes are held at the ASU Polytechnic campus; there is also an opportunity to participate via live video conferencing.

To apply for the Water Management Certificate Program, send a resume and statement of interest to Kathy Rappleye at kathy@agribusinessarizona.org.¤

Election (continued)

Stephens counted 137 ballots.

Steve Macaulay.

Steve Macaulay is Vice President of Macaulay Water Resources, a consulting firm in Davis, California. He received a B.S. Degree from the University of California, Davis, and an M.S. from California State University, Sacramento, and is a registered civil engineer. He has been a Member of USCID since 1991, an Advisor to the USCID Board for the past three years, and a frequent author and speaker at USCID conferences. He was a co-chair of the recent USCID Conference in Sacramento. Macaulay is very active in western water irrigation water supply issues, with 40 years of experience in a broad range of activities related to water contract negotiations, water supply reliability, water rights, environmental issues and conflicts, water transfers, conservation, water quality, surface and groundwater storage, conjunctive use, climate change and integrated regional water management. A consultant since 2002, he previously served as California Department of Water Resources Chief Deputy Director, General Manager of the State Water Contractors (customers of the California State Water Project), and Executive Director of the California Urban Water Agencies.

Sam Schaefer.

Samuel W. Schaefer is a Senior Engineer, GEI Consultants, Inc., Santa Barbara, California. He received B.S. and M.S. Degrees in Agricultural and Water Resources Engineering from South Dakota State University, Brookings, in 1984 and 1988. During the past 30 years, he worked on Federal evaluation for irrigation in South Dakota as a water resources engineer for the Water Resources Research Institute at SDSU; on various complex drainage issues as an agricultural drainage engineer for the Bureau of Reclamation in Denver; and as a consultant in California since 2001. Presently, he facilitates the implementation of a regional integrated water management group for agricultural and community water districts in California. The agricultural districts practice conjunctive management of surface water and groundwater supplies from local, state and federal sources. He is a Registered Professional Engineer in Colorado and California and served in the past as the Chair of the EWRI Agricultural Drainage and Water Quality Committee. As a Life Member of USCID, has served on several conference planning committees.

Del Smith.

Delbert M. Smith is Manager of the Water Resources Planning and Operations Support Group and Economics and Resources Planning Team, Bureau of Reclamation, Denver, Colorado. He has 24 years of experience working for the Bureau of Reclamation in the field of water resources planning and engineering. His experience with Reclamation includes working in the Ground Water and Drainage Group and the Land Suitability and Water Quality Group of the Environmental and Water Resources Division. Most of his work has been tied to shallow ground water and surface water investigations of irrigation lands and more recently river restoration projects. This includes working on projects in 16 of the 17 Reclamation Western states. He spent 12 years working on the Department of the Interior's Irrigation Water Quality Program. He manages a staff of 15 engineers and eight economists at Reclamation; this staff continues to advance the state of the science of performing permeability testing for irrigation drainage design. He has been a Member of USCID since 2008 and served on the Planning Committee for the 2011 USCID Conference in San Diego.¤

USCID 2014 Awards and Scholarship

Nominations are being accepted for the 2014 USCID Merriam Improved Irrigation Award and the USCID Service to the Profession Award. Nominations are due October 1, 2014. Visit www.uscid.org/awards.html for more information.

The **USCID Merriam Improved Irrigation Award**, endowed by the late John L. Merriam, is given to a Member of USCID who has made meritorious contributions to the advancement, understanding or attainment of the goals and objectives of USCID, ICID and/or furthering the value of flexible irrigation water supply and distribution systems.

The **USCID Service to the Profession Award** recognizes service to the irrigation, drainage, flood control or water resources management profession by an individual, organization or agency. Nominees need not be USCID Members.

Scholarship

Applications for the **USCID/Summers Engineering Scholarship** are also being accepted. Only USCID Student Members are eligible to apply for the Scholarship, which will be awarded during the USCID Water Management Conference in Phoenix, December 2-5, 2014. The scholarship recipient will be invited to make a poster presentation during the Conference, and the registration fee and travel expenses to attend the Conference will be covered by USCID.

Applicants should send a 750-word summary of their academic program, a copy of their transcript and a letter of endorsement from their advisor or department head. Applications should be sent by e-mail, no later than October 1, 2014. For more information, visit www.uscid.org/scholar.html.

The Scholarship winner will be notified by November 1, in time to make plans to attend the Phoenix Conference.¤

Previous USCID Award Recipients

USCID Merriam Improved Irrigation Award	USCID Service to the Profession Award
Joseph B. Summers, 1999	Marvin E. Jensen, 2000
E. Gordon Kruse, 2001	Maurice L. Albertson, 2001
John A. Replogle, 2002	Richard G. Allen, 2002
Grant G. Davids, 2003	Jack Keller, 2003
Jesse Silva, 2004	Walter J. Ochs, 2004
Charles M. Burt, 2005	Darell D. Zimbelman, 2005
Arnold K. Dimmitt, 2006	John W. Keys III, 2006
Marshall J. English, 2008	Larry D. Stephens, 2007
Albert J. Clemmens, 2009	Kenneth and Ruth Wright, 2008
Steve Knell, 2010	Allen R. Dedrick, 2009
Thomas J. Trout, 2011	Rick L. Gold, 2010
Stuart Styles, 2012	Joseph I. Burns, 2011
Guy Fipps, 2013	Clifford I. Barrett, 2012
	Mark A. Limbaugh, 2013

Irrigation Short Course Offered

The Biological and Ecological Engineering Department, Oregon State University, will offer an intensive short course on **Advanced Irrigation Management: Optimum and Sustainable Irrigation for a Resource-Limited World**. Irrigation for the Future will co-sponsor the course.

The course will be held September 22-25, 2014, at OSU's Hatfield Marine Science Center in Newport, Oregon.

The course will be structured as a series of seminars conducted by a team of widely recognized leaders in irrigation management and related sciences. The technical content will be a distillation of relevant information drawn from field experience, emerging technological developments and recent research. The lectures and seminar presentations will be augmented with hard copies of lecture materials, video recordings of the proceedings and annotated bibliographies to enable participants to go deeper into topics of particular interest.

The course is designed for senior professionals in irrigation water use: irrigation managers; policy planners; educators; equipment designers; and consultants.

For more information, visit http://advancedirrigation2014.com.¤

New Member

Individual Member

Patrick Hubbard
Oakdale Irrigation District
324 45th Street
Oakland, CA 94609
Office: 925-381-5381
E-mail: pbhubbard@gmail.com¤

News of Members

Guy Fipps is the recipient of ASABE's 2014 PEI Professional Engineer of the Year Award, in recognition of his exceptional service in the interests of peace through application of engineering principles in solving water supply and management problems.

Mary Jay (Vestal) Martens is now affiliated with Brown and Caldwell in Boise, Idaho.

Dorota Haman, Department of Agricultural and Biological Engineering, University of Florida and USCID Life Member, has been named a Fellow of ASABE.

Suat Irmak is the recipient of the 2014 ASABE Heermann Sprinkler Irrigation Award in recognition of his outstanding global leadership and contributions to improved understanding of soil, water and plant relationships.

Kenneth R. Wright, along with his wife, Ruth Wright, and the Wright Family Foundation, has created the Ruth Wright Water Archive Endowment, at Colorado State University. The endowment will support student assistants at the CSU Water Resources Archive who are organizing and preserving historical water documents.¤

Flood Warning System Workshop

The **Pacific Northwest Advanced Flood Warning System Workshop will** be held October 21-22, 2014, in Grand Mound, Washington. The Workshop, sponsored by the Northwest Hydrologic Warning Council, will explore opportunities and challenges for improved flood warning systems in the Pacific Northwest.

Topics to be covered include:

- Overview of successful flood warning systems across the U.S.
- Designing and implementing flood warning systems
- Creating robust natural hazard monitoring and prediction systems, including floods, landslides, wild fire, etc.
- Managing social media during flood emergencies
- Coalition-building among flood warning system owners/operators
- Sharing ways to strengthen support for flood warning systems
- Emerging flood warning system technologies
- Using flood warning systems to strengthen your CRS rating.

The workshop is designed for floodplain managers, owners and operators of existing hydrologic warning systems, river authorities, emergency managers, flood control districts, public works officials, owners and operators of high hazard dams and levees, drainage and flood control engineers, and any others who have a need to better understand the benefits of hydrologic warning systems in managing flood risk.

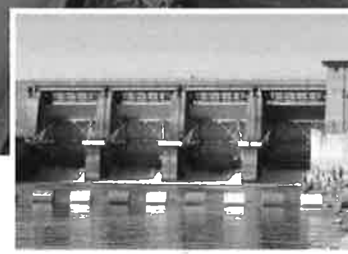
For more information, contact NHWC President David C. Curtis at dcurtis@westconsultants.com.¤

Irrigation Impact Study Released

According to a white paper recently released by the Family Farm Alliance and the Irrigation Association, the western United States accounted for $171 billion in total production (farm gate) in 2011, with an estimated $117 billion tied to irrigated agriculture. The study was commissioned by FFA and IA, developed by the Pacific Northwest Project, and is now available at www.irrigation.org/uploadedFiles/Policy/PNP-WesternIrrigationImpact_8-2013.pdf.

The report, *The Economic Impacts of Western Irrigated Agriculture*, addresses specific policy questions about water resources economics raised by senior staff from the U.S. Environmental Protection Agency's Office of Water. The white paper summarizes basic economic information about irrigated agriculture and quantifies its impact on annual household income in 17 states.¤


Worthington
Waterway Barriers
Floodway Trash Barrier, US/Mexico Border, CA (USA)



USCID Notes

by Larry D. Stephens,
Executive Vice President

First, my thanks to **Luis Garcia**, **Laura Schroeder** and **John Sweigard** for their service to USCID as Members of the Board of Directors. We will all miss their leadership and guidance. I urge all of you to thank Luis, Laura and John when you next see them.

And, welcome to the three newly elected Board Members **Steve Macaulay**, **Sam Schaefer** and **Del Smith**. All three are new to the Board but they have all been active Members of USCID for many years. Steve served as a Board advisor and will be missed in that role, but Laura Schroeder will now serve as an advisor, so the outstanding talents and perspectives that she has brought to the Board will continue. Certainly good news!

As you have reviewed this issue of the USCID Newsletter, I hope you noticed the support we have received from advertisers. When you need professional services and irrigation related products, please make your first contacts with the advertisers — they provide a key part of making this Newsletter a success. And, you will have an opportunity to see many of them at future USCID conferences. Please say thanks to their representatives when you see them.

Speaking of conferences — the upcoming Phoenix Conference on December 2-5 is going to be an outstanding meeting. Led by co-chairs **Brian Wahlin** and **Charles Burt**, the Conference Planning Committee has developed an excellent technical program featuring irrigation professionals from the U.S. and abroad. The Cooperating Organization for the Conference is the Environmental and Water Resources Institute of the American Society of Civil Engineers. The Opening Plenary Session will feature the new *ASCE Manual of Practice 131: Canal Automation for Irrigation Systems*. Several USCID Members were directly involved in writing the Manual. Your registration fee for the Conference will include a copy of the Manual. The Program and registration information may be found on the USCID website.

Congratulations to **Suat Irmak** for receiving ASABE's Heermann Sprinkler Irrigation Award. This Award was named for the late **Dale F. Heermann**, a USCID Member who was associated with the Agricultural Research Service, USDA, in Fort Collins, Colorado.

This *USCID Newsletter* features two technical articles, one by **Jim Ayres** and the other by **Jeff Davids** and their colleagues. Both were the bases for oral presentations during the Sacramento USCID Conference last spring, and are included in the Conference Proceedings. These are typical of the quality of the excellent technical presentations made during USCID Conferences. Plan now to attend the Phoenix Conference in December and see for yourself!

As noted in the calendar to the right, the ICID Congress will be held in Korea during mid-September. The Congress will include meetings of the ICID working groups as well as a number of technical presentations. ICID provides an excellent way to network with irrigation professionals from many countries. Go to www.icid2014.org to see the program and schedule of activities. Plan to attend the Congress and attend some working group meetings — the working groups need support from USCID! I hope to see you in Gwangju.¤

USCID Meetings

December 2-5, 2014, Phoenix, Arizona. *Planning, Operation and Automation of Irrigation Delivery Systems.*

ICID Meetings

September 14-20, 2014, 65th IEC Meeting and 22nd Congress, Gwangju, Korea.

2016, 67th IEC Meeting and 9th Asian Regional Conference, Thailand.

October 11-16, 2015, 66th IEC Meeting, Montpellier, France.

March 2017, 13th International Drainage Workshop, Ahvaz City, Iran

2017, 23rd Congress, Mexico.