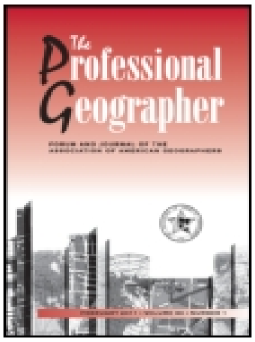

The Professional Geographer

ISSN: 0033-0124 (Print) 1467-9272 (Online) Journal homepage: http://www.tandfonline.com/loi/rtpg20

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To cite this article: Peggy Hauselt & Richard Plant (2010) Spatial Modeling of Water Use in California Rice Production, The Professional Geographer, 62:4, 462-477

To link to this article: http://dx.doi.org/10.1080/00330124.2010.500983

Published online: 11 Aug 2010.

Spatial Modeling of Water Use in California Rice Production

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There are growing concerns over the water use efficiencies in California rice production. To address these concerns it is necessary to better understand the balance of flows within the system. A spatial water-balance model was developed, using a geographic information system (GIS), to estimate the inflows to and outflows from the Glenn-Colusa Irrigation District in California's Sacramento Valley. System inflows included precipitation and irrigation. Outflows included evapotranspiration, surface runoff, and percolation. The storage capacity of the system was also estimated. The model was run to simulate twenty-four months from January 2003 through December 2004. The model was assessed by determining if the equation was balanced. Throughout the study the model remained balanced within the system's maximum storage capacity. The results suggest that even with limited data, spatial water-balance models provide useful descriptions of regional agricultural water use. **Key Words: agriculture, California, rice, Sacramento Valley, water-balance model.**

美国加州大米生产过程中水分利用效率问题已引起了越来越多的关注。针对这些关注，有必要更好地了解系统内的流量平衡。本研究利用地理信息系统（GIS）创建了一个空间水平衡模型，用于估计在加州萨克拉门托河谷的葛兰－科卢萨灌区水的流入和外流。系统流入包括降水和灌溉。外流包括蒸散，地表径流和渗透。本文同时对该系统的存储容量也进行了估算。该模型运行模拟了从 2003 年 1 月到 2004 年 12 月二十四个月的流量。通过确定方程是否平衡对该模型进行了评估。在整个研究过程中，此模型在该系统的最大存储容量内维持了平衡。结果表明，即使数据有限，空间水量平衡模型对区域农业用水提供了有用的描述。**关键词：农业，加利福尼亚州，大米，萨克拉门托河谷，水平衡模型。**

Hay creciente inquietud sobre el grado de eficiencia en el uso de agua para la producción de arroz en California. Para abocar esta preocupación es necesario analizar mejor el balance de flujos dentro del sistema. Para tal efecto se desarrolló un modelo espacial de balance del agua mediante la utilización de un sistema de información geográfica (SIG), para calcular los flujos de entrada y salida en el Distrito de Riego Glenn-Colusa en el Valle del Sacramento de California. Los flujos de entrada del sistema incluyeron agua de precipitación e irrigación; los de salida, evapotranspiración, escorrentía y percolación. Se calculó también la capacidad de almacenaje del sistema. El modelo se corrió para simular veinticuatro meses de enero del 2003 hasta diciembre del 2004. Se evaluó el modelo determinando si la ecuación estaba balanceada. Durante todo el estudio el modelo se mantuvo balanceado dentro de la capacidad máxima de almacenamiento del sistema. Los resultados sugieren que aún con datos limitados los modelos espaciales de balance del agua generan descripciones útiles sobre el uso regional de agua para fines agrícolas. **Palabras clave: agricultura, California, arroz, Valle del Sacramento, modelo del balance del agua.**

Over 200,000 hectares of rice are grown annually in California's Sacramento Valley. Despite increasing concerns over water use efficiencies in California's water supply (State of California and Office of Legislative Counsel 2005), there are few estimates of the quantities of water used in rice production across the region. Understanding regional water use is becoming more important as rice growers increasingly sell their water to districts in other regions. The California Department of Water Resources (DWR 2000) reported

*This research was supported by the California Department of Water Resources and by a William F. Golden Fellowship to P. Hauselt.

The Professional Geographer, 62(4) 2010, pages 462–477
Initial submission, September 2009; final acceptance, April 2010.
Published by Taylor & Francis Group, LLC.

the annual average crop water use and water applied for rice per county. The University of California (UC) Cooperative Extension estimated the range of average seasonal water outflows, evapotranspiration, runoff, and percolation from a rice system (Williams 2003b). The California Rice Commission compiled the total water inflows to and outflows from state-wide rice production (CH2M Hill 1996). However, there is no spatially explicit description of the regional rice production water flow.

A spatial water-balance model was developed, using a geographic information system (GIS), to estimate the inflows to and outflows from a rice-growing region. Spatial layers were created describing the monthly variation of precipitation, irrigation, evapotranspiration, surface runoff, percolation, and soil storage and field surface water capacity at the field, subdistrict, and district scales. The model is parameterized for the Glenn-Colusa Irrigation District (GCID). The model was run to simulate twenty-four months from January 2003 through December 2004 for the GCID.

Study Site

The GCID is located in the northwestern region of the Sacramento Valley (Figure 1). The irrigation district supplies water to more than 50,000 ha of agricultural land (GCID 2005). Generally more than 70 percent of the irrigation district's land is devoted to rice production (GCID 2006). In 2003 and 2004 the GCID diverted more than 111,000 ha-m of water from the Sacramento River[1] (GCID 2005).

The rice-growing region of California experiences hot, dry summers and cool winters. Approximately 50 cm of rain falls annually in the Sacramento Valley, primarily in the winter (Hill et al. 1992). The rice-growing region is low lying and flat (Pudup and Watts 1987; Maclean et al. 2002). California rice is generally grown in soils that have high clay content or a cemented hardpan (Williams 2003a). These soils have low permeability and tend to pond water. Nearly all California rice fields have been precision leveled so growers can maintain uniform water depths (Maclean et al. 2002).

In California rice is generally grown from May to September. Given the dry summer, most of the water inputs to rice production are from irrigation. In the Sacramento Valley more than 90 percent of the fields are irrigated with surface water (Hill et al. 1992). In 2003–2004 the GCID used no groundwater (GCID 2005). The overall amount of applied water varies annually due to changes in the number of fields planted. In 2003 approximately 5,000 ha-m less water was used in rice production than in 2004, because many growers chose to participate in a short-term water sale to the Metropolitan Water District of Southern California instead of producing rice (GCID 2005).

Most growers flood the basins with 0.1 to 0.13 m of water prior to seeding and then direct seed into flooded basins (Williams 2003b). Some growers drain fields shortly after seeding to improve stand establishment, apply herbicides, or both (Williams 2003b). After draining, the fields are typically reflooded within a few days. This early drainage practice increases overall irrigation and surface runoff in the rice production system and was used extensively in the study site during the 2004 growing season. Typically growers then maintain a permanent flood of 0.1 to 0.13 m of water through the growing season (Williams 2003b). Near the end of the season the grower might increase the water levels to 0.2 m to protect against cold night temperatures (Williams 2003b). Two to four weeks prior to the rice harvest water inflows are stopped in preparation for using the heavy harvest equipment. Water is allowed to subside but some is drained, causing an increase in the amount of surface runoff in the rice-growing region. Following harvest, many growers incorporate rice straw and reflood their fields to hasten straw decomposition.

Agricultural Water Balance

To estimate the inflows to and outflows from the rice production system we constructed a monthly spatial water-balance model in a GIS (ArcGIS version 9.1–9.2). The inflows and outflows were divided into the following types of water movement: precipitation, irrigation, crop evapotranspiration, surface runoff, and percolation (Figure 2). Based on the conservation of matter, the volume of water entering the rice production system was assumed to equal the sum of the volume of water leaving the system

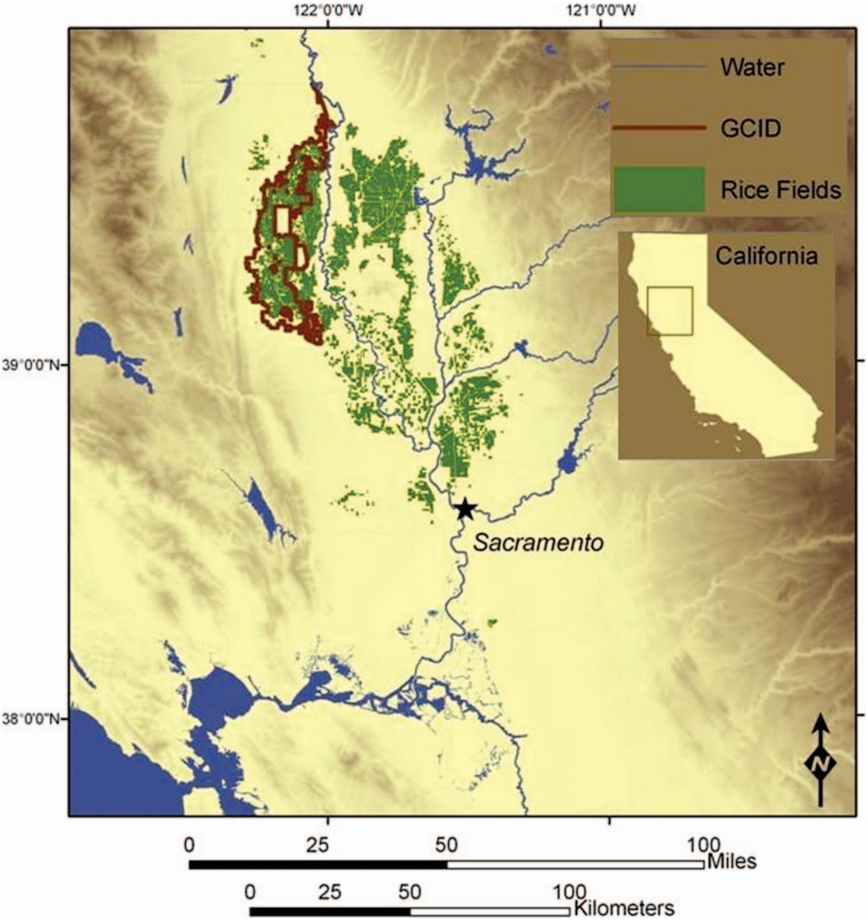

Figure 1 *Glenn-Colusa Irrigation District (GCID) in the rice production region of the Sacramento Valley, California. Sources: California Spatial Information Library (1997); California Department of Water Resources (2000); GCID (2004a).*

and the volume remaining in the system:

$$(IR + P) - (ETc + RO + D) = (S + F) + e \quad (1)$$

where IR = applied irrigation water, P = precipitation, ETc = crop evapotranspiration, RO = surface runoff, D = percolation, S = saturated soil storage; F = in-field surface water, and e = error.

The changes in water storage in the system equal the inputs of water less the outputs of water (Maidment 1993). Additionally, we estimated the total storage capacity of the system. Storage within the system was divided into in-field surface water and soil storage. Water entering the system does not immediately leave the system. Instead, it can remain in the system for an indefinite amount of time. Therefore, on a month-by-month basis the inflows and outflows might not balance due to water remaining within the system.

The water-balance model is a simple and well-studied description of hydrologic and hydraulic systems. Spatially distributed water-balance models have been used to describe other agricultural water systems. Young and Wallender (2002) described drainage and

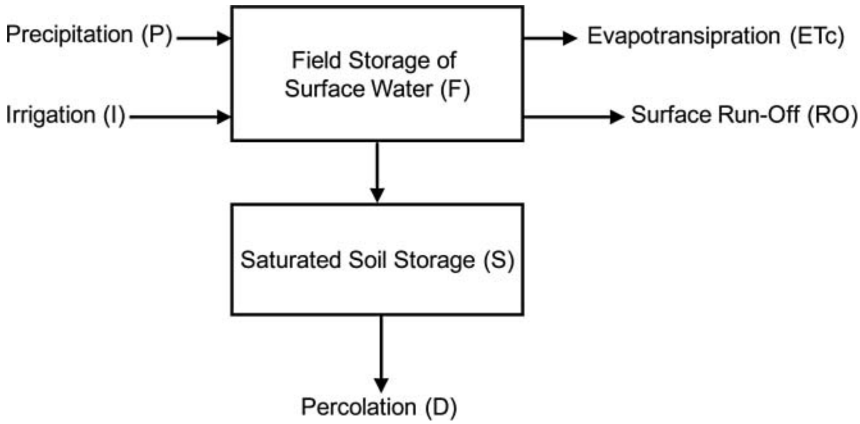

Figure 2 *Water-balance model.*

water management practices in the California San Joaquin Valley using a spatially distributed water-balance model. Spatially distributed water-balance models have also been applied to rice production. A climatic water-balance model was developed to determine the water surplus available for a rice-growing region of eastern India (Kar and Verma 2005).

To include a spatial component in the water-balance model we developed GIS layers describing the monthly components (IR, P, S, F, ETc, RO, D). The components were estimated at multiple spatial scales. Three different versions of each layer were created for the field, subdistrict, and district scale. The field layers described the monthly variation of each component among the fields, the subdistrict layers described the variation of each component among the ten GCID subdistricts, and the district layers described the total monthly component across the GCID.

Water-Balance Components

Irrigation (IR)

Irrigation modeling was based on the GCID and DWR water use reports. The GCID recorded the monthly distribution of surface water to each subdistrict (GCID 2004b, 2005). The GCID did not record the locations of water deliveries within the subdistricts to each field nor to which crop.

The DWR (2000) crop water-use estimates were used to determine the average amount of water applied to the nonrice crops in each subdistrict. The amount of water applied to nonrice crops was calculated by multiplying the average amount of applied water to each nonrice crop by its acreage in the GCID. This annual total was divided across the dry months when irrigated water would be applied to nonrice crops and also divided by the ten subdistricts.

To estimate the amount of water distributed to the rice fields in each subdistrict, the total amount of water applied to nonrice crops was subtracted from the total irrigation water delivered to each subdistrict. The total amount of rice irrigation water distributed to the district was calculated by summing the total volume of rice irrigation water in each subdistrict. The amount of irrigation water distributed to each rice field was based on field size. In each subdistrict the average volume of applied irrigation water per hectare was determined. Then the average volume of irrigation water per hectare was multiplied by the size of each field.

In the 2003 system there was 95,000 ha-m of irrigation input. In the 2004 system there was 105,000 ha-m of irrigation input. Within a subdistrict the amount of irrigation water was assumed to be proportional to the field size. There were no prominent spatial irrigation patterns in either 2003 or 2004 (Figure 3). Temporal patterns of irrigation inputs were similar in 2003 and 2004, as irrigation peaked during the

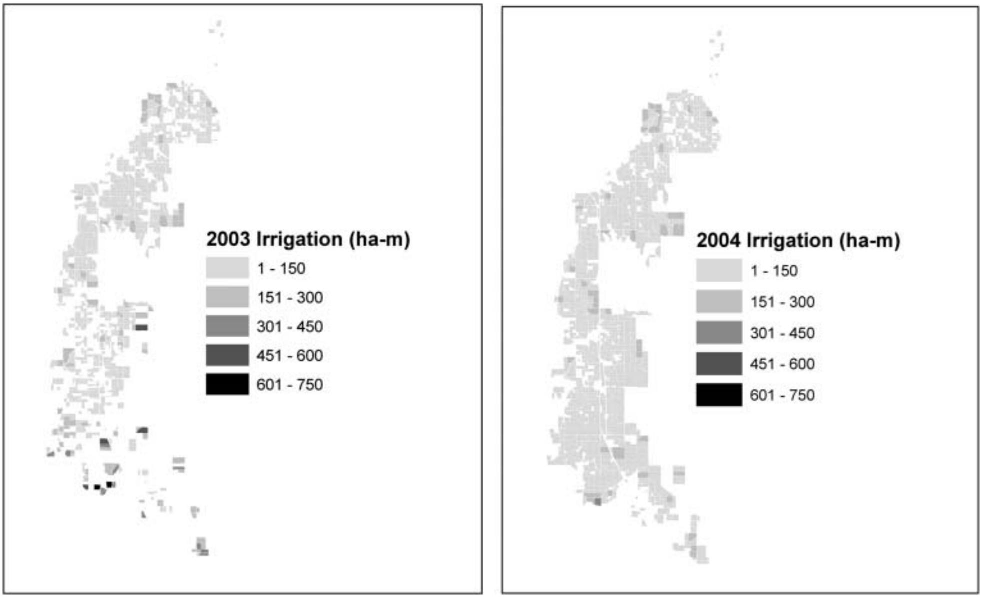

Figure 3 *Glenn-Colusa Irrigation District (GCID) irrigation. Source: GCID (2004b, 2005).*

summers, dropped for the harvests, increased for fall floodings, and was minimal during winters (Figure 4).

There was a discrepancy between the estimated total applied irrigation in the summer of 2003 and the summer of 2004. The 2003 fields received an estimated average of 3.6 ha-m/ha of irrigation, and the 2004 fields received an estimated average of 2.6 ha-m/ha of irrigation. Given that the evapotranspiration rates for

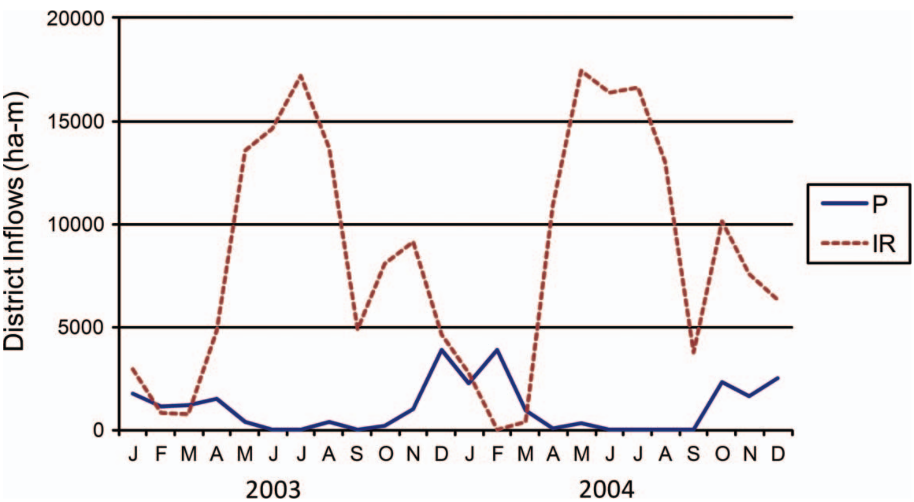

Figure 4 *Monthly district inflows. Note: P = precipitation; IR = irrigation.*

2003 and 2004 were very similar, the discrepancy between the 2003 and 2004 irrigation rates was probably due to problems with the model. We did not estimate the water that might have flowed through the subdistrict and was never taken up on a field. In 2003 a large number of fields were fallowed to participate in an interdistrict water transfer (GCID 2004b). This could have altered the proportion of water going to the rice fields compared to the water passing through the system.

Additionally, we did not account for water used on multiple fields. An upstream grower might use water on a field and release the excess water back in the canals several days later. This water is then available for use by downstream growers. In 2004 there was much higher demand for water, due to changes in pest management. The district met the higher demand with increased use of recaptured water (GCID 2005).

Precipitation (P)

Precipitation was modeled from observations taken at ten weather stations. The stations were chosen from the California Irrigation Management Information System (CIMIS), the National Oceanic and Atmospheric Administration Cooperative, and the Leslie Nickels Soil Laboratory. The daily observations from these stations are reported online at the UC Integrated Pest Management (2006) Web site. Weather stations are located throughout the Sacramento Valley, but no appropriate stations are located within the GCID. The ten stations surrounded the GCID, so they characterized meteorological changes across the latitudinal and longitudinal gradients. The ten stations had similar elevations to the GCID. Elevations within the GCID ranged from 13 to 130 m (California Spatial Information Library 1997). The weather stations ranged from 12 to 240 m (UC Integrated Pest Management 2006). Although not ideal, the existing stations recorded observations that were assumed to be representative of the weather patterns in the GCID.

The daily totals for each station were summed over months. A spline interpolation was used to approximate the monthly precipitation across the GCID. The values of the interpolated surface cells were summed to determine the total precipitation for each field, subdistrict, and district. Most of the precipitation in the region came in the form of rain. Precipitation accounted for approximately 10 percent of the overall inputs to the water-balance systems in 2003 and 2004. Approximately 11,000 ha-m of precipitation were added to the 2003 rice field system, and approximately 14,000 ha-m were added to the 2004 rice field system. The greater amount of 2004 precipitation inputs was at least partly due to an increase in the overall size of the system. In 2004 more rice fields were cultivated. The 2004 precipitation increase was also due to changes in rainfall patterns (Figure 4). The winter of 2003–2004 was much wetter than the preceding and following winters. Additionally, the summer of 2003 was slightly wetter than in 2004, due to an August 2003 rain event. Spatially the rain patterns did not appear to vary much between 2003 and 2004 (Figure 5). In 2003 and 2004 more rain fell in the north and south than in the center of the GCID.

Evapotranspiration (ET)

Evapotranspiration of rice was modeled with observations from six weather stations. The weather stations are part of the CIMIS network. As with the precipitation weather stations, the evapotranspiration stations surround the GCID but are not located within the GCID. CIMIS weather stations do not directly measure evapotranspiration, but they do measure variables such as temperature, precipitation, solar radiation, and relative humidity (California Department of Water Resources 2007). To estimate evapotranspiration we used the Basic Irrigation Scheduling (BIS) model (Snyder et al. 2000). BIS was developed by the DWR and UC Cooperative Extension as a tool to improve irrigation management for various California crops. BIS uses meteorological observations from CIMIS weather stations to determine when growers should irrigate their crops. As part of its calculations the BIS model estimates the specific daily reference evapotranspiration (ETo) using the modified Penman–Monteith and the crop evapotranspiration (ETc) for various crops (Allen et al. 1998). Daily ETo and ETc were estimated for the location of the weather station where the input observations

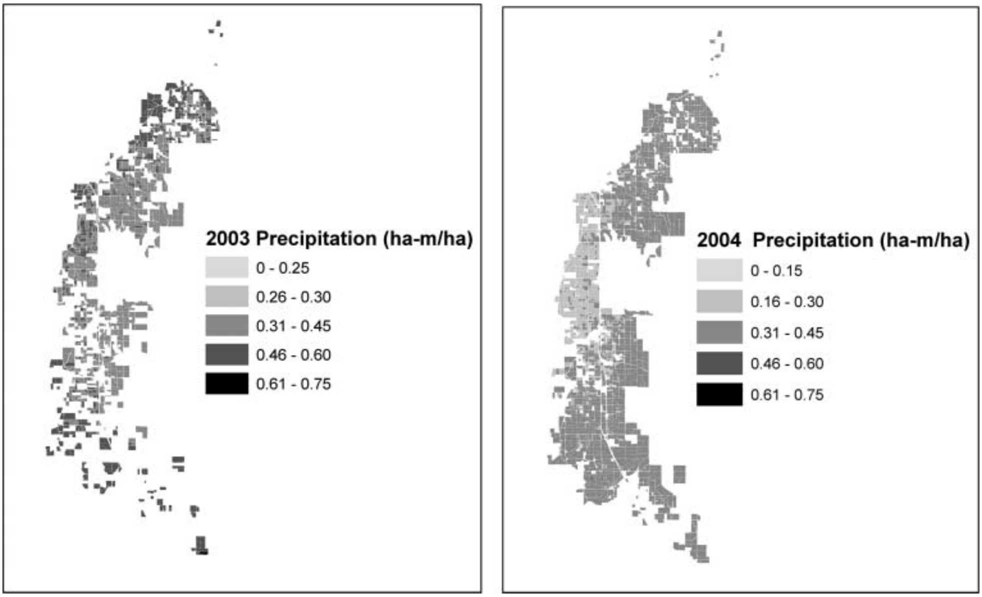

Figure 5 *Glenn-Colusa Irrigation District (GCID) precipitation. Sources: GCID (2004b, 2005), University of California Integrated Pest Management (2006).*

were recorded. BIS modeled ETc of rice using the estimated ETo and the rice crop coefficient.

Using the BIS model we calculated the daily ETc of rice at each of the six weather stations. The daily ETc estimates were summed to determine the monthly ETc losses at each of the weather stations throughout 2003 and 2004. A spline interpolation was used to determine monthly ETc across the entire GCID surface. Then cells of the interpolated surface were summed to determine the monthly ETc losses for each field, subdistrict, and district.

The estimated total evapotranspiration losses were much lower in 2003 than in 2004. In 2003 approximately 26,000 ha-m of water left the system through evapotranspiration. In 2004 approximately 45,000 ha-m of water left the system through evapotranspiration. The 2004 increase in evapotranspiration was probably due to the increase in the overall size of the system. Despite the change in system size, the overall seasonal rates of evapotranspiration were very similar between 2003 and 2004 (Figure 6). Most of the evapotranspiration occurred during the summer months, and 2003 and 2004 had similar summer evapotranspiration rates. Likewise, the spatial patterns of 2003 and 2004 evapotranspiration were very similar (Figure 7).

Surface Runoff (RO)

Surface runoff was modeled from the GCID drain outflow estimates. Water entered the system from the main input canal along the western edge of the district, flowed southeast, and left the system through eleven drains along the eastern edge of the district. The GCID assumed their drain measurements only captured 80 percent of the actual outflow (GCID 2004b 2005). We estimated the actual outflow from each drain by increasing the GCID's drain measurements by 20 percent. In 2003 annual estimated drain flow ranged from 1,600 ha-m to 11,000 ha-m. We assumed that all of the estimated water leaving through the GCID drains was surface runoff from rice fields and that runoff from other crops grown in the GCID was negligible.

We used the estimated runoff to each of the GCID drains to approximate the amount of surface runoff from each field. By assuming that water flowed downhill to the nearest canal, we reconstructed the GCID drainage system and

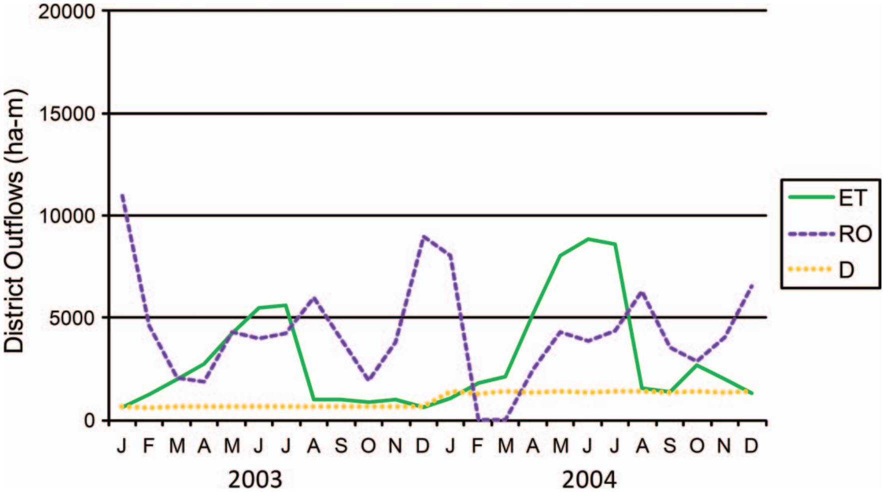

Figure 6 *Monthly district outflows. Note: ET = evapotranspiration; RO = runoff; D = percolation.*

approximated the pattern of drain, canal, and field connectivity. We divided the amount of estimated monthly outflow from a drain equally among the fields that contributed to that drain.

To determine surface runoff from each subdistrict we summed all of the field runoff in each subdistrict. The total district surface runoff was the sum of the subdistricts' surface runoff.

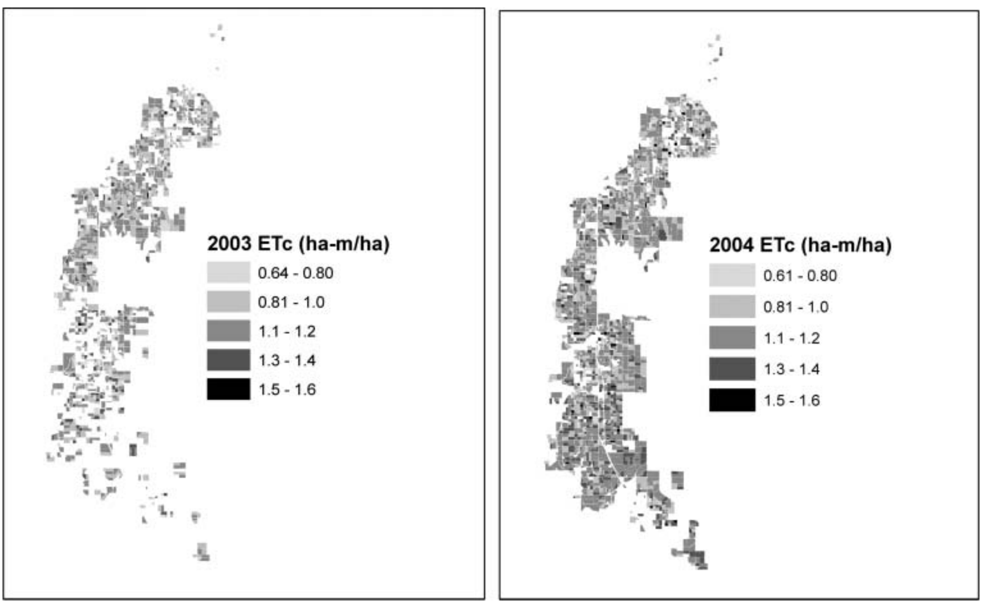

Figure 7 *Glenn-Colusa Irrigation District (GCID) evapotranspiration. Sources: GCID (2004b, 2005), University of California Integrated Pest Management (2006).*

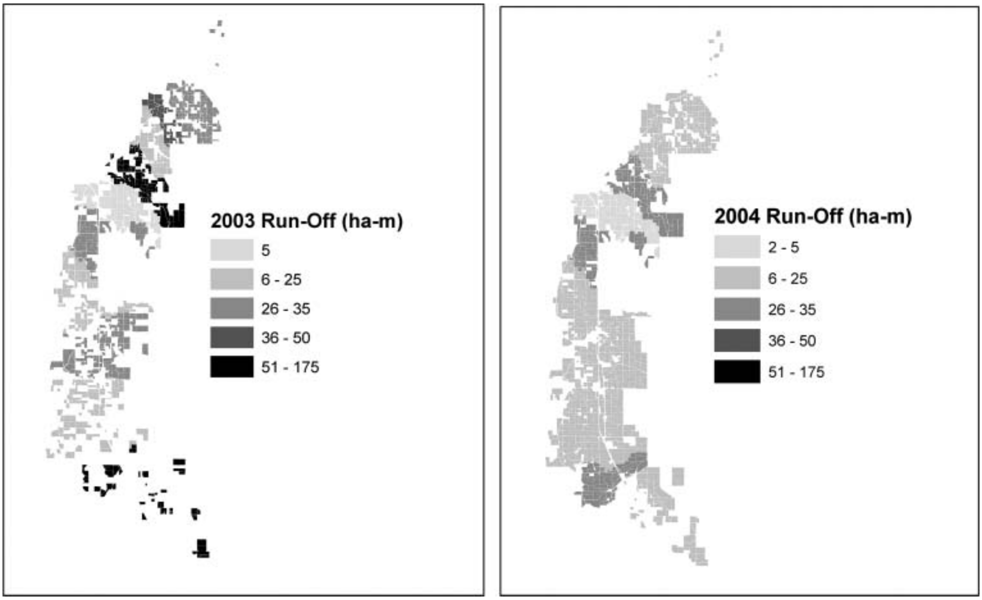

Figure 8 *Glenn-Colusa Irrigation District (GCID) surface runoff data. Sources: GCID (2004b, 2005).*

In 2003 it was estimated that 58,000 ha-m of water left the system as surface runoff. The surface runoff for 2004 was estimated to be 46,000 ha-m of water. This was surprising given that there were more precipitation and irrigation inputs in 2004 than in 2003, and estimated evapotranspiration rates were similar in 2003 and 2004. Perhaps the decrease in runoff was related to the increase in the number of 2004 rice fields and recaptured water use, which was not included in this model. There might have also been greater percolation amounts and soil storage in 2004 because the water was spread across greater numbers of fields, resulting in less surface runoff.

In 2004 the average field was estimated to have 16 ha-m of runoff. In 2003 the average field runoff was 30 ha-m, but there were eighty fields in the southern end of the study site that averaged greater than 100 ha-m of runoff (Figure 8). The large amounts of surface runoff in the southern fields might be a result of inappropriate modeling assumptions. We assumed that only water from fields in a drainage catchment flowed to a drain. Perhaps water from up-system catchments was being measured at downstream drains.

Although the estimated magnitude of surface runoff was greater in 2003 than in 2004, the 2003 and 2004 temporal patterns of surface runoff were similar (Figure 6). In both 2003 and 2004 there were surface runoff peaks in December and January, followed by a drop of runoff during February and March. The other noticeable peak was in August 2003 and August 2004 prior to the rice harvests.

Percolation

Percolation was estimated using previous field observations and the digital Soil Survey Geographic (SSURGO) Database. The water outputs of a California rice system, evaporation, surface runoff, and percolation, tend to be of similar orders of magnitude (Williams 2003b). Following Williams's estimations there is a percolation-to-evapotranspiration ratio of 1:2.72. In 2003 we estimated that 26,000 ha-m of water left the system via evapotranspiration. Therefore, Williams's ratio predicts that 9,700 ha-m would have left the system via percolation. In 2004 we estimated that approximately 45,000 ha-m of water left the system through evapotranspiration; therefore, 16,000 ha-m of water would have left via percolation (Figure 6).

SSURGO soil data were used to estimate how this percolation was spatially distributed. Large areas of the study site had some sort of restrictive soil layer, such as cemented hardpan (Soil Survey Staff, Natural Resources Conservation Service [NRCS], and United States Department of Agriculture [USDA] 2007a, 2007b). Thirty percent of the study site has such a restrictive soil layer. Restrictive layers tend to be in the northern and western parts of the study site. Because of the lack of vertical water flows in these areas, the percolation was assumed to be zero. The estimated percolation was distributed across the remaining 70 percent of the study site based on variations in minimum saturated hydraulic conductivity (Ksat).

SSURGO's saturated hydraulic conductivity provides an estimate of the spatial variation in relative flow rates under the flooded conditions across our study site (Soil Survey Division Staff 1993). Each soil map unit was assigned the minimum conductivity of its horizons. Seventy-five percent of the study site had soils with minimum conductivity below 1 μm/s (Soil Survey Staff, NRCS, and USDA 2007a, 2007b). Conductivity was especially low in the southern area of the study site.

The field polygons were overlaid with the saturated hydraulic conductivity polygons, and the conductivities attribute was averaged for each field. To calculate the monthly saturated flow volumes for each field, the saturated hydraulic conductivity rate was multiplied by the field area and the time in a month.

$$FlowVolume = Ksat^{*}FieldArea^{*}Time \qquad (2)$$

The SSURGO flow volumes indicate the spatial variability of conductivity across the study site, but they assume constant flow through time and do not account for alterations to the rice field soils over many years of rice production that minimize percolation. In 2003 more than 830,000 ha-m of water would have left the system through constant flow, and in 2004 more than 1,100,000 ha-m of water would have left the system through constant flow. Williams's ratio estimated that the system percolation would have been 1.1 percent of the annual Ksat flow volumes, so the field flow volumes were weighted by 1.1 percent. Weighting the SSURGO flow volume estimates preserved the spatial variability of the spatial percolation model (Figure 9) while maintaining the total percolation volumes predicted by the Williams's ratio.

Soil Storage (S)

Soil water storage was estimated from the SSURGO database. Saturated soil storage is the water that has infiltrated the soil profile under prolonged flooded conditions. In California, rice soils are flooded throughout most of the year, so it was assumed that most of the soil pore spaces were saturated with water. Pore space was assumed to represent the maximum volume of water held in soil storage. We calculated pore space based on the bulk density and particle density of each soil horizon. In the study site bulk density ranged from 1.0 to 1.7 Mg/ m^3. Particle density was not reported for the study site (Soil Survey Staff, NRCS, and USDA 2007a, 2007b). Because the study site soils typically had less than 5 percent organic matter, we assumed a constant particle density of 2.65 Mg/m^3 (Brady and Weil 1999; Soil Survey Staff, NRCS, and USDA 2007a, 2007b). Percentage pore space was calculated from bulk density and particle density of each soil horizon

$$\%PoreSpace = 100 - \left(\frac{BulkDensity}{ParticleDensity} \times 100\right) \qquad (3)$$

Inversely related to bulk density, percentage pore spaced ranged from 36 to 62 percent across the study site.

To determine the total pore space of each soil horizon we multiplied the total volume of each horizon by its percent pore space. Then the volume of pore space for each horizon in a map unit was totaled to determine the total volume of pore space for each SSURGO map unit polygon. This total pore space volume was assumed to be the total volume of water in saturated soil storage. Similar to the percolation component, the GCID field polygons were overlaid with the soil saturated water map unit polygons to determine the amount of water in the soil

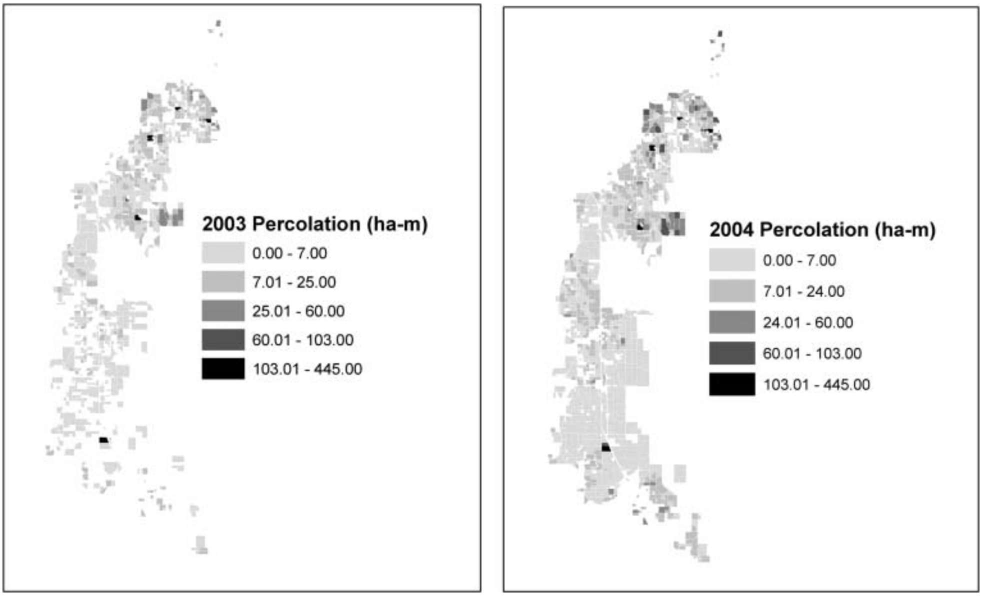

Figure 9 *Glenn-Colusa Irrigation District (GCID) percolation. Sources: GCID (2004b, 2005), Soil Survey Staff, Natural Resources Conservation Service, and United States Department of Agriculture (2007a, 2007b).*

profile of each field. The GIS intersect of the field polygons and the soil polygons resulted in an output layer where most fields were split into multiple soil types. The soil saturated water volumes attributes were averaged for each field to reaggregate the field polygons. To scale up to the subdistrict scale the soil saturated water volume for each field in a subdistrict were summed. To scale up to the district scale, the soil saturated water volumes for all subdistricts were summed.

The maximum potential amount of water held in saturated soil storage varied across the GCID. Estimated soil storage was greatest in the southern region of the GCID (Figure 10). The maximum potential amount of soil storage available per field did not vary through time, as the soil properties were assumed to be constant. The increase in soil storage from 2003 to 2004 reflected the higher number of rice fields in production during 2004, not a change in soil properties. Unlike the other model components, water saturated soil storage is not an inflow to or outflow from the water-balance system. Instead, it represents the maximum portion of water that may be stored within the soil (Figure 2).

In-Field Surface Storage (F)

In-field surface water-holding capacity calculations were based on the GCID land-use data and the UC estimations. The GCID produced GIS layers detailing the 2003 and 2004 fields in rice production. GIS attributes included location, shape, and area of the rice fields. To avoid weed problems, the UC Cooperative Extension recommends that fields should be flooded with 0.10 to 0.13 m of water during most of the growing season (Hill et al. 1992). Late in the rice-growing season, the water should be raised to 0.20 m to protect the maturing rice from cold night air (Hill et al. 1992). The actual timing of the increased flooding depends on the rice variety.

To determine the maximum in-field surface water-holding capacity, the recommended height of the water was multiplied by the area of each field. The amount of surface water held in each field varied across the GCID based on field size. The total volume of field water in a subdistrict was determined by adding the volumes of water in all fields in that subdistrict. The total amount of field water in the district was determined by adding the volumes of water in all subdistricts. There was higher field

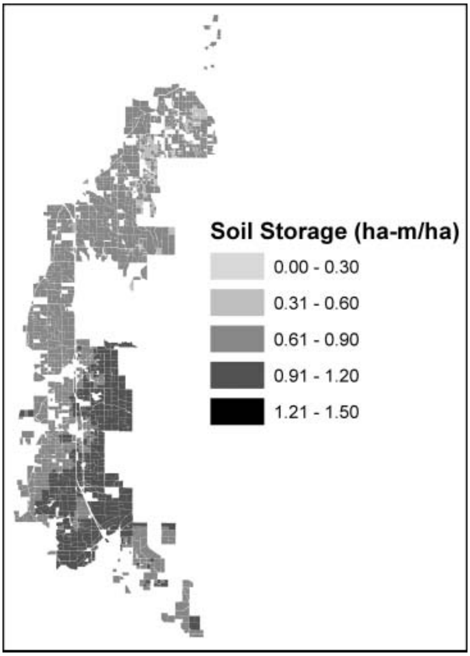

Figure 10 *Glenn-Colusa Irrigation District (GCID) saturated soil storage. Sources: GCID (2004b, 2005); Soil Survey Staff, Natural Resources Conservation Service, and United States Department of Agriculture (2007a, 2007b).*

capacity in 2004 than in 2003, because there were more fields in the system in 2004.

The surface water-holding capacity is an estimate of the maximum amount of water that can be held in the fields. The amount of water actually in the system is not modeled and might be less than the estimated maximum. Growers can add water to the fields, allow the water to gradually draw down through evapotranspiration and percolation, and then replenish the water when it gets too low for effective weed management or rice growth. As the water is gradually drawn down, especially when stopping water inflows in preparation for harvest, the field has less water than its maximum holding capacity. Additionally, growers might not follow the recommendations of the UC Cooperative Extension due to variations in-field shape and weed management practices. Even with precision leveling the depths of the basins do vary. The deeper end of the basin will have higher water levels. Additionally, some herbicides require lowered water levels during application.

Total Storage Capacity

To determine the total storage capacity, the soil storage and the field storage layers were added together. During most of the 2003 rice-growing season there was an estimated 23,000 ha-m of potential storage across the entire district; at the end of the season there was 25,000 ha-m of potential storage. During most of the 2004 rice-growing season there was an estimated 39,000 ha-m of total potential storage; at the end of the season there was 42,000 ha-m of total potential storage. Across the twenty-four months of the study the total storage capacity never dropped below 20,000 ha-m of water.

Discussion

The contributions of each component varied throughout the year. Irrigation was the dominant input during the summer growing season and during the fall months as growers reflooded the fields. Precipitation was highest during winter months (Figure 4). Evapotranspiration peaked during the hot summer months, and surface runoff increased when growers drained their fields and during the early winter rainy season (Figure 6). Percolation was constant throughout the year (Figure 6). Among the components, percolation was the most problematic. Because estimated percolation was adjusted to fit the magnitude of the other water-balance inputs and outputs, it was not an independent estimate. Instead, it reflected the variation of percolation across the GCID.

In a water-balance model it is expected that over time the amount of water entering the system will be equal to the amount leaving the system (Equation 4a). The water model was assessed by determining if the equation was balanced (Equation 4b).

$$(IR + P) = (ETc + RO + D) + e \tag{4a}$$

$$(IR + P) - (ETc + RO + D) = e \tag{4b}$$

The monthly spatial layers were added (Figure 11). The closer to zero the sum was, the more balanced the model. Positive results indicated that more water flows into the system than flows out, and negative results indicate more outflows than inflows. For comparison the monthly district inflow and outflows were

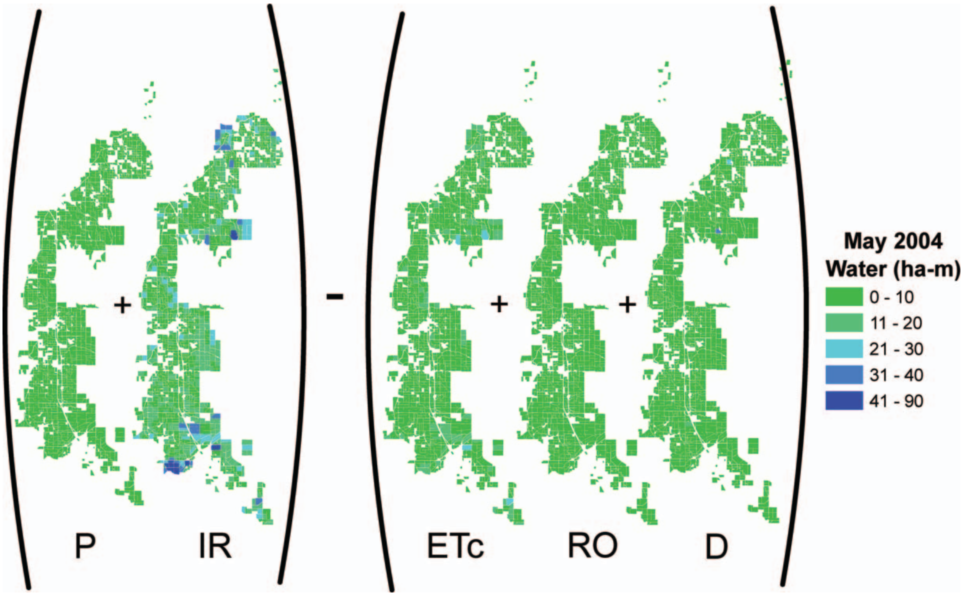

Figure 11 *Adding May 2004 water-balance layers (ha-m). Note: P = precipitation; IR = irrigation; ETc = crop evapotranspiration; RO = runoff; D = percolation. Sources: Glenn-Colusa Irrigation District (2004b, 2005); Soil Survey Staff, Natural Resources Conservation Service, and United States Department of Agriculture (2007a, 2007b); University of California Integrated Pest Management (2006).*

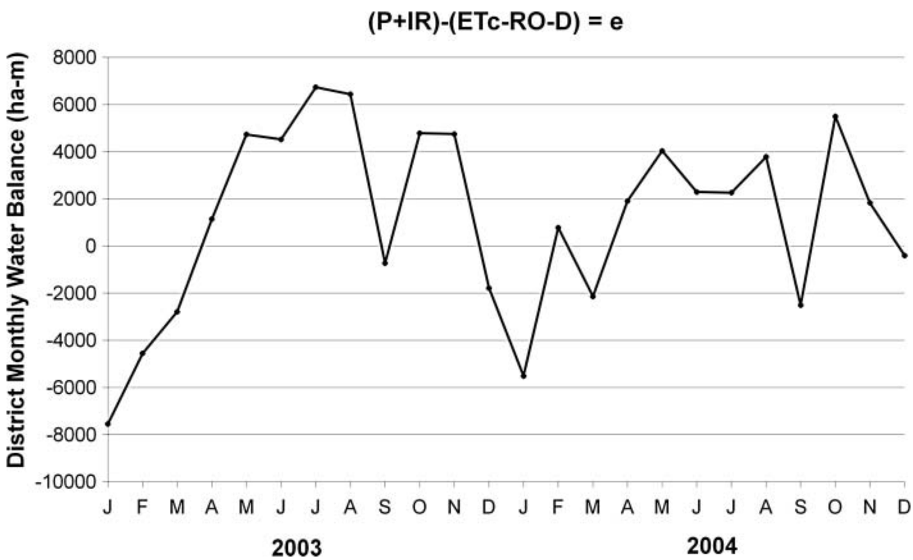

Figure 12 *Error factor: Total monthly district flows. Note: P = precipitation; IR = irrigation; ETc = crop evapotranspiration; RO = runoff; D = percolation; e = error.*

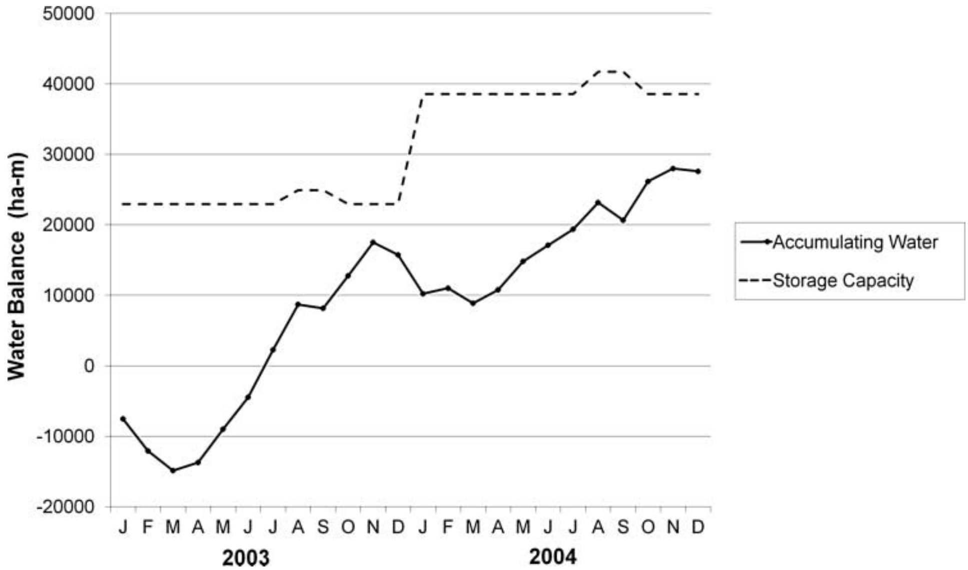

Figure 13 *Accumulating water balance across 2003–2004.*

totaled (Figure 12). The model was most balanced at the beginning and the end of the rice-growing season. Summer months tended to have greater inputs than outputs, indicating increased storage in the system. During the winter months the model tended to overestimate outflow.

The imbalance was assumed to be the monthly error factor. The error values represent a combination of factors. Although not quantified individually, each model component is subject to errors. In addition to the measurement errors, irrigation and surface runoff estimations might not have correctly interpreted how water moves through the rice production system. For example, recaptured water was not included in the model. Precipitation and evapotranspiration estimations were subject to errors with the field instrumentation and the interpolation and evapotranspiration models. Much of the error could be due to the weighted percolation component. Another problem with the model is the lack of information on lateral hydraulic flow. Some error might also be due to the omission of groundwater flow.

The most problematic aspect of the error values is their relationship with the storage components. Because this is a dynamic model, the amount of water entering the system might not immediately leave the system, and some of it could be temporally stored within the system's soil or field surfaces. The amount of water in the system is equivalent to the amount of water entering the system minus the amount of water leaving the system (Equation 1). Although the total storage capacity of the system was estimated, the actual contribution of water in storage was not assessed. The change in water storage was not included in this model and cannot be separated from the error factor.

One check on the model was that the error factor should not be larger than the total storage capacity of the system. Across the twenty-four months of this project the total storage capacity for the district varied from 23,000 to 42,000 ha-m of water. The excessive amount of monthly inputs and outputs ranged from ±8,000 ha-m of water and never exceeded the potential storage capacity. Even during successive months of excessive water inputs (e.g., April–August 2003), the multimonth total never exceeded the system's maximum storage capacity. A noteworthy drawback with the model is the overall excessive accumulation of water (Figure 13). Over two years there were more inflows than outflows to the system. From January 2003 to December 2004 the overall amount of water in the system increased.

The amount of accumulated water remained less than the storage capacity of the system, but over the long term, the model does not appear to be balancing. Refining the percolation and soil storage inputs might minimize long-term accumulation. Now that the model has been developed it can be applied to other regions and years. Field observations can also be compared with the model's water use estimates.

Conclusion

The multiscale spatial water-balance model is a useful description of rice production water use. The results of the model provide a much needed revision to water use estimates. The model also provides a comparison between a year when many growers sold their water (2003) and a year when most growers did not sell their water (2004). The model and results are robust enough to describe complex hydraulic flows, but they are also straightforward enough to be usable by professionals from many disciplines. With rising concerns over California's water use efficiencies and increasing pressure on rice growers to sell their water to other districts, this study provides much needed information on regional water use. ■

Note

[1] One hectare-meter (ha-m) is equivalent to 10,000 cubic meters (m^3) or approximately 8.1 acre-feet (af).

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