Hydrologic and land–energy feedbacks of agricultural water management practices

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Abstract
Recent studies demonstrate strong interdependence between groundwater dynamics, land surface water and energy fluxes over some regions, including significant negative correlation between latent heat flux and groundwater depth. Other studies show that irrigation increases latent heat flux and decreases the Bowen ratio (ratio of sensible to latent heat flux), with subsequent feedbacks on local and regional climate. We use an integrated hydrologic model to evaluate impacts of groundwater pumping, irrigation, and combined pumping and irrigation on groundwater storage, land surface fluxes, and stream discharge over the Little Washita River watershed in the Southern Great Plains of North America. Pumping and irrigation are shown to impact simulated water and energy fluxes at local and watershed scales, with the magnitude of impacts governed by local water table depth. When pumping and irrigation are combined, irrigation has a dominant impact on spatially distributed surface energy processes while pumping has a dominant impact on basin-integrated hydrologic conditions.

Keywords: hydrology, land–energy balance, land–atmosphere interactions, water management

1. Introduction

Soil moisture governs the partitioning of incoming radiation at the land surface between sensible, latent, and ground heat fluxes, which in turn influences evapotranspiration (ET) and movement of water through the soil matrix. Feedbacks between soil moisture and land surface fluxes significantly influence atmospheric boundary layer development and regional climate (Koster et al 2003, Maxwell et al 2007, Patton et al 2005), including the magnitude and persistence of extremes such as droughts and heat waves (Hong and Kalnay 2000, Schubert et al 2004). Recent studies show that local hydrologic response to global climate change will feed back on regional climate, with drying of soils amplifying the global climate signal over continental regions (Diffenbaugh et al 2005, Seneviratne et al 2006).

This interdependence between soil moisture, land–atmosphere fluxes, and regional climate suggests that in addition to altering watershed hydrology, agricultural water management practices that alter the distribution of water between the subsurface and surface—namely, groundwater pumping and irrigation—will also impact the land–energy balance and may feed back on climate. Irrigation has an obvious impact on soil moisture, and recent studies demonstrate that irrigation feeds back on latent and sensible heating, atmospheric temperature and moisture profiles, and precipitation (Boucher et al 2004, Kueppers et al 2007, Lobell et al 2009, Lobell and Bonfils 2008, Ozturan et al 2010). However, these studies rely largely on land surface models that have shallow subsurface depths (generally <5 m) and lack lateral subsurface flow and integrated overland flow, and therefore cannot simulate feedbacks across the full terrestrial hydrologic cycle. In addition, few model studies account for the source of irrigation water, which may bias simulated impacts on basin-scale water budgets.

In many regions, local groundwater is the main source of irrigation. Recent modeling studies have shown strong feedbacks between groundwater depth and land–atmosphere fluxes (Ferguson and Maxwell 2010, Kollet and Maxwell 2008a, Maxwell et al 2007, Maxwell and Kollet 2008a). These studies have identified three regimes of the land–energy balance with respect to groundwater depth. In areas of...
shallow groundwater (water table depth \( D \lesssim 1 \) m), moisture is readily transported from the water table to the surface and land–atmosphere fluxes are controlled predominantly by atmospheric energy availability (e.g., temperature, wind, solar radiation). In areas of deep groundwater (\( D \gtrsim 10 \) m), the water table is disconnected from the land surface and land–atmosphere fluxes are controlled largely by atmospheric moisture supply (i.e., precipitation). In regions of intermediate groundwater depth (\( 1 < D < \sim 10 \) m), small changes in water table depth directly impact surface moisture availability and land–atmosphere fluxes are dependent on groundwater–land surface feedbacks. Notably, feedbacks between groundwater and land–energy fluxes have been shown to propagate into the atmosphere, affecting boundary layer development and precipitation on diurnal to seasonal timescales (Anyah et al. 2008, Bierkens and van den Hurk 2007, Ferguson and Maxwell 2010, Jiang et al. 2009, Maxwell et al. 2007). These results suggest that where groundwater pumping causes drawdown of shallow or intermediate groundwater, pumping will feed back on the land–energy balance, with potential impacts on weather and climate.

The individual and combined influence of groundwater pumping and irrigation on both watershed hydrology and land–energy fluxes has not been previously evaluated. Here we use ParFlow, a fully integrated three-dimensional hydrologic model that couples surface (overland) and subsurface (groundwater and vadose zone) flow with the land surface water and energy balance, to evaluate impacts of groundwater pumping, irrigation, and combined pumping and irrigation on water and energy budgets at local and watershed scales over the Little Washita River watershed in Oklahoma, USA.

2. Methods and study area

2.1. Model description

ParFlow solves the three-dimensional variably saturated Richards equation for subsurface flow (Ashby and Falgout 1996, Jones and Woodward 2001); overland flow is represented through a free-surface overland flow boundary condition, which routes ponded water via the kinematic wave and Mannings equations (Kollet and Maxwell 2006, Maxwell and Kollet 2008b).

Subsurface and overland flow equations are solved simultaneously to ensure full coupling between surface and subsurface flows. ParFlow is coupled with a modified version of the Common Land Model (CLM3.0), which solves the land surface water and energy balance (Dai et al. 2003, Kollet and Maxwell 2008a, Maxwell and Miller 2005). CLM calculates evaporation from the vegetation canopy and ground surface, transpiration from plants, snow accumulation and melt, and latent, sensible, and ground heat fluxes as a function of soil moisture (calculated by ParFlow) and atmospheric forcings. The coupled model is mass and energy conservative and explicitly represents interactions between three-dimensional groundwater dynamics, runoff generation and overland flow processes, and land surface water and energy fluxes (Kollet and Maxwell 2006, Maxwell and Kollet 2008b, Maxwell and Miller 2005). Details of the model physics and numerical implementation are provided by (Ashby and Falgout 1996, Dai et al. 2003, Jones and Woodward 2001, Kollet and Maxwell 2006, 2008a) and the coupled model has been tested and validated with respect to field observations (Kollet and Maxwell 2008a, 2008b, Maxwell and Miller 2005, Tompson et al. 1999). Here, discrete, transient groundwater withdraws are represented explicitly through a general sink term. Spray irrigation is the dominant method of irrigation throughout the study region; discrete irrigation applications are therefore simulated as spray irrigation by adding the irrigation rate to the precipitation rate above the vegetation canopy, allowing for canopy interception, throughfall, runoff and infiltration.

2.2. Study area

ParFlow is used to simulate a 32 km \( \times \) 45 km study area encompassing the Little Washita River watershed in central Oklahoma, USA (figure 1). The study area lies within the Southern Great Plains, an important agricultural region; irrigation is the dominant component of water use throughout the region, and the majority of irrigation is supplied by local groundwater. Within the watershed, crops occur primarily along the river valley and encompass 21.4% of the basin area. The study area is characterized by rolling terrain, with land cover dominated by grasslands, open shrubs, and croplands. The watershed experiences sub-humid to semi-arid climate with mean annual precipitation of approximately 745 mm and daily mean temperatures ranging from 1.5°C in January to 27.5°C in July. Soils in the watershed are primarily loam and loamy sand, with areas of sand and silt loam (see Kollet and Maxwell 2008a). Soils are underlain by layered sandstone and shale formations, with shallow alluvial deposits along the main channel network; detailed data on subsurface hydraulic properties are not available.

ParFlow was configured with a uniform horizontal discretization (\( \Delta x = \Delta y \)) of 1 km and uniform vertical discretization (\( \Delta z \)) of 0.5 m. Spatially distributed vegetation and soil categories were used for the model surface layer (top 0.5 m below the land surface); given sparse subsurface data, uniform soil parameters were used for deeper layers based on previous analysis of some 200 boreholes in the region (Kollet and Maxwell 2008a). The configuration used here was previously tested and validated against observations and shown to agree quite well with measurements of soil moisture, latent and sensible heat flux, and stream discharge with in the study area (Kollet and Maxwell 2008a).

2.3. Model scenarios

Simulations were carried out for four water management scenarios: (1) no pumping, no irrigation (CNTRL); (2) pumping, no irrigation (PUMP); (3) irrigation, no pumping (IRRIG); and (4) combined pumping and irrigation (P + I). These scenarios are designed to evaluate the individual and combined effects of groundwater pumping and irrigation on local and basin-scale water and energy budgets for the study area. Scenario P + I is consistent with irrigation practices throughout the study region, where irrigation is supplied.
Figure 1. (Left) Digital elevation model of the study area. (Right) Distribution of vegetation cover over the model domain. The watershed outline is shown in gray and agricultural cells are delineated in black; note that pumping and irrigation are applied only in crop areas, which occur primarily along the river valley.

primarily by on-farm groundwater pumping; scenarios PUMP and IRRIG correspond to inter-basin groundwater transfers out (export) and into (import) the watershed, respectively, and are used to evaluate the individual influences of groundwater pumping and irrigation.

Pumping and irrigation were imposed only in crop cells. Detailed information on irrigation practices within the study area is not available; in the scenarios analyzed here, irrigation was applied daily from 07:00–19:00 local time during the growing season (1 June–15 September) at a rate of 0.396 mm h\(^{-1}\), for a total of 508 mm (20 inches), approximately equal to the average annual irrigation demands of wheat, alfalfa, and corn in the study region (Masoner et al. 2003). Sensitivity analysis with respect to irrigation schedule found that irrigating at a greater rate for a shorter period (06:00–07:00) with the same total applied irrigation resulted in nearly identical feedbacks on water table depth, soil moisture, and latent heat flux, with a slight increase in irrigation feedbacks on runoff. Total groundwater pumping was assumed to equal total irrigation; a constant pumping rate of 0.212 mm h\(^{-1}\) was applied during the growing season, for a total withdrawal of 508 mm (20 inches). Wells were assumed to be located at the center of each crop cell; all wells were assumed to have a depth of 50 m, approximately equal to the average well depth based on well logs for the region.

It should be noted that because pumping and irrigation both affect soil moisture, moisture-dependent irrigation scheduling would result in different irrigation timing and rates between scenarios; in order to ensure total applied irrigation in all irrigation scenarios equals total groundwater extraction in all pumping scenarios, irrigation scheduling was not varied in response to weather or soil moisture conditions.

Simulations were carried out for water year 1999 (1 September 1998–31 August 1999), driven with spatially uniform meteorological forcings derived from the North American Regional Reanalysis (NARR) (Mesinger et al. 2006), including precipitation rate (mm s\(^{-1}\)), air temperature (K), shortwave radiation (W m\(^{-2}\)), downward longwave radiation (W m\(^{-2}\)), easterly wind speed (m s\(^{-1}\)), westerly wind speed (m s\(^{-1}\)), air pressure (Pa), and specific humidity (kg kg\(^{-1}\)). Monthly precipitation and temperatures over water year 1999 are close to their 1971–2000 climatological means; given the small model domain, spatially uniform forcing is a reasonable approximation and ensures that spatial variations in simulated land–atmosphere fluxes are attributable to hydrologic feedbacks rather than atmospheric forcings. To avoid confounding effects of interannual climate variability and to allow slow groundwater processes to respond to the imposed scenarios, simulations were carried out for six years with the same forcings to achieve quasi-equilibrium (cyclostationary) conditions; only the last year of each scenario is analyzed. The model configuration and equilibrium approach used here has been extensively tested in previous studies (Ferguson and Maxwell 2010, Kollet and Maxwell 2008a, 2008b, Maxwell and Kollet 2008a); the CNTRL scenario was previously tested and validated by Kollet and Maxwell (2008a).

3. Results

Spatial distributions of simulated monthly mean water table depth, soil saturation (top 0.5 m below surface), and latent heat flux (LE) from CNTRL are shown in figure 2 for the month of August, along with differences between management scenarios and CNTRL (scenario–CNTRL). August is hot and dry over the study area and falls near the peak of irrigation season. Topographically driven groundwater flow maintains shallow water table conditions throughout the river valley and lower hillslopes in all simulations, with deeper water table conditions below hilltop areas. In CNTRL, high saturation (>0.5) occurs only in the river valley, where shallow groundwater contributes to moisture availability for ET. High temperatures and low humidity result in high LE (>150 W m\(^{-2}\)) over these areas, while low saturation strongly limits LE over the rest of the domain.

Groundwater pumping causes declines in monthly mean water table depth greater than 1.0 m over more than 15% of the watershed, with peak declines greater than 5.0 m (figure 2(b)). Despite pumping from crop areas along the river valley, groundwater convergence maintains a shallow water table throughout these areas; groundwater declines are
Figure 2. (a) Monthly mean water table depth (m), saturation (top 0.5 m), and latent heat flux (W m$^{-2}$ for August from CNTRL scenario; ((b)–(d)) differences between management scenarios and CNTRL (scenario–CNTRL). Note that pumping and irrigation are applied only in crop areas (gray areas in figure 1).

Figure 2. (a) Monthly mean water table depth (m), saturation (top 0.5 m) [−], and latent heat flux (W m$^{-2}$) for August from CNTRL scenario; ((b)–(d)) differences between management scenarios and CNTRL (scenario–CNTRL). Note that pumping and irrigation are applied only in crop areas (gray areas in figure 1).

Figure 2. (a) Monthly mean water table depth (m), saturation (top 0.5 m) [−], and latent heat flux (W m$^{-2}$) for August from CNTRL scenario; ((b)–(d)) differences between management scenarios and CNTRL (scenario–CNTRL). Note that pumping and irrigation are applied only in crop areas (gray areas in figure 1).

greatest under upland areas, where groundwater elevations are highest and groundwater flow is divergent. While irrigation is known to increase groundwater levels and contribute to salinization and water logging in some areas, particularly in areas of groundwater convergence and poor drainage, irrigation has a weak impact on water table depth in the watershed and scenarios evaluated here. In contrast to pumping, irrigation-induced increases groundwater levels greater than 1.0 m occur over just 1.6% of the watershed and are predominately local to crop areas (figure 2(c)). When pumping and irrigation are combined, irrigation moderates groundwater declines in the vicinity of crop areas, but has a negligible impact on the overall magnitude and extent of groundwater declines (figure 2(d)).

As expected, irrigation increases saturation in crop areas, with a corresponding increase in LE of as much as 110 W m$^{-2}$ (100%) (figure 2(c)); previous studies have shown similar irrigation impacts (Lobell et al 2009, Ozdogan et al 2010). Pumping impacts saturation and LE throughout crop areas and adjacent low-lying areas, where changes in water table depth affect moisture availability at the surface. Pumping decreases saturation in these areas by more than 50%, resulting in moisture-limited conditions which in turn decrease LE by up to 65 W m$^{-2}$ (50%; figure 2(b)). Impacts of combined pumping and irrigation are mixed: irrigation increases simulated monthly mean saturation and LE over most crop areas, while pumping-induced groundwater declines decrease over some crop areas and adjacent non-crop areas (figure 2(d)). Corresponding impacts on sensible and ground heat fluxes, net radiation, and ground temperature exhibit similar spatial signatures as those of LE (not shown).

The magnitude of pumping and irrigation impacts is governed by local water table depth. Figure 3 shows differences in simulated monthly mean saturation and LE between each scenario and CNTRL for all crop cells as a function of initial (CNTRL) water table depth. During August, irrigation increases saturation and LE over areas of deep groundwater, where the land surface is disconnected from the water table and most severely moisture-limited, as seen in figures 3(a) and (c) for IRRIG (green) and P + I (blue). In areas of shallow groundwater, moisture transport from the water table to the surface reduces moisture limitations, muting the impacts of pumping and irrigation. Over these areas, irrigation results in a small increase in LE due to evaporation from wetted vegetation (figure 3(c)), but has no impact on monthly mean saturation (figure 3(a)). In contrast, pumping impacts saturation and LE only over areas of intermediate water table depth, where changes in groundwater levels feed back on moisture availability at the surface, as seen in figures 3(a) and (c) for PUMP (red). In the case of combined pumping and irrigation, the influence of irrigation dominates over areas of shallow and deep groundwater, increasing saturation and LE as seen in figures 3(a) and (c). Over areas of intermediate groundwater depth, pumping-induced groundwater declines decrease saturation (figure 3(a)), while irrigation increases LE by evaporation from wetted vegetation (figure 3(c)).

It should be noted that over areas of deep and intermediate groundwater, impacts of pumping and irrigation on simulated saturation persist outside of the growing season (figures 3(b) and (d)); however, impacts are damped by predominately energy-limited conditions during winter. Despite relatively weak persistence of LE impacts, the persistent impact on saturation is likely to affect local and basin-scale water balances by influencing infiltration, runoff generation, and groundwater recharge. Lastly, it should be noted that the three
Figure 3. Differences (scenario–CNTRL) in monthly mean ((a), (b)) saturation [−] and ((c), (d)) latent heat flux (W m$^{-2}$) over crop areas as a function of water table depth (m) for ((a), (c)) August and ((b), (d)) February ($P$ = red; $I$ = green; $P + I$ = blue).

Tiers of saturation differences apparent in figures 3(a) and (b) for the PUMP and $P + I$ correspond to the three soil types in that coincide with crop areas. The highest tier (change in saturation greater than 100%) corresponds to the soil with the steepest soil water characteristic curve (silt loam), while the lowest tier (change in saturation less than 25%) corresponds to the soil with the shallowest characteristic curve (sandy loam). This tiered behavior highlights the role of soil characteristics in governing hydrologic and land–energy feedbacks.

Pumping and irrigation affect not only local, spatially distributed processes, but basin-integrated processes as well (figure 4). Irrigation results in a 4.4% increase in simulated basin-averaged ET, similar to previous results at the continental scale using a shallow-column, one-dimensional (vertical) land surface model (Ozdogan et al. 2010). Groundwater pumping reduces basin-integrated ET by 2.1%, and combined pumping and irrigation increase ET by 3.3%. Impacts on streamflow are more substantial. Irrigation increases baseflow and saturation excess runoff, resulting in a 41.7% increase in simulated annual discharge at the watershed outlet; groundwater pumping reduces both baseflow and saturation excess runoff, resulting in a 62.5% decrease in annual discharge. Notably, combined pumping and irrigation results in a 30.8% decrease in annual discharge. This decrease is primarily due to decreased baseflow throughout the year, as well as decreased surface runoff during the transition season from dry summer to wet winter conditions. Thus while the impacts of groundwater pumping on streamflow outweigh those of irrigation, return flows reduce the impacts of groundwater pumping by a factor of two.

Impacts of pumping and irrigation are likely to differ between regions depending on climate, geologic, and hydrologic conditions, as well as irrigation rate and timing. The modeling results presented here suggest that impacts on land–atmosphere interactions will depend on the distribution of groundwater depths within a given watershed, while impacts
on stream flow will depend on the dominant streamflow generation mechanisms (e.g., saturation excess, infiltration excess, or baseflow). Impacts of pumping in particular are confined to areas of initially shallow or intermediate water table depth, where drawdown impacts moisture availability at the surface; one would expect pumping to have negligible impacts on soil moisture and LE in regions where the water table is disconnected from the land surface. While irrigation rate and timing depending on a variety of climate and economic factors, sensitivity analysis carried out with respect to irrigation schedule found that irrigating at a greater rate for a shorter period (with the same total applied irrigation) resulted in nearly identical feedbacks on soil moisture and LE (not shown), with a slight increase in irrigation feedbacks on runoff. Varying irrigation throughout the growing season in response to real-time weather conditions is likely to reduce irrigation-induced saturation excess runoff, but is not likely to alter the affect feedbacks on water table depth, soil moisture, or LE.

4. Conclusions

Results presented here based on simulations of an agricultural watershed in the Southern Great Plains, USA, with a fully integrated hydrologic model suggest that groundwater pumping and irrigation can significantly impact both spatially distributed land–energy fluxes as well as basin-integrated hydrologic conditions. Our analysis shows important differences between impacts of pumping versus irrigation:

• impacts of groundwater pumping are dominant in terms of basin-integrated hydrologic quantities such as groundwater storage and stream discharge;
• impacts of irrigation are dominant in terms of spatially distributed processes and land–energy fluxes.

Notably, the magnitude of pumping and irrigation impacts at a given location within the watershed is governed by local water table depth through groundwater–land surface feedbacks.

Land–energy fluxes play a critical role in atmospheric boundary layer development and weather and climate processes over continental regions. Our results demonstrate the significant impacts of pumping and irrigation on land–energy fluxes, and thus have important implications for land–atmosphere interactions and continental hydrometeorology. Given the fine-scale spatial heterogeneity of local water management practices, these effects cannot be resolved at the typical resolutions of weather and climate models and may represent a significant limitation of these models of agricultural regions. Further research is necessary to quantify the scope and magnitude of these important feedbacks of groundwater pumping and irrigation on weather and climate.

Lastly, it is important to note that while the results presented here contribute a growing body of model results that suggest groundwater dynamics strongly influence land–energy fluxes and atmospheric boundary layer development in some regions, field data to confirm these results are not currently available. New field campaigns are needed to identify the critical zone of groundwater–land surface interaction in natural systems and to quantify the influence of groundwater feedbacks on land–energy fluxes and land–energy response changing climate, land cover, and water management practices.

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