

Use of satellite data to assess the impacts of irrigation withdrawals on Upper Klamath Lake, Oregon

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Abstract. Competition for scarce water resources in the Upper Klamath River Basin, Oregon has generated conflict among its stakeholders, as demonstrated by recent regulations on withdrawals from Upper Klamath Lake. Information on agricultural water usage can help assess the hydrologic impacts of irrigation and support operational decisions. This paper presents an experimental satellite-based evapotranspiration estimation system that is combined with the Variable Infiltration Capacity (VIC) hydrological model to estimate irrigation consumption, which is then used to assess the effects of irrigated agriculture on lake storage volumes and water levels. The hydrological model is calibrated with streamflow observations and used to estimate unmeasured lake inflows and guide water budget calculations. When combined with the VIC model, the satellite-based evapotranspiration estimation system shows that irrigation caused a decline of 0.3 m in average annual water levels and 0.5 m in mean October water levels, and an increase of 0.5 m in annual water level ranges at the lake from 2001 to 2005. The results demonstrate the potential of satellite data for agricultural water resource management at the regional scale.

1 Introduction

Globally, about 67% of water withdrawals from streams, reservoirs, and lakes are used for irrigation, accounting for 87% of the world's consumptive water use (withdrawal minus return flow) and more than 40% of its food supply (Döll and Siebert, 2002). Despite the benefits of irrigation for food production, its impacts on the environment have become of increasing concern. Sustainable management of water resources is required to balance the needs of irrigated agricul-

ture against those of the natural environment. The value of management strategies is in turn dependent on the availability of adequate information about potential water supplies, irrigation demands, and other hydrometeorological conditions at scales ranging from farm fields to river basins.

Estimates of evapotranspiration (ET) from irrigated land can be used as a proxy for agricultural water consumption and allow the assessment of agricultural impacts on streamflow and water bodies. At the regional scale, advanced tools that are available to aid in these estimates include satellite remote sensing data and hydrological models. Hydrological models typically estimate ET through a water balance that represents the linkage of hydrological processes such as precipitation, runoff, and soil moisture (e.g. Liang et al., 1994; Tang et al., 2006, 2007). Most hydrological models simulate “natural” conditions, that is, the interaction of land surface hydrological processes that would occur in the absence of water management by diversions from streams, return flow, and reservoir storage. In principle, spatially distributed hydrological models could be applied to environments influenced by man, if sufficient data were available to quantify the artificial movement and storage of water. In general, though, estimates of large-scale water consumption patterns are limited by the availability of local observations, particularly in irrigated areas containing regulated, but often ungauged, flow in natural and manmade channels. Satellite data offer opportunities to map actual water consumption in large areas, including those regions where measured hydrometeorologic data may be sparse (Engman, 1995), reducing or eliminating the need for detailed knowledge of local water supply systems.

Despite substantial research activity in the estimation of ET via remote sensing (e.g. Nemani and Running, 1989; Bastiaanssen et al., 1998; Stewart et al., 1999; Bastiaanssen et al., 2002; Nishida et al., 2003; Neale et al., 2005), few reports of applications of these methods to regional-scale agricultural water management exist (Bastiaanssen et al., 2000).



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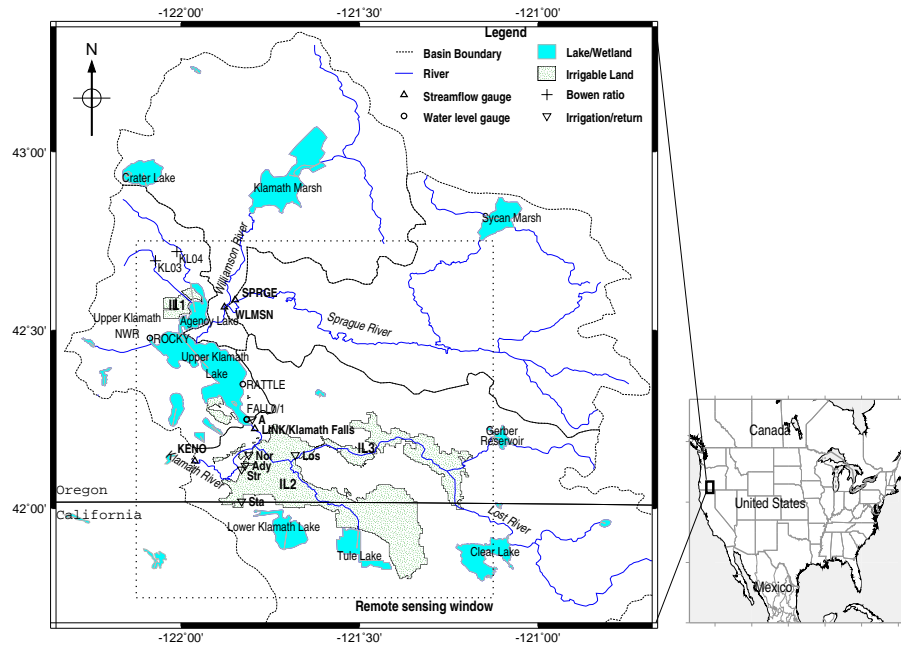


Fig. 1. Upper Klamath River Basin and the remote sensing window (dotted line) in which the satellite-based ET estimation system was implemented.

Two factors pose serious constraints to the operational adoption of remote sensing technology in water resources management. First, the spatial and temporal resolution of sensors that provide information in near real-time is often too coarse to provide useful data on crop water use (Cleugh et al., 2007; Mu et al., 2007). Second, remote sensing estimates of ET are seldom directly comparable to ground-based meteorological observations and streamflow measurements. To address the first constraint, Tang et al. (2009b) developed a satellite-based ET estimation system based on MODIS (MODerate Resolution Imaging Spectroradiometer) and NOAA/NESDIS Surface Radiation Budget (SRB) products. With daily observations at spatial resolutions as high as 250 m, MODIS provides remote sensing data that are suitable for the operational environment. The system presently runs in an experimental mode at the University of Washington (http://www.hydro.washington.edu/forecast/rset_ca/). The second constraint can be addressed by using hydrological models to bridge the gap between remote sensing-based and ground-based measurements of ET.

This paper assesses the impacts of irrigation on regional hydrology through a combination of remote sensing and hydrological modeling techniques. ET estimates based on remote sensing data are used to calculate net irrigation consumption for irrigated areas within the Klamath River basin that are supplied with water from the Upper Klamath Lake. The irrigation consumption estimates are then used in conjunction with reservoir inflow information to assess irrigation-related variations in the lake water depth. An in-

roduction to the study area and data sources is provided in Sect. 2, followed by a description of the experimental methodology in Sect. 3. Results and evaluations are given in Sect. 4. The paper concludes with a discussion on the potential of satellite-based techniques in agricultural water resources management.

2 Study area and data

The Klamath River, draining 40 795 km² of south-central Oregon and north-central California, has become a focal point for local and national discussions on water management and scarcity (Powers et al., 2005). The Upper Klamath River Basin is managed by the US Bureau of Reclamation's (USBR) Klamath Project, which provides irrigation water to about 1000 km² of irrigable land (IL) divided into three main areas of about 50, 700, and 250 km² (IL1, IL2, and IL3, respectively, in Fig. 1). Sources of Project water include Upper Klamath Lake, Klamath River, Clear Lake Reservoir, Gerber Reservoir, and the Lost River, which flows within a closed basin at the southeast corner of the watershed. The Lost River Diversion Channel connects the Lost River to the Klamath River, which flows out of Upper Klamath Lake. Upper Klamath Lake provides water to IL1 and IL2, a portion of which is transferred through the Klamath River and Lost River Diversion Channel. Clear Lake Reservoir and Gerber Reservoir typically provide water to IL3 through the Lost River, although the Diversion Channel has the potential to

Table 1. Sources of streamflow data, water level and storage data at Upper Klamath Lake, and irrigation/return flow data for IL2.

Data Type	Name	ID	Observation Period (mm/dd/yyyy)	Time frequency	Remarks
Streamflow	WLMSN	USGS 11502500	10/1/1917–1/31/2008	Daily	Headwater of the lake
Streamflow	SPRGE	USGS 11501000	3/1/1921–1/31/2008	Daily	Headwater of the lake
Streamflow	LINK	USGS 11507500	10/1/1961–1/31/2008	Daily	Downstream of the lake
Streamflow	KENO	USGS 11509500	6/1/1904–1/31/2008	Daily	Downstream of the lake
Water level	ROCKY	USGS 11505800	9/13/1973–1/31/2008	Daily	At the lake
Water level	RATTLE	USGS 11505900	9/13/1973–1/31/2008	Daily	At the lake
Water level	FALL0	USGS 11507000	10/1/1969–1/31/2008	Daily	At the lake
Water level	FALL1	USGS 11507001	10/1/1974–1/31/2008	Daily	At the lake
Water Storage	KLM	CDEC KLM	10/1954–1/2008	Monthly	At the lake
Irrigation	A	“A” Canal	1/1/2001–12/31/2005	Daily	Conveys water from Upper Klamath Lake to IL2
Irrigation/return flow	Los	Lost River Diversion Channel	1/1/2001–12/31/2005	Daily	Includes several diversions and return flows (see Risley et al., 2006).
Irrigation	Nor	North Canal	1/1/2001–12/31/2005	Daily	Conveys water from Klamath River to IL2
Irrigation	Ady	Ady Canal	1/1/2001–12/31/2005	Daily	Conveys water from Klamath River to IL2
Return flow	Str	Straits Drain	1/1/2001–12/31/2005	Daily	Conveys drainage from IL2
Return flow	Sta	Ady Canal State-line	1/1/2001–12/31/2005	Daily	Provides water to Lower Klamath Lake

supplement IL3’s supply with water from Upper Klamath Lake (USBR, 2005; Risley et al., 2006).

Upper Klamath Lake is a large, shallow freshwater lake that has been regulated as part of the Project since 1919, when the natural lake was diked to establish a new perimeter for its open water surface. The lake’s surface elevation fluctuates from 1261 to 1264 m due to regulation of its water supply. The lake has a surface area of 271 km² (including Agency Lake). Several large marshes, including Upper Klamath National Wildlife Refuge (NWR), are located at its margins, although the area of these marshes has been greatly reduced as a result of diking and water level management.

Water level fluctuations are an important factor in emergent vegetation species composition and dynamics. Persistently high lake levels may lead to a substantial reduction in the extent of wetlands and to the dominance of species relatively tolerant to constant water depths. Low lake levels may have adverse consequences by exposing wetland floors. The effects of widely varying water levels are less well known (USFWS, 2001a). Water levels have become a focus of recent biological assessments, generating conflict among various interest groups, including farmers, commercial and sport fishermen, federal wildlife refuge managers, environmental groups, and state, local, and tribal governments (USFWS,

2001a; USBR, 2002; Lewis, 2003; NRC, 2004, 2008). In a very dry period in 2001, the US District Court stopped water deliveries to farms in the irrigation area to preserve adequate water levels for the protection of two endangered species of Mullet fish (also known as suckers). The effect of irrigation on lake water levels is therefore not only of scientific interest, but carries political implications as well.

Daily water level observations of Upper Klamath Lake are available from the US Geological Survey (USGS), and monthly lake storage data can be found at the California Data Exchange Center (CDEC) (Table 1). Stage-storage relationships for the lake were developed from monthly averaged water level and water storage data (Fig. 2). These relationships were then applied to the daily water level observations to estimate daily storage volumes within the lake. Estimated daily storage volumes are plotted in Fig. 3, and show good agreement with the monthly storage data from CDEC. Two USGS streamflow stations (WLMSN and SPRGE) are located near the headwaters of the lake and measure runoff from the Williamson River and Sprague River, a tributary of the Williamson. Runoff in the region between WLMSN and LINK is unmeasured and must be estimated to account for total inflow to the lake. A USGS station at Klamath Falls (LINK) gauges only a part of the lake’s outflow; data for

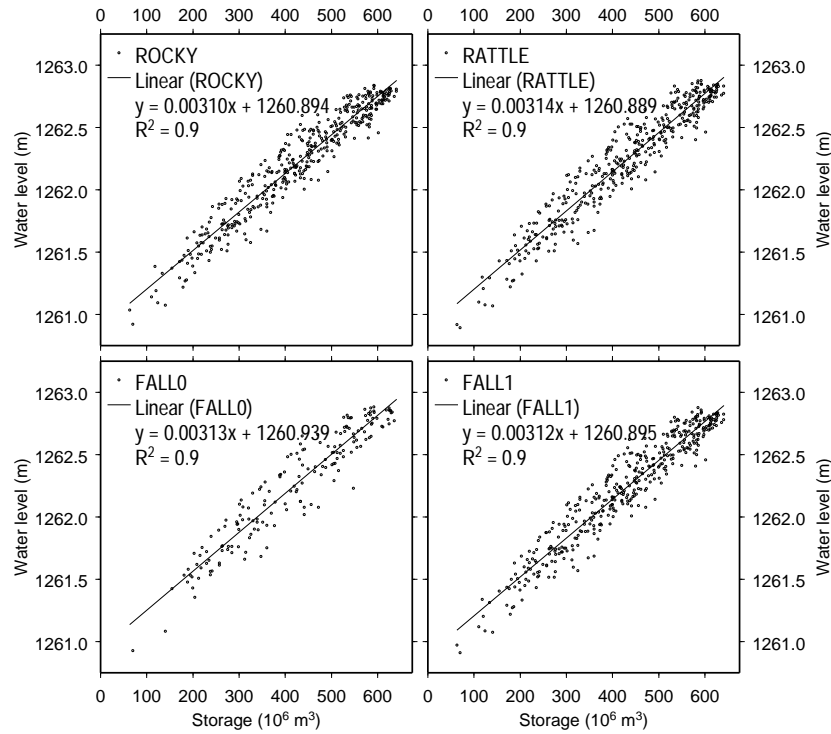


Fig. 2. Stage-storage curves for Upper Klamath Lake.

the remaining portion of the outflow are unavailable. Table 1 also lists the six locations in IL2 at which irrigation and return flows are measured (“A” canal, Lost River Diversion Channel, North Canal, Straits Drain, and Ady Canal at Stateline). These sites are operated by USBR and various irrigation/drainage districts (Risley et al., 2006).

3 Methodology

We estimated the effects of irrigation on Upper Klamath Lake water levels using a daily water budget approach:

$$D_s = A_{\text{lake}} \Delta D = I_{ws} + I_{\text{roff}} + P_{\text{lake}} - E_{\text{lake}} - O_{\text{irr}} - O_{\text{fall}} \quad (1)$$

where D_s (m^3) is lake water storage change; A_{lake} (m^2) is lake area; D (m) is lake water depth; I_{ws} (m^3) is daily streamflow from the Williamson River watershed measured at WLMSN; I_{roff} (m^3) is unmeasured runoff in the region between USGS stations WLMSN and LINK; P_{lake} (m^3) is precipitation over the open water surface of the lake; E_{lake} (m^3) is evaporation over the open water surface of the lake; O_{fall} (m^3) is regulated outflow from the lake at Klamath Falls to the Klamath River downstream; and O_{irr} (m^3) is water withdrawn for irrigation purposes. Because observations were only available for a portion of the lake’s outflow, a broad-crested weir equation was used to determine O_{fall} (Fenton, 1992; Hager and Schwalt, 1994; Fritz and Hager, 1998).

$$O_{\text{fall}} = B(D - D_{\text{min}})^{3/2} \quad (2)$$

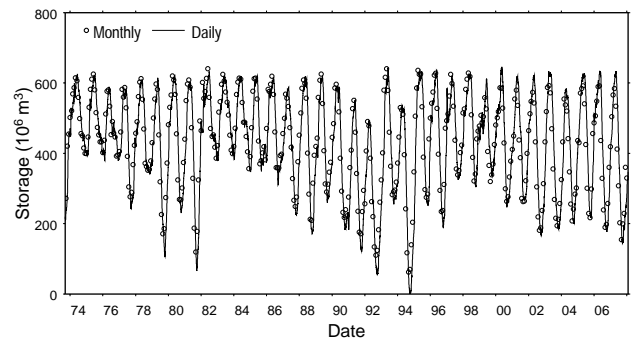


Fig. 3. Recorded monthly and estimated daily storage volumes in Upper Klamath Lake from 1974 to 2008.

where B is an integrated discharge coefficient adjusted to a value of 60 and D_{min} (m) is the minimum lake water depth set at 0.9 m. A maximum storage level was fixed at $635 \times 10^6 \text{ m}^3$, with excess volumes contributing to lake discharge as O_{fall} .

O_{irr} was set to equal the net irrigation consumption under various scenarios, as calculated by:

$$\text{CON}_{\text{irr}} = \text{ET}_{\text{actual}} - \text{ET}_{\text{natural}} \quad (3)$$

where $\text{ET}_{\text{actual}}$ is the actual ET that exists in the irrigable lands under irrigated conditions, and $\text{ET}_{\text{natural}}$ is the hypothetical ET that would exist in the irrigable lands under natural conditions. $\text{ET}_{\text{actual}}$, $\text{ET}_{\text{natural}}$, and the remaining

terms in Eq. (1) (I_{roff} , P_{lake} , and E_{lake}) were determined as described below.

The conventional (without irrigation algorithm) VIC macroscale hydrology model (Liang et al., 1994) was employed to simulate the regional hydrology under natural conditions. VIC is a semi-distributed grid-based model that is typical of the land surface schemes now used in many numerical weather prediction and climate models (Mitchell et al., 2004); it does not account for human regulation of streamflow or water diversions. The model is forced with daily precipitation, maximum and minimum temperature, and daily averaged wind speed, which are obtained from the NOAA Cooperative Observer (Co-op) network and processed into model forcing grids at 1/16 degree spatial resolution (Maurer et al., 2002; Tang et al., 2009a). For this study, the VIC model was calibrated with observed streamflow data recorded from 1950 to 2005 at USGS stations SPRGE and WLMSN (Fig. 1). The calibrated model was then used to simulate the unmeasured runoff between stations WLMSN and LINK (I_{roff}). P_{lake} and E_{lake} were obtained from precipitation and evaporation estimates in grid cells containing open water surfaces. The hypothetical ET that would exist without irrigation (ET_{natural}) was calculated in grid cells containing land surfaces by applying the principle of mass conservation to observed precipitation and discharge. The VIC lake algorithm (Hostetler and Bartlein, 1990; Bowling et al., 2000) was used to estimate ET in grid cells containing marsh, wetlands, and lakes.

Although observations of actual ET that exists with irrigation (ET_{actual}) are available, these measurements are sparse, and the combination of hydrological models and satellite data offer opportunities to improve their spatial and temporal resolution. We examined two methods for estimating ET_{actual} , i.e., total crop water consumption, in those grid cells containing irrigable lands. The first approach employed the VIC irrigation model described by Haddeland et al. (2006). In order to provide a realistic vegetation parameterization, MODIS LAI data (MOD15A2) were directly assimilated into the model for the period 2001 to 2005; prior to 2001, when MODIS data were unavailable, mean monthly MODIS values were assumed. One drawback to this method involves the model's assumptions about how and when irrigation water is added to remove the deficit between the model's simulated soil moisture and field capacity. These assumptions are somewhat difficult to verify in practice and can have a considerable effect on the model's estimate of crop water use.

In contrast, satellite-based methods offer opportunities to estimate actual ET without detailed knowledge of local water data such as soil parameters. This motivated our second approach, which employed the satellite-based ET estimation system developed by Tang et al. (2009b) to retrospectively estimate ET in the irrigation area of the basin (Fig. 1) from 2001 to 2005. The system is based on the MODIS and NOAA/NESDIS SRB products, has daily calculation time steps, and is employed at about a 250 m spatial resolution.

ET is estimated via a VI- T_s diagram method, in which the primary parameters, vegetation index (VI) and surface temperature (T_s) are derived from satellite data (Nemani and Running, 1989; Carlson et al., 1995; Jiang and Islam, 2001).

The VI- T_s method works best over areas where there is substantial diversity in vegetation types within the remote sensing window, and hence diversity of VI- T_s combinations (Roerink et al., 2000; Courault et al., 2005). This condition is well met by the substantial contrast in VI and T_s across the interface between irrigated cropland and surrounding areas (Tang et al., 2009b). Tang et al. (2007) compared ET from the VI- T_s method with three AmeriFlux tower observations in California and showed that ET biases can be significantly reduced over long averaging periods, although substantial discrepancies in instantaneous ET estimation remain in savanna and forest ecosystems.

A significant drawback to the VI- T_s diagram method is cloud/aerosol contamination of the optical remote sensing data. In the ET estimation system, the vegetation index (i.e., normalized difference vegetation index, NDVI) is calculated from MODIS daily surface reflectance data (MOD09GQ) using an 8-day maximum compositing method; the 16-day maximum compositing vegetation index product (MOD13Q1) is employed as auxiliary data in the case of 8 continuous cloudy days. T_s is obtained from the MODIS land surface temperature (LST) product MOD11A1. For days when cloudy conditions prohibit data acquisition, the surface temperature for the closest available day is used instead. Although the surface temperature can have large day-to-day variations, small day-to-day variations of evaporative fraction, defined as the ratio of ET to available energy, and energy conservation effectively constrain errors from this source (Tang et al., 2009b). Because the system uses only satellite data to estimate ET, it is well suited for large-scale regions in which ground observation networks cover only a small portion of the land surface.

Daily ET estimated by the satellite-based system have been found to agree reasonably well with ground Bowen ratio observations in the Upper Klamath River Basin (see Fig. 1), as well as a more sophisticated satellite-based ET mapping system with internalized calibration (METRIC) (Allen et al., 2007; Tang et al., 2009b). The system provides high temporal and spatial resolution estimates of actual water consumption, which describes depletion from all water sources, including precipitation, irrigation, groundwater, and soil moisture in the unsaturated zone. The system simulates ET independently from the models and accounts for human regulation of streamflow and water diversions.

Net irrigation consumption (CON_{irr}) was determined through Eq. (3) by substituting the actual ET estimated by each of these two methods for ET_{actual} and the hypothetical ET estimated by the conventional VIC model for ET_{natural} . In the following discussion, CON_{irr} based on actual ET estimated by the VIC irrigation model is referred to as VIC_{irr} , and CON_{irr} based on actual ET estimated by the satellite-

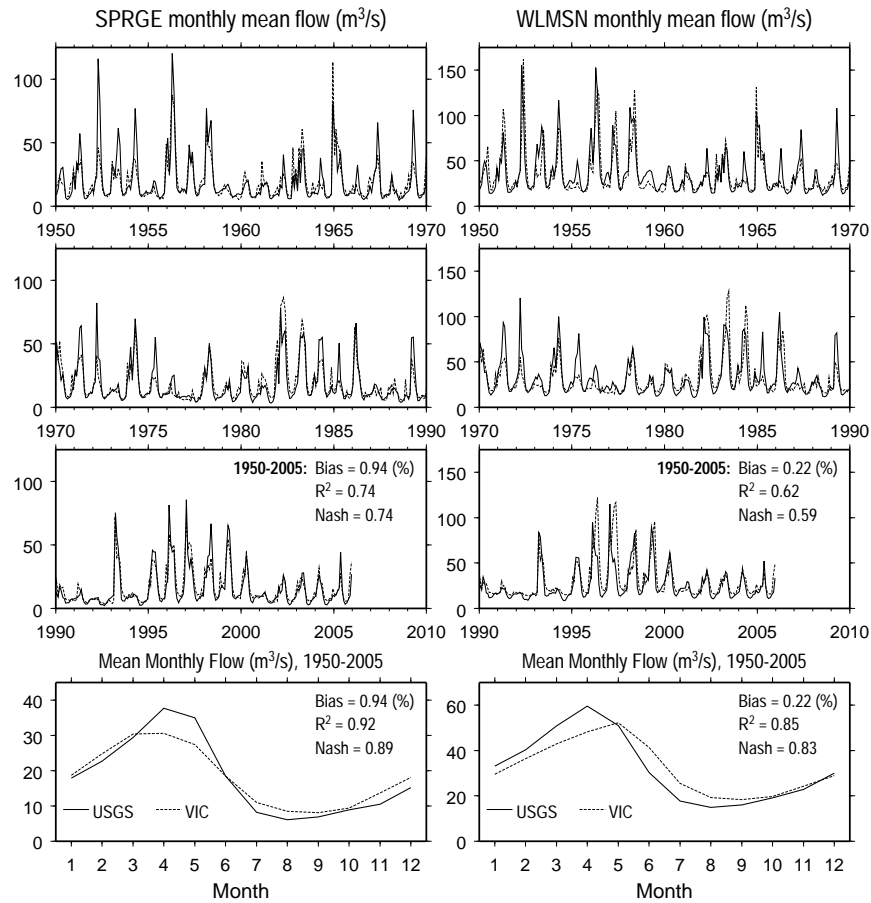


Fig. 4. Results of the conventional VIC model calibration, as demonstrated by simulated and observed streamflow at USGS station SPRGE (left) and WLMSN (right).

based system is referred to as MOD_{irr} . Four scenarios were designed in order to assess the effects of irrigation on lake water levels. The baseline scenario (Non_IL) assumes that no water is withdrawn from the lake for irrigation (i.e., $O_{irr}=0$). In Scenario IL_1, representing irrigation of the smallest area, O_{irr} is set to equal the net irrigation consumption in area IL1. Scenario IL_12, which is most representative of actual conditions (see Sect. 2), sets O_{irr} to equal the net irrigation consumption in areas IL1 and IL2. Scenario IL_123, representing irrigation of the maximum possible area, sets O_{irr} to equal the net irrigation consumption in areas IL1, IL2, and IL3.

4 Results and evaluation

Figure 4 shows streamflow at SPRGE and WLMSN (see Fig. 1 and Table 1) as simulated by the conventional VIC model from 1950 to 2005. Mean monthly simulated streamflows show good agreement with observations, with biases of about 1% and Nash-Sutcliffe efficiency coefficients (Nash and Sutcliffe, 1970) of 0.89 and 0.83 for each of the two sta-

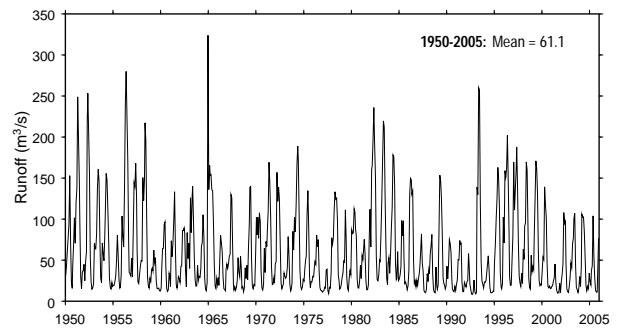


Fig. 5. Simulated surface inflows to Upper Klamath Lake ($I_{ws}+I_{roff}$)

tions, respectively. The calibrated model was used to simulate the unmeasured runoff between stations WLMSN and LINK (I_{roff}), which was then added to the streamflow observations at WLMSN (I_{ws}) to generate a time series of total surface inflows to the lake (Fig. 5). The long term mean of these inflows is estimated at $61.1 \text{ m}^3/\text{s}$, which differs by

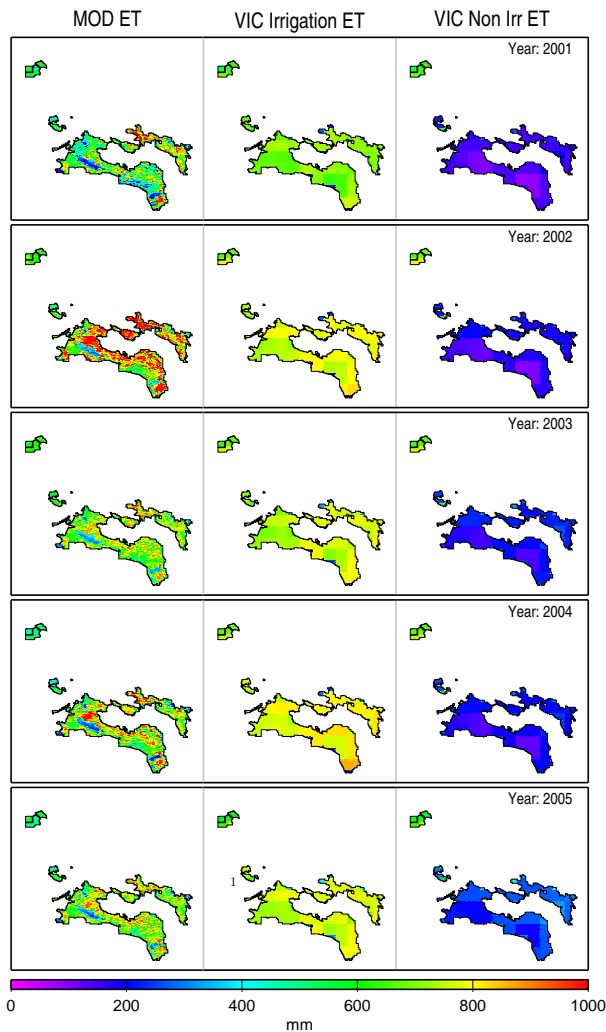


Fig. 6. Spatial distribution of ET in the irrigable lands as estimated by satellite data (left), VIC irrigation model simulations (center), and conventional VIC model simulations (right) from 2001 to 2005. See Fig. 1 for delineation of IL1, IL2, and IL3.

about 1% when compared with the value of $60.3 \text{ m}^3/\text{s}$ that was reported in a detailed USBR investigation of the natural hydrology of the lake (USBR, 2005).

Figure 6 compares spatial distributions of ET in IL1, IL2, and IL3 as estimated by satellite data, VIC irrigation model simulations, and conventional VIC model simulations from 2001 to 2005. As expected, satellite-based estimates of ET are generally higher than conventional VIC model estimates, with differences representing the effects of irrigation. Estimates of ET from VIC irrigation model simulations are comparable to those based on satellite data, although spatial resolution is much lower (1/16 degree, or roughly 5 to 7 km, for VIC vs. 250 m for MODIS).

Figure 7 shows time series of 8-day ET for the three irrigation areas from 2001 to 2005. As above, estimates

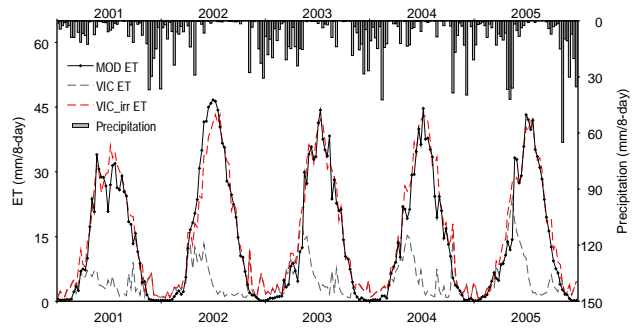


Fig. 7. Time series of ET for the three irrigation areas from 2001 to 2005.

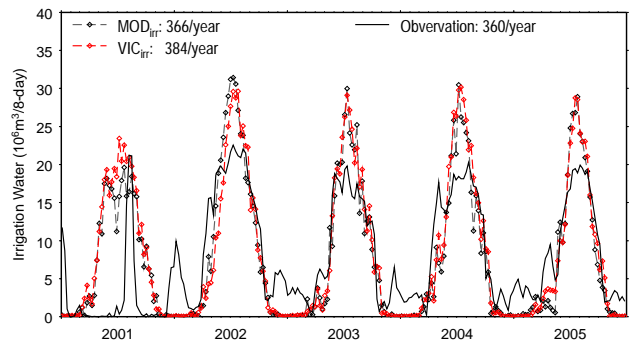


Fig. 8. Time series of estimated net irrigation consumption (MOD_{irr} and VIC_{irr}) and observed net irrigation supply for IL2 from 2001 to 2005. Annual mean values over the period are given in the plot.

of ET based on the VIC irrigation model (with MODIS LAI parameterization) agree closely with satellite-based estimates. Both are significantly higher than conventional VIC-simulated estimates during the growing season of May to October, although estimates agree more closely during the high rainfall spring months, when irrigation needs diminish. Differences between satellite-based and conventional VIC model-based estimates of ET were used to determine MOD_{irr} ; differences between VIC irrigation model and conventional VIC model estimates were used to compute VIC_{irr} . These values provide good indicators of net irrigation consumption, although actual withdrawals from Upper Klamath Lake also depend on conveyance losses and operational restrictions.

Figure 8 shows estimated net irrigation consumption (MOD_{irr} and VIC_{irr}) and observed net irrigation supply for IL2 from 2001 to 2005. Net irrigation supply was determined by the difference between measurements of irrigation canal deliveries and return flows, where available (see Table 1). Both MOD_{irr} and VIC_{irr} show reasonable agreement with observations in most years, although in general, estimates of net irrigation consumption are larger in summer and smaller in winter than observations of net irrigation

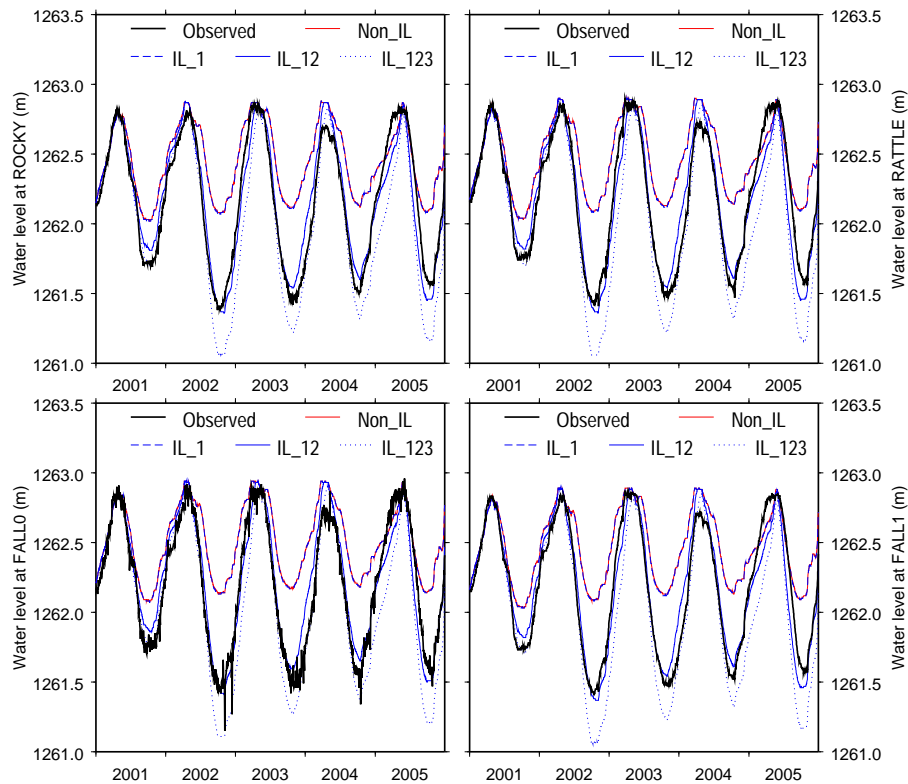


Fig. 9. Simulated and observed water levels at Upper Klamath Lake from 2001 to 2005. The baseline scenario (Non_IL) assumes no irrigation; Scenario IL_1 assumes irrigation for IL1 only; Scenario IL_12 assumes irrigation for IL1 and IL2; and Scenario IL_123 assumes irrigation for IL1, IL2, and IL3.

supply. Despite these discrepancies in timing, total annual net irrigation volumes supplied match up quite well with total annual net irrigation volumes consumed, suggesting that water delivered during the winter is stored in the irrigation area as groundwater or soil moisture, where it remains until consumed by crops during the summer. According to USFWS (2001b), pre-irrigation, or the delivery of water during the winter, is current practice, and is used to enhance the ability of the combined irrigation and cropland system to store water from wet periods to the much drier growing season. The lone recent exception to this practice occurred in the very dry year 2001, when a US District Court order to protect endangered fish restricted irrigation volumes to about half of the estimated demand.

The stage-storage curves in Fig. 2 were used to compute modeled daily water levels at each of the USGS water level gauges, as shown in Fig. 9. For each scenario, O_{irr} was set to meet net irrigation consumption as estimated by the satellite-based system (MOD_{irr}) from 2001 to 2005 and the VIC irrigation model (VIC_{irr}) prior to 2001; in 2001, O_{irr} was reduced by half to simulate restrictions on water deliveries. Under the baseline scenario (Non_IL), which represents the hydrology under natural conditions, simulated water levels are higher than observed beginning at the start of the ir-

rigation period in May. When only IL1 is irrigated (Scenario IL_1), water levels are close to the baseline, indicating that irrigation of this small area has a negligible impact on lake hydrology. When both IL1 and IL2 are irrigated (Scenario IL_12), water levels are lower than the baseline beginning at the start of the irrigation period in May. This scenario is most representative of actual conditions, and as expected, simulated water levels agree most closely with those observed. Scenario IL_123, which assumes irrigation of all three areas, yields the lowest water levels during the growing season. Comparisons of baseline estimates with observations show that irrigation causes an average decline of 0.5 m in the mean water levels of October, when they are generally at their lowest. Average annual water levels estimated by the baseline scenario (1262.5 m) are about 0.3 m higher than those estimated by Scenario IL_12 (1262.2 m). Annual ranges in water levels under the baseline scenario (0.8 m) are likewise about 0.5 m lower than those estimated by Scenario IL_12, suggesting impacts on surrounding wetland environments that are influenced by water level fluctuations.

Table 2 gives the simulated annual mean water budget terms for the lake for Scenario IL_12 from 2001 to 2005 and the water storage change (water storage difference between 1 January 2001 and 31 December 2005). Surface runoff

Table 2. Annual mean water budget terms for Upper Klamath Lake (10^6 m^3) for Scenario IL_12 from 2001 to 2005, and the water storage change (D_s , water storage difference between 1 January 2001 and 31 December 2005).

I_{ws}	I_{roff}	P_{lake}	E_{lake}	O_{irr}	O_{fall}	D_s
671	474	166	315	351	629	79

($I_{ws} + I_{roff}$) makes up the majority of lake inflows; precipitation over the open water surface of the lake (P_{lake}) is small by comparison. Outflow from the lake (O_{fall}), evaporation over the open water surface of the lake (E_{lake}), and irrigation water withdrawals (O_{irr}) account for 48%, 24%, and 27% of the net inflow to the lake on average, respectively. The simulated water storage on 31 December 2005 is $79 \times 10^6 \text{ m}^3$ (about 6% of the annual net inflow to the lake) larger than that on 1 January 2001. The water storage change agrees well with the observed change of $86 \times 10^6 \text{ m}^3$.

Simulated and observed monthly mean water budget components are shown in Fig. 10 for Scenario IL_12 from 2001 to 2005. Total lake inflows exceed total lake outflows from October to April, at which point lake storage volume reaches its annual peak. Although high May inflows keep lake levels near peak stage during that month, storage volumes decrease from April to October due to increasing amounts of evaporation and irrigation withdrawals, the latter accounting for the greatest part of lake outflows (48%) during this period. Total lake outflows are greatest during the months of May, June, and July, decreasing as storage volumes approach the regulated minimum in late summer. Mean monthly simulated storage volumes correspond well with those observed, as do VIC lake model estimates of E_{lake} with those estimated by USBR (2005). The water budget simulations illustrate the importance of irrigation withdrawals to lake storage volumes, particularly during the high irrigation season of June to September.

Long-term impacts of irrigation on lake hydrology were assessed by estimating net irrigation consumption using the satellite-based system from 2001 to 2005 and VIC irrigation model simulations prior to 2001 when MODIS data do not exist. Figure 11 shows simulated and observed daily water levels at USGS station FALL1, beginning in October 1974 when the earliest observations are available. As before, the baseline scenario (Non_IL) yields larger storage volumes and higher water levels, while Scenario IL_12, which is most representative of actual conditions, agrees better with observed values. Comparisons of baseline estimates with observations show that irrigation causes an average decline of 0.3 m in the mean water levels in October, with drops of up to 1 m in some years. Average annual water levels estimated for the baseline scenario (1262.4 m) are about 0.2 m higher than those observed and estimated by Scenario IL_12 (1262.2 m).

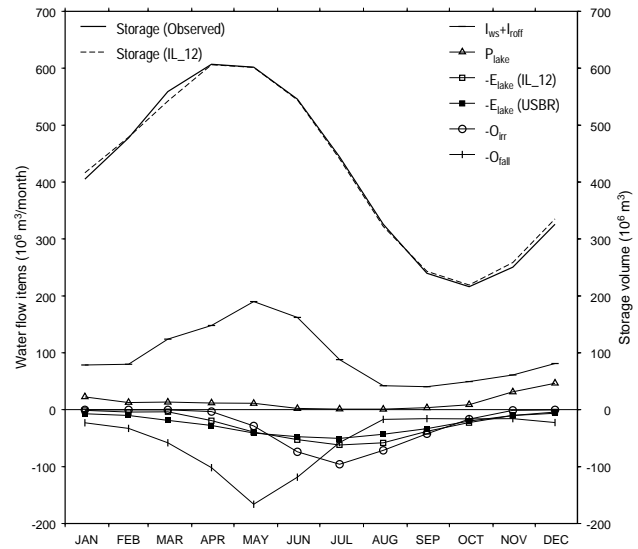


Fig. 10. Simulated and observed monthly mean water budget terms at Upper Klamath Lake for Scenario IL_12 from 2001 to 2005. Total surface inflows are represented by ($I_{ws} + I_{roff}$), precipitation over the open water surface is P_{lake} , evaporation over the open water surface is E_{lake} , water withdrawn for irrigation purposes is O_{irr} , and outflow from the lake to the Klamath River downstream is O_{fall} . Observed storage volumes were obtained from CDEC station KLM.

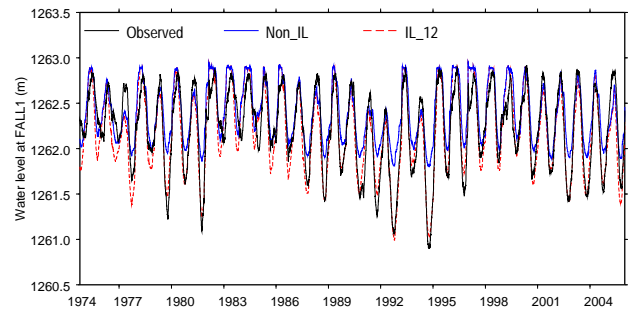


Fig. 11. Simulated and observed daily water levels at USGS station FALL1 from 1974 to 2005. The baseline scenario (Non_IL) assumes no irrigation; Scenario IL_12 assumes irrigation for IL1 and IL2.

Annual ranges in water levels under the baseline scenario are about 0.3 m lower than those estimated by Scenario IL_12.

5 Conclusions and discussion

This paper demonstrates the feasibility of using satellite data and hydrologic models to assess the impacts of irrigation withdrawals on lake hydrology. The conventional VIC model was used to estimate hypothetical crop water usage in the absence of irrigation withdrawals. Since measurements of irrigation withdrawals are limited, these were determined by

estimates of consumptive irrigation use, which in turn, were derived from the difference between hypothetical and actual estimates of crop water use as determined by a satellite-based ET estimation system (Tang et al., 2009b). Estimates of consumptive irrigation use under a realistic irrigation scenario agree fairly well with observations of net irrigation supply from 2001 to 2005 at Upper Klamath Lake, Oregon.

Model-simulated lake inflows are consistent with streamflow observations and published reports of long-term natural flows (USBR, 2005). Model-simulated lake storage volumes and water levels under a realistic irrigation scenario also agree well with those observed. Simulated baseline (non-irrigation) water levels are greater than those observed on average, while the amplitude of seasonal variations is less than those observed. When combined with the VIC model, the satellite-based ET estimation system shows that irrigation caused a decline of 0.3 m in mean annual water levels and 0.5 m in mean October water levels, while leading to an increase of 0.5 m in annual water level ranges at the lake from 2001 to 2005. Although the use of satellite data is complicated by limited record lengths, model simulations were used to extend these records to 1974 and yielded largely comparable results.

Estimates of crop water consumption can, of course, be made using methods like tower observations or model estimates, such as those provided by the VIC irrigation model. The greatest advantage provided by the ET estimation system described herein is the ability to make such estimates at higher spatial resolutions and without detailed knowledge of the specifics of water supply system operating rules. These estimates are essential for establishing both baseline lake levels and levels under various other irrigation scenarios, which can then be used to mitigate environmental impacts, among other purposes. The satellite-based ET estimation system also provides the potential, when combined with model simulations, to produce realistic estimates of lake water budget terms in real-time, and more efficiently match irrigation withdrawals with demands.

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