XVIII International Conference on Water Resources
CMWR 2010
J. Carrera (Ed)
CIMNE, Barcelona 2010

GROUNDWATER—LAND SURFACE—ATMOSPHERE FEEDBACKS: IMPACTS OF GROUNDWATER PUMPING AND IRRIGATION ON LAND-ATMOSPHERE INTERACTIONS

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Key words: groundwater, water management, climate, feedbacks, coupled modeling

Summary: Recent studies have shown that interactions between groundwater, surface water, and land surface processes significantly influence the land surface water and energy balance. These studies suggest that water management practices which alter the distribution of water between the subsurface and near-surface—viz., groundwater pumping and irrigation—will impact land surface water and energy budgets, with potentially significant feedbacks across the hydrologic cycle. Here we use an integrated watershed model to examine impacts of groundwater pumping and irrigation on terrestrial water and energy budgets. For a study area in the Southern Great Plains region of North America, pumping is shown to impact groundwater levels throughout the watershed and root-zone saturation and land-atmosphere fluxes over regions of shallow and intermediate groundwater depth throughout the year. By contrast, irrigation impacts groundwater levels, root-zone soil moisture, and land-atmosphere fluxes only over irrigated areas and during the growing season. Impacts of combined pumping and irrigation are shown to depend on local water table depth: irrigation impacts on surface fluxes are greatest for crop areas with water table depths greater than 2m, while impacts of groundwater pumping are greatest for areas with water table depths less than 2m. Further analysis is needed to evaluate feedback of water management practices on the atmospheric boundary layer and local and regional climate.

1 INTRODUCTION

The terrestrial water and energy cycles are tightly coupled through the latent heat of evaporation: evapotranspiration (*ET*) depends on energy availability at the land surface, while latent heat flux (*LE*) depends on moisture availability. Changes in soil moisture influence the partitioning of incoming radiation into sensible, latent, and ground heat fluxes, which in turn influences *ET* and thus the movement of water through the soil column. Feedbacks between soil moisture and surface fluxes significantly influence the atmospheric boundary layer and regional climate[1-3] and contribute to the magnitude and persistence of extreme events such as droughts and heat waves[4,5]. Other studies suggest that temperature-driven drying of soils under global warming will feed back on regional climate, amplifying the global climate change signal over continental regions[6].

Groundwater processes significantly influence spatial and temporal variability of soil moisture—and thus land-atmosphere interactions—over some regions[7,8]. In areas of shallow groundwater ($D < \sim 10^0$ m), moisture is readily transported from the water table to the surface, and land-atmosphere fluxes are predominately controlled by atmospheric energy availability (temperature, wind, solar radiation). In areas of deep groundwater ($D > \sim 10^1$ m), groundwater is disconnected from the surface by a thick vadose zone and surface fluxes are controlled by the balance of atmospheric energy and moisture availability (temperature, wind, solar radiation vs. precipitation). In regions of intermediate groundwater depth ($D \sim 10^0$ m), however, small changes in water table depth result in significant changes in surface moisture availability, and land-atmosphere fluxes are governed by groundwater-land surface feedbacks.

Water management practices that alter the distribution of water between the subsurface and surface—viz. groundwater pumping and irrigation—thus have the potential to significantly impact land-atmosphere interactions. In fact, irrigation has recently been shown to affect local and regional climate[9]. However, the influence of groundwater pumping on the land surface water and energy balance and land-atmosphere interactions has not been evaluated. Here we use ParFlow, a variably-saturated groundwater model with integrated land-surface and overland flow processes, to examine the impacts of pumping and irrigation on water table depth, land-atmosphere fluxes, and groundwater-land surface feedbacks under four water management scenarios: (1) no pumping, no irrigation; (2) pumping, no irrigation (pumping for out of basin use), (3) irrigation, no pumping (irrigation with imported water); (4) pumping and irrigation (pumping for in-basin irrigation).

2 STUDY SITE

We evaluate impacts of groundwater pumping and irrigation on the Little Washita River watershed in Oklahoma, USA, in the Southern Great Plains (SGP) of North America. SGP is an important agricultural region, and recent studies suggest that land-atmosphere feedbacks contribute to climate extremes over the region, including severe droughts and heat waves[4,5]. The Little Washita watershed encompasses approximately 700 km^2 of rolling terrain. Vegetation cover is dominated by grassland, crops, and open shrublands. The watershed lies within the US Department of Energy Atmospheric Radiation Monitoring (ARM) facility, which provides high-quality meteorological and hydrologic observations over the region. The watershed outline and vegetation cover are shown in Figure 1.

3 MODEL DESCRIPTION AND SCENARIOS

ParFlow solves the variably-saturated Richards equation in three dimensions. Overland flow and groundwater–surface water interactions are represented through a free-surface overland flow boundary condition, which routes ponded water via the kinematic wave equation, with depth-discharge relationships defined by Mannings equation. The land surface water and energy balance is solved by coupling ParFlow with the Common Land Model (CLM)[10]. CLM calculates evaporation from the vegetation canopy and ground surface, transpiration from plants, infiltration, snow accumulation and melt, and latent, sensible, and ground heat fluxes as functions of soil moisture (calculated by ParFlow), prescribed atmospheric conditions (air temperature, wind speed, specific humidity, precipitation, and solar radiation), and prescribed soil and vegetation types. ParFlow and CLM are coupled over the top 5 m of the soil column using an operator-split approach. Full details of the model physics and numerical implementation are provided by [7, 10-13].

In this study, ParFlow was configured over a 32km by 45km domain encompassing the Little Washita watershed. The domain was discretized with lateral resolution ($\Delta x = \Delta y$) of 1km and vertical resolution (Δz) of 0.5m. The lowest model layer has uniform elevation of 260m above sea level; subsurface depths range from 63m to 191m based on surface topography. Spatially distributed vegetation and soil categories were defined for the model surface layer based on USGS observational datasets; given sparse subsurface observations, uniform soil parameters were used for deeper subsurface layers based on analysis of public records from some 200 boreholes in the region (see [7]). Van Genuchten parameters required for saturation-pressure relationships were obtained from the RAWLS database[14].

Simulations were carried out for four water management scenarios (Table 1). Groundwater pumping and irrigation were imposed only in grid cells with crop vegetation type. Irrigation was applied daily from 07:00h to 19:00h local standard time (LST) during the growing season (June 1 – September 15) at a rate of 0.396 mm/hour, for a total of 508 mm (20 inches) over the growing season, approximately equal to the average annual irrigation water demands of wheat, alfalfa, and corn in the study region[15]. Total groundwater pumping was assumed to equal total irrigation; a constant pumping rate of 0.212 mm/hr was applied during the growing season, for a total withdrawal of 508 mm (20 inches). In the pumping and irrigation scenario, constant pumping assumes temporary on-farm storage prior to irrigation.

Simulations were forced with observed meteorology from water year 1999 (September 1, 1998 – August 31, 1999) calculated from the North American Regional Reanalysis (NARR). Each scenario was run for six years with the same meteorological forcings to bring the subsurface into equilibrium; only the last year of each scenario is analyzed.

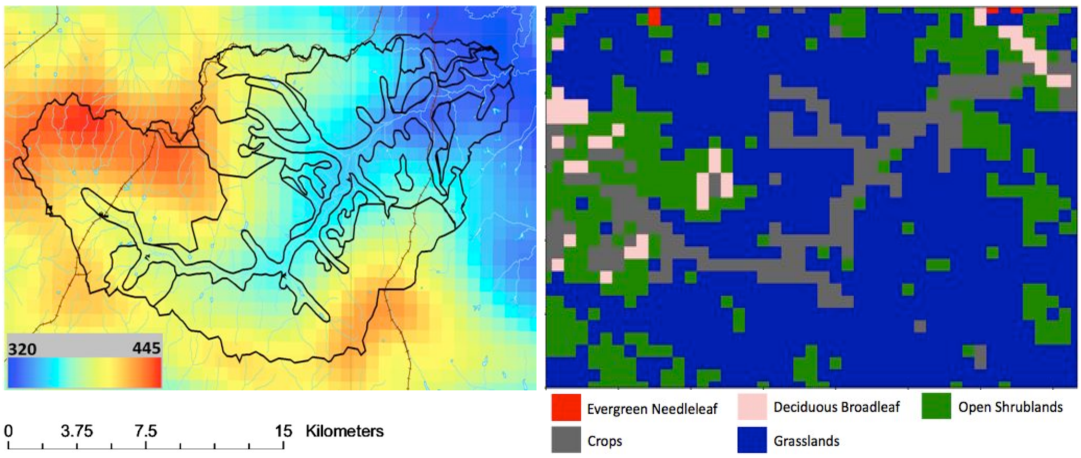

Figure 1: (left) Outline of the Little Washita River watershed, overlain on topographic elevations. (right) Distribution of vegetation cover over the model domain. Note that pumping and irrigation are applied only in crop cells, which occur primarily along the river valley.

Scenario	Description
Control (CNTRL)	No groundwater pumping or irrigation.
Pumping Only (PUMP)	Groundwater pumping from crop cells during growing season (June 1 – September 15); continuous pumping (24 hr/day) at 0.212 mm/hr (211.6 m^3/hr)
Irrigation Only (IRRIG)	Irrigation of crop cells during growing season (June 1 – September 15); irrigation applied daily from 07:00h – 19:00h LST at 0.396 mm/hr (396 m^3/hr)
Pumping and Irrigation (P+I)	Combination of irrigation and pumping applied to crop cells during the growing season as in IRRIG and PUMP scenarios

Table 1 : Summary of water management scenarios evaluated in this study.

4 RESULTS

4.1 Impacts of Pumping and Irrigation on Water and Energy Budgets

Spatial distributions of monthly mean water table depth, saturation (top 0.5m below land surface), and *LE* from the control simulation are shown in Figures 2 and 3 for March and September, respectively, along with changes in each variable under the three water management scenarios considered here (scenario-CNTRL). March is characterized by mild temperatures and abundant precipitation, and is prior the start of irrigation; September is hot and dry over the Little Washita basin, and encompasses the end of the irrigation season.

Topographically-driven flow results in a shallow water table in the river valley and low elevation areas and deeper water table conditions below hilltop areas in all simulations. In the control simulation, abundant precipitation maintains saturations greater than 0.5 throughout the domain during March, while convergence of groundwater and overland flow result in saturated conditions throughout the river valley. *LE* is generally weak during March due to moderate temperatures and high humidity, but is greatest over the river valley where soils are saturated. During September, water table conditions in the control simulation are similar to those during March, but saturations greater than 0.5 occur only in the river valley and low-lying areas where shallow groundwater contributes to surface moisture availability. High temperatures and low humidity during September result in high *LE* over these areas, while low soil moisture limits *ET* (and thus *LE*) over the rest of the domain.

Groundwater pumping significantly impacts water table depth throughout the basin during both March and September. Note, however, that pumping increases water table depths in the river valley only during September. During March, there is no pumping and abundant precipitation (along with overland flow and groundwater convergence) maintains shallow water table conditions in low-lying areas. During September, groundwater pumping, low precipitation, and high evaporative demand contribute to decreased groundwater levels throughout the domain. Effects of irrigation on water table depth is local in both space and time: irrigation increases groundwater levels in crop areas during the growing season, but has negligible residual affect during other months. Irrigation in combination with pumping reduces the magnitude and spatial extent of water table declines throughout the year, and contributes to a temporary increase in groundwater levels in some irrigated areas during the growing season. All management scenarios result in increased seasonal variability of water table depth throughout the river valley and lower hillslope areas.

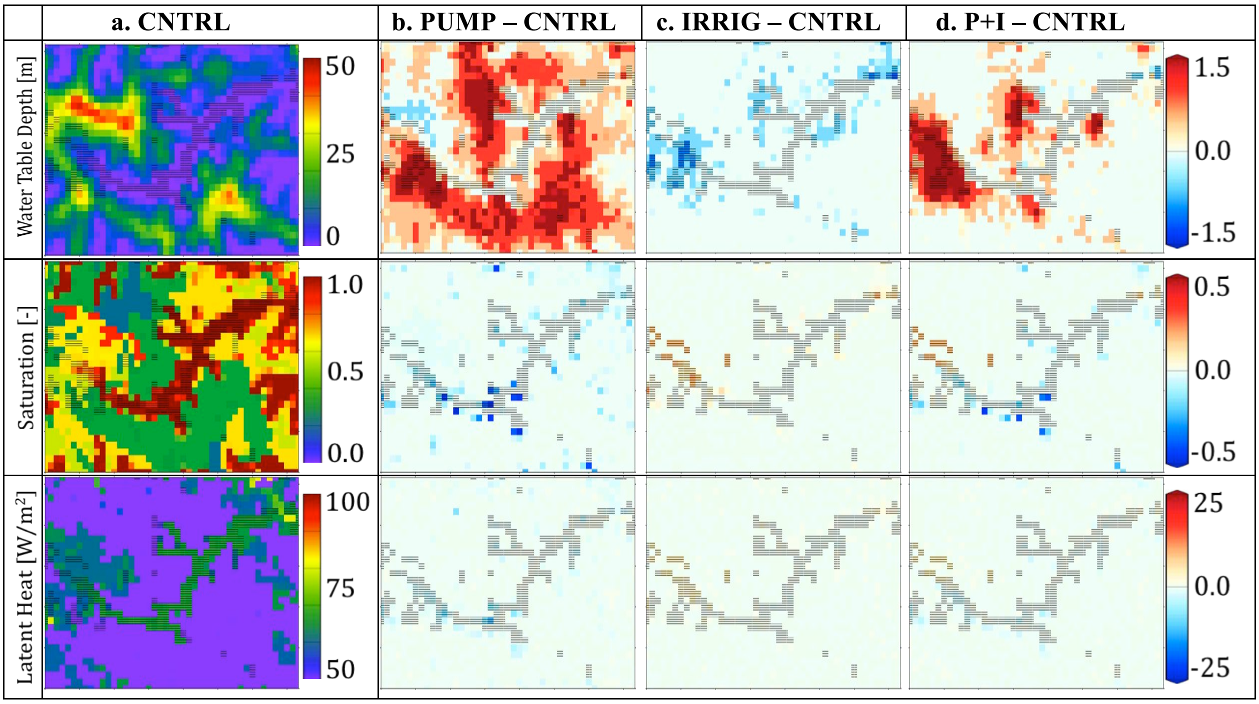

Figure 2: (a) monthly mean water table depth [m], saturation [-], and latent heat flux [W/m^2] for the month of March for CNTRL scenario; (b-d) differences between management scenarios and CNTRL (scenario - CNTRL). Crop areas where pumping and/or irrigation are applied are indicated in all plots by gray hatching.

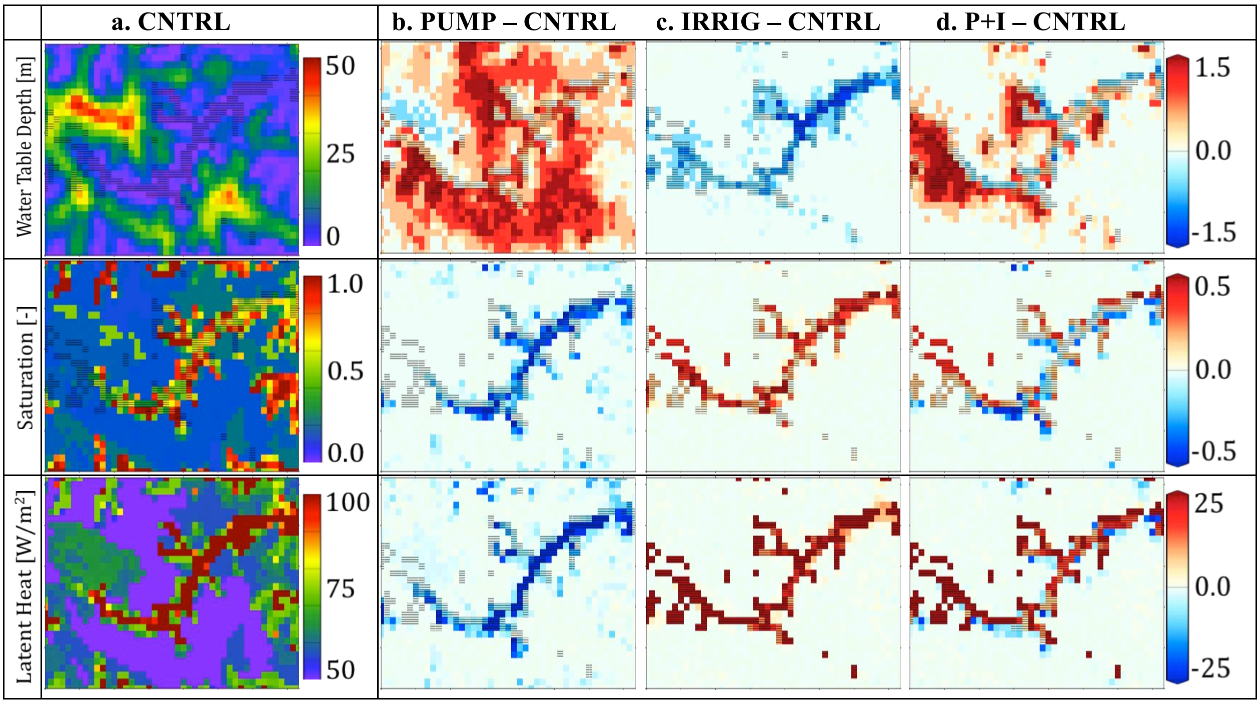

Figure 3: Same as Figure 2, except for the month of September.

Pumping and irrigation significantly impact saturation and *LE* over crop areas throughout the growing season (Figure 3). During September, pumping decreases saturation throughout crop areas from ~0.5–1.0 to ~0.1–0.25, increasing moisture-limited conditions and thus decreasing *LE* compared to the control simulation. As expected, irrigation increases saturation in crop areas, with a corresponding increase in *LE*. Impacts of combined pumping and irrigation are mixed, with increases in saturation and *LE* over some areas and decreases over others. Increases occur primarily over crop areas located at the upper extent of the river valley or in hilltop areas, while decreases occur over crop areas in the lower river valley. In areas of deep groundwater, irrigation directly increases saturation and *LE*, but pumping-induced changes in water table depth have little influence on the surface water and energy balance. In areas of shallow groundwater, pumping-induced changes in water table depth strongly influence the surface water and energy balance, and declining groundwater levels may outweigh the effects of irrigation. Lastly, it should be noted that the impacts of groundwater pumping on saturation are detectable outside of crop areas (gray areas in Figure 1), while irrigation impacts saturation only over irrigated crop areas.

4.2 Groundwater-Land Surface Feedbacks

Recent studies demonstrate that groundwater processes influence the land surface water and energy balance over some regions[7,8]. Figure 4 shows monthly mean saturation (top 0.5m below land surface) and *LE* over crop areas as a function of water table depth for March and September from the four simulations analyzed here. Saturation and *LE* exhibit strong spatial dependence with respect water table depth during both months in all scenarios, with high saturation and *LE* in areas of shallow groundwater and low saturation and *LE* in areas of deep groundwater. Note that variability in saturation and *LE* with respect to water table depth in a given scenario is due to spatial differences in soil properties.

The magnitude of groundwater-land surface feedbacks (i.e., difference between areas of shallow and deep groundwater) is notably weaker in scenarios that include irrigation. In areas of shallow groundwater, moisture is readily transported from the water table to the land surface and the surface water and energy balance is energy-limited in all scenarios. Because these areas are energy-limited under both irrigated and non-irrigated conditions, irrigation has little affect on the relationship between water table depth and surface water and energy budgets. Over regions of deep groundwater, the land surface is essentially disconnected from the water table in all scenarios and surface fluxes become moisture-limited between precipitation events. Irrigation directly increases saturation, thereby reducing moisture-limited conditions and increasing *LE*; by contrast, changes in water table depth due to groundwater pumping have little impact on surface water and energy budgets over these regions.

5 CONCLUSION

Irrigation is one of the leading water uses throughout the SGP region, and the majority of irrigation is supplied by groundwater. Results presented here demonstrate that groundwater pumping and irrigation can significantly impact terrestrial water and energy cycles over a mid-size watershed in the SGP. Specifically:

(1) Pumping impacts groundwater levels throughout the watershed during all seasons; irrigation impacts are limited to irrigated areas during the growing season.
(2) Pumping significantly reduces saturation and *LE* over crop areas (where pumping occurs) during the growing season, with residual impacts over non-crop areas and outside of the growing season.
(3) Irrigation significantly increases saturation and *LE* over crop areas during the growing season, but has little affect over other areas and seasons.
(4) Impacts of combined pumping and irrigation depend on groundwater depth, with greater impacts on water table depth in areas of shallow groundwater and greater impacts on surface fluxes in areas of deep groundwater.

Land-atmosphere interactions strongly influence weather and climate on a broad range of spatial and temporal scales. Additional analysis is needed to evaluate feedbacks between local water management practices and local and regional climate.

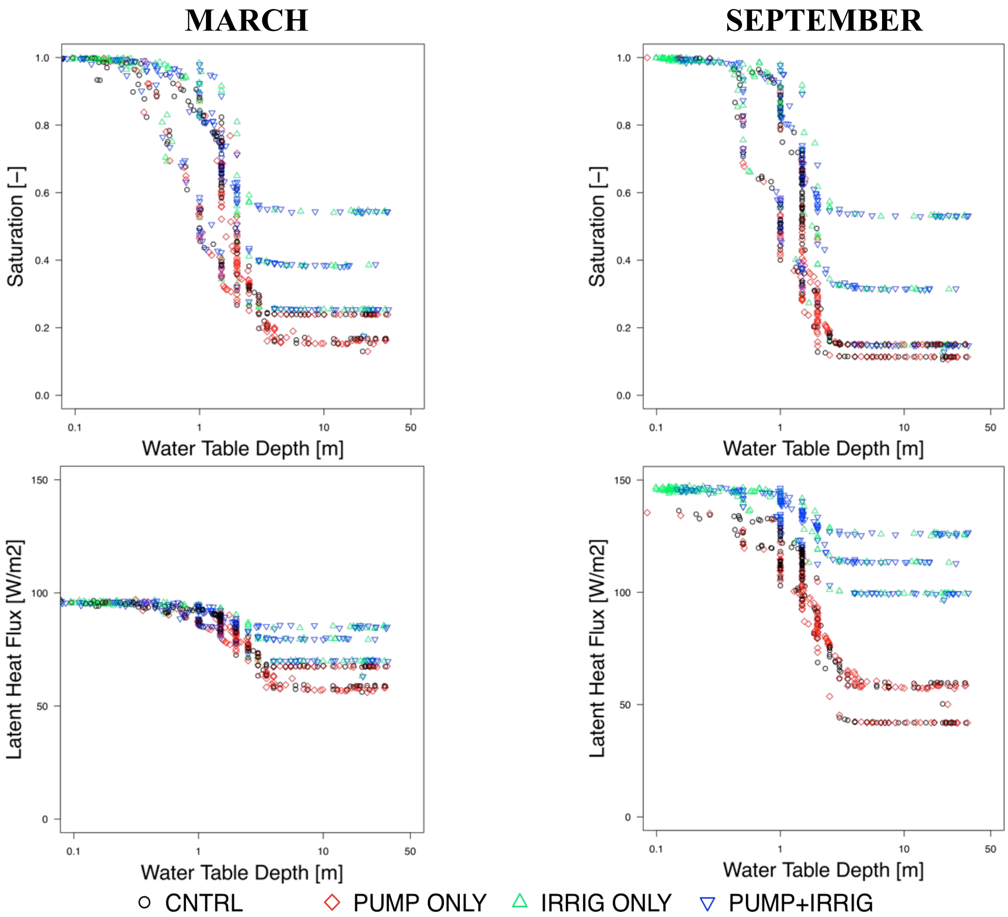

Figure 4: (top) Monthly mean saturation [-] and (bottom) latent heat flux [W/m^2] over crop areas as a function of water table depth for (left) March and (right) September.

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