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Human impacts on terrestrial hydrology: climate change versus pumping and irrigation

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Abstract

Global climate change is altering terrestrial water and energy budgets, with subsequent impacts on surface and groundwater resources; recent studies have shown that local water management practices such as groundwater pumping and irrigation similarly alter terrestrial water and energy budgets over many agricultural regions, with potential feedbacks on weather and climate. Here we use a fully-integrated hydrologic model to directly compare effects of climate change and water management on terrestrial water and energy budgets of a representative agricultural watershed in the semi-arid Southern Great Plains, USA. At local scales, we find that the impacts of pumping and irrigation on latent heat flux, potential recharge and water table depth are similar in magnitude to the impacts of changing temperature and precipitation; however, the spatial distributions of climate and management impacts are substantially different. At the basin scale, the impacts on stream discharge and groundwater storage are remarkably similar. Notably, for the watershed and scenarios studied here, the changes in groundwater storage and stream discharge in response to a 2.5 °C temperature increase are nearly equivalent to those from groundwater-fed irrigation. Our results imply that many semi-arid basins worldwide that practice groundwater pumping and irrigation may already be experiencing similar impacts on surface water and groundwater resources to a warming climate. These results demonstrate that accurate assessment of climate change impacts and development of effective adaptation and mitigation strategies must account for local water management practices.

Keywords: water resources, climate change, water management

1. Introduction

Humans impact the hydrologic cycle on a range of scales. At the global scale, anthropogenic climate change is altering large-scale heat and moisture transport, with subsequent impacts on air temperatures and precipitation patterns,

frequency and intensity (Trenberth *et al* 2003, Bates *et al* 2008). At the local scale, groundwater pumping for irrigation and local consumption is well documented to have caused widespread groundwater declines and stream depletion in the High Plains and Central Valley regions of USA (McGuire 2007, Faunt 2009), the North China Plain (Wang *et al* 2008), northwest India (Rodell *et al* 2009) and watersheds around the world (Wada *et al* 2012). Climate change affects terrestrial water and energy budgets—and ultimately surface water and groundwater resources—through changes in surface inputs (precipitation) and surface flux potentials



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(potential evapotranspiration). Water management practices on the other hand directly alter terrestrial water storage, including groundwater storage (via groundwater pumping) and shallow soil moisture (via irrigation), with subsequent feedbacks on surface fluxes.

In both cases, anthropogenic impacts on terrestrial water resources depend on interactions and feedbacks within and between water and energy cycles (Diffenbaugh *et al* 2005, Seneviratne *et al* 2006, Maxwell and Kollet 2008a, Ferguson and Maxwell 2010, 2011). It is well established that the hydrologic response to meteorological forcing (e.g., a precipitation event) is dependent on antecedent moisture conditions: the amount of runoff and recharge generated by a given precipitation event depends on the initial soil moisture content and water table distribution within the affected watershed. Anthropogenic changes in soil moisture and groundwater storage through water management practices such as irrigation and groundwater pumping thus have the potential to affect runoff generation, infiltration and recharge, with subsequent effects on streamflow, groundwater storage and evapotranspiration (Sophocleous 2002, Haddeland *et al* 2006).

Similarly, recent studies have shown that the hydrologic response to changing climate conditions depends on feedbacks between atmospheric, land surface and subsurface processes. Land energy fluxes have been shown to play an important role in driving local and regional-scale weather and climate, particularly in semi-arid plains regions where land–atmosphere interactions drive a significant portion of seasonal-to-interannual climate variability (e.g. Hong and Kalnay 2000, Koster *et al* 2003). Changes in temperature and precipitation, for example, alter soil moisture through impacts on evaporation and infiltration, respectively. Changes in soil moisture in turn affect the land energy balance, including the partitioning of incoming solar radiation between latent heat (evapotranspiration), sensible heat and ground heat fluxes. Changes in the land energy balance subsequently affect atmospheric boundary layer development, including mass and energy exchange between the land surface and the atmosphere as well as precipitation generating processes such as convection. These changes in boundary layer development ultimately feed back on weather and climate conditions, with potentially significant effects on local and regional hydrologic variability (Eltahir 1998, Diffenbaugh *et al* 2005, Patton *et al* 2005, Seneviratne *et al* 2006, Maxwell *et al* 2007, Anyah *et al* 2008).

Climate change adaptation and mitigation in the water resources sector will require an improved understanding of hydrologic response to anthropogenic perturbations, including local water management. While many studies have evaluated individual impacts of climate change, irrigation or groundwater pumping on terrestrial hydrology, few of these studies account for feedbacks between groundwater dynamics, overland (surface) flow, and land surface water and energy fluxes. Moreover, no previous study has directly compared hydrologic impacts of climate change and water management on local and basin-scale water and energy budgets.

Here we evaluate and compare impacts of climate change and water management on local and basin-scale water and energy budgets of a representative watershed in the Southern Great Plains, USA, an important agricultural region. We use a fully-integrated model of three-dimensional variably-saturated groundwater flow, overland flow, and land surface and vegetation processes that includes a complete coupling of water and land energy fluxes, important for land–atmosphere interactions. This model was used to simulate watershed response to three climate change scenarios and three water management scenarios. Climate scenarios were developed by perturbing observed meteorological forcings to reflect the median projected temperature change and range of projected precipitation change over central North America by year 2050 (Christensen *et al* 2007). Water management scenarios were developed by imposing groundwater pumping and irrigation in agricultural grid cells during the growing season at a rate equal to the estimated mean irrigation demand for the study region (Masoner *et al* 2003). Climate and management scenarios are compared to an unperturbed (control) simulation to evaluate impacts on local (grid cell) and basin-integrated water and energy fluxes.

2. Study area and modeling approach

This study used the integrated watershed model ParFlow. ParFlow is a parallel watershed model capable of simulating mass and energy transport in the deep subsurface, vadose zone, root zone and land surface (Ashby and Falgout 1996, Jones and Woodward 2001, Maxwell and Miller 2005, Kollet and Maxwell 2006, 2008). ParFlow simulates overland flow (river and hillslope flows) via a free-surface overland flow boundary condition (Kollet and Maxwell 2006, Maxwell and Kollet 2008b) and includes a land surface model (CLM) which computes energy and plant processes at the land surface (Dai *et al* 2003, Maxwell and Miller 2005, Kollet and Maxwell 2008). ParFlow uses parallel, or high performance, computing and runs efficiently across many processors (Kollet *et al* 2010). The ParFlow used here (commonly referred to as PF.CLM) is forced with a dataset of meteorology at the top of the vegetation canopy, and meteorological conditions are transmitted through the rest of the domain via the integration of ParFlow and CLM. That is, depending on land cover (e.g. vegetation type) precipitation fluxes to the land surface and evapotranspiration from the root zone are all based on atmospheric conditions and land surface (e.g. soil moisture) constraints.

ParFlow was used to simulate a 45 km × 32 km domain encompassing the Little Washita River watershed in Oklahoma, USA, located within the semi-arid Southern Great Plains. Climate, topography and agricultural practices in the region—including heavy reliance on groundwater pumping for irrigation—are broadly representative of many semi-arid agricultural regions around the world, including the North China Plain and northern India (Döll *et al* 2012). The domain was discretized with uniform horizontal resolution of 1 km and vertical resolution of 0.5 m, with a deep subsurface (>90 m) to capture deeper groundwater flow as well as

shallow subsurface flow. The watershed is characterized by rolling terrain; soils within the watershed are predominately loam and loamy sand, with some areas of sand and silt loam. Vegetation includes grasslands, open shrublands, croplands and interspersed trees. The domain was constructed using previously published elevation, soils and vegetation data (Maxwell *et al* 2007, Kollet and Maxwell 2008).

Seven equilibrium simulations were conducted to quantify watershed response to climate change and water management practices: one control (CNTRL) based on observed meteorology and no treatment of water management; three climate perturbation scenarios; and three water management perturbation scenarios. The CNTRL simulation was previously described in detail by Kollet and Maxwell (2008) and was shown to agree quite well with available observations of streamflow, soil moisture, and latent and sensible heat flux from within the study area. Climate scenarios are based on future climate projections for central North America based on some 20 global climate models (Christensen *et al* 2007); perturbations consisted of (1) systematic increase in air temperature by 2.5 °C with all other forcings unchanged (hot, H); (2) increase in air temperature by 2.5 °C with a 20% increase in precipitation (hot-wet, HW); and (3) increase in temperature by 2.5 °C with a 20% decrease in precipitation (hot-dry, HD). Climate scenarios analyzed here were previously analyzed by Maxwell and Kollet (2008a) and Ferguson and Maxwell (2010) and represent the median projected temperature change and range of precipitation change over the study region by the year 2050. Changes were not made to rainfall timing (as suggested by e.g. Crosbie *et al* 2012), though changes in intensity are included in these systematic perturbations of precipitation. It should be noted that predicted rainfall frequencies and intensities for future climate scenarios depend upon cloud parameterizations and are thus highly uncertain (Solomon *et al* 2007).

Water management scenarios are designed to evaluate the individual and combined effects of groundwater pumping and irrigation on local and basin-scale water and energy budgets. They consisted of (1) daily irrigation application to agricultural grid cells over the growing season (irrigation-only, I); (2) groundwater pumping from agricultural grid cells over the growing season (pumping-only, P); and (3) combined irrigation and pumping from agricultural grid cells (pumping + irrigation, PI). Scenario PI is representative of irrigation using groundwater from on-farm wells, and is consistent with the dominant irrigation practice throughout the study region; scenario I is representative of irrigation using water imported via inter-basin transfer. Scenario P is not representative of water management practices in the study area, but serves as an end-member in assessing impacts of local water management practices. Management scenarios were previously analyzed by Ferguson and Maxwell (2011) and are based on estimated annual irrigation demand for a nearby watershed as detailed information on irrigation practices within the study area is not available. Irrigation was applied daily from 07:00–19:00 local time during the growing season (1 June–15 September). The rate of irrigation was 0.396 mm h⁻¹ for a total of 508 mm (20 inches) of water

applied to the crop cells. While actual irrigation practices depend on on-farm conditions, this amount is consistent with the average annual irrigation demands for common crops in the study area (e.g. wheat, alfalfa and corn) and across the Southern Great Plains of North America (Masoner *et al* 2003). For the pumping cases (P and PI) the amount of pumping was equal to the irrigation applied at each cell, for consistency, and water was only withdrawn from the agricultural cells. Additionally, the timing of groundwater pumping was assumed to equal that of irrigation and irrigation scheduling was not varied in response to weather or soil moisture conditions.

Each scenario was spun-up for several years to achieve quasi-equilibrium conditions. Scenarios were initialized from CNTRL state and forced repeatedly with perturbed meteorology or water management treatment until the change in mass and energy balance over the water year dropped below a specified threshold. Only the last year of each simulation is analyzed.

3. Results and discussion

Figure 1 shows the spatial distributions of annual mean latent heat flux (LE, (W m⁻²)), potential recharge (precipitation plus irrigation minus evapotranspiration, referred to here as P–E, (mm)), and water table depth (D_{wt} , (m)) for CNTRL and annual mean differences for each scenario (scenario – CNTRL). LE is representative of the coupled water and energy balance at the land surface, while P–E and D_{wt} are representative of the water balance at the land surface and subsurface, respectively. All three variables exhibit similar spatial structures in CNTRL, highlighting the strong interdependence between local-scale water and energy budgets. Topographically driven groundwater flow results in groundwater convergence and shallow D_{wt} along the river valley; vertical moisture transport from shallow groundwater contributes to root zone soil moisture and high evapotranspiration (equivalently, high LE) and negative P–E in these areas. Where D_{wt} is greater, groundwater is disconnected from the land surface; soils in these areas become moisture limited during hot, dry summer conditions, resulting in decreased evapotranspiration (decreased LE) and positive P–E.

Figure 1 shows significant differences in local-scale water and energy budgets for all scenarios with respect to CNTRL. The magnitude of differences is similar between climate and management scenarios; however, spatial distribution varies substantially, with climate change scenarios exhibiting widespread differences throughout the study area and management scenarios exhibiting differences only in crop areas where pumping and irrigation occur. Maximum absolute difference in annual mean LE exceed 10 W m⁻² in all scenarios, with corresponding differences in evaporative fraction (fraction of total land–atmosphere energy flux as latent heat) greater than 25% (not shown). Difference in P–E exceeds 1 mm/day over irrigated areas, with negligible change outside of crop cells (figure 1; I and PI); pumping has a weaker but notable effect on P–E, with the maximum

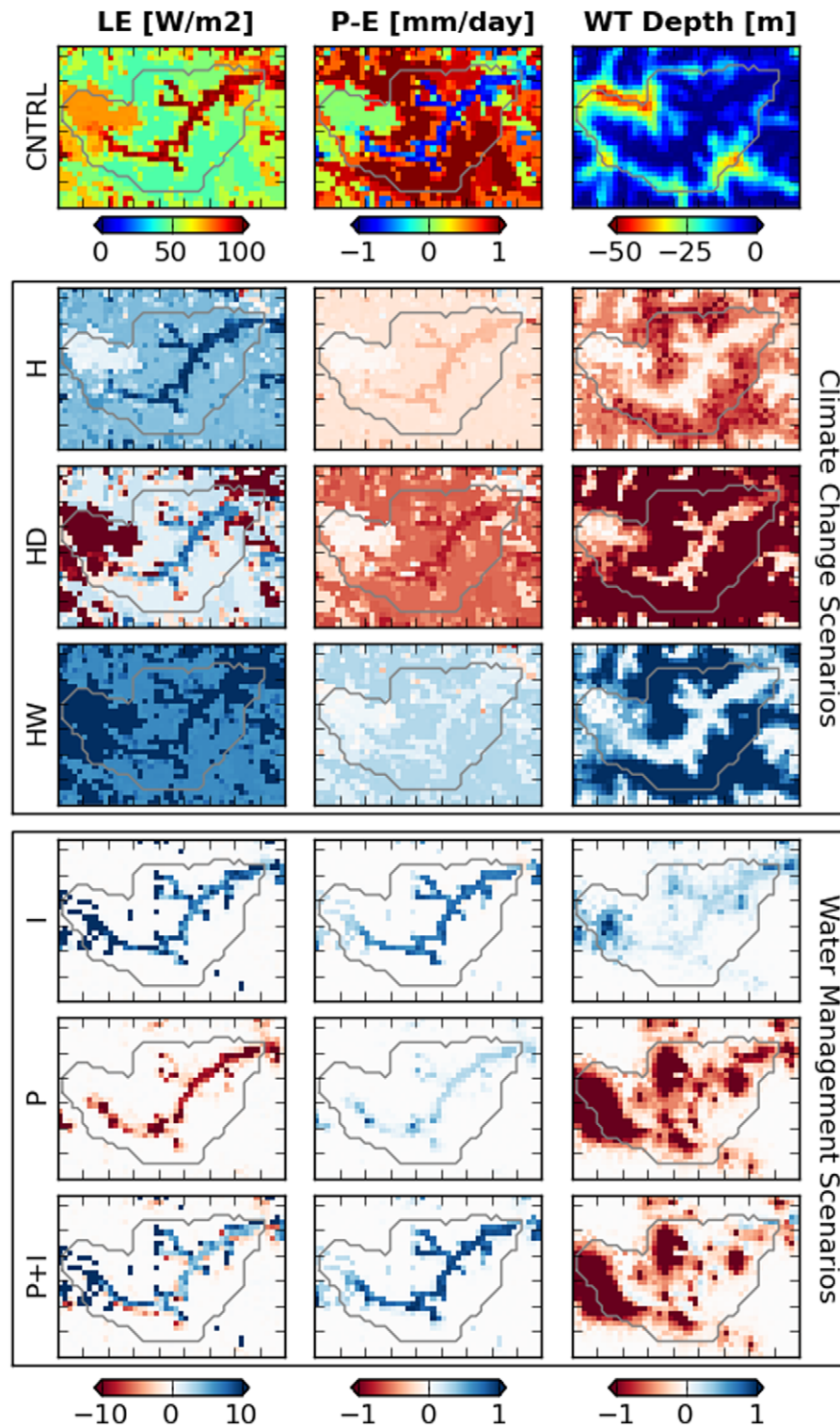


Figure 1. Spatial distributions of annual mean latent heat flux (LE) (W m^{-2}), potential recharge (P-E) (mm), and water table depth (D_{wt}) (m) for CNTRL (top row) and annual mean differences for each scenario (scenario – CNTRL). The Little Washita watershed is shown in gray; boxes delineate climate change scenarios (hot H, hot-wet HW, hot-dry HD) and water management scenarios (irrigation-only I, pumping-only P, pumping + irrigation PI).

difference exceeding 0.5 mm/day (figure 1; P). Differences in P-E in climate scenarios are generally weaker but encompass most of the watershed (figure 1; H, HW and HD). Note that pumping and irrigation both result in positive differences in potential recharge: pumping reduces moisture

availability, reducing evapotranspiration, thus increasing P-E; by contrast, increased inputs from irrigation outweigh the resulting increase in evapotranspiration, thus increasing P-E. Differences in D_{wt} in scenarios P, I and PI are similarly limited to areas up-gradient of wells or irrigation; by contrast,

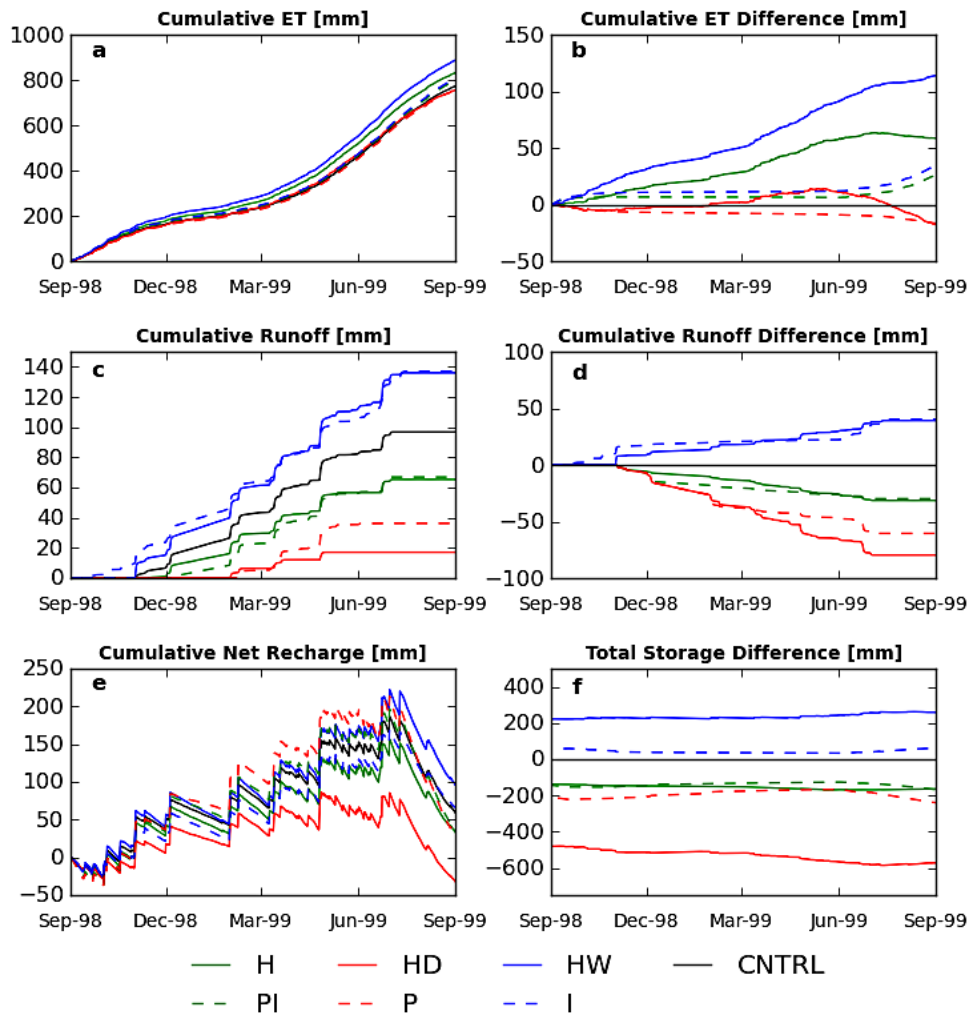


Figure 2. Basin-integrated water balance; all variables are integrated over the watershed and normalized by basin area. Top row shows cumulative evapotranspiration (ET) for CNTRL and all scenarios (mm) (left) and differences between each scenario and CNTRL (mm) (right). Middle row shows cumulative discharge (Q) from the watershed outlet for each scenario and CNTRL (mm) (left) and differences between each scenario and CNTRL (mm) (right). Bottom row shows cumulative net groundwater recharge (ΔS) (recharge minus losses) (mm) (left) and differences in total groundwater storage (S) between scenarios and control (right). Note in this figure that climate change scenarios are hot H, hot-wet HW, hot-dry HD and water management scenarios (irrigation-only I, pumping-only P, pumping + irrigation PI).

differences in scenarios H, HW and HD all encompass areas except those with initially shallow groundwater levels ($D_{wt}[CNTRL] < 2.5$ m), where groundwater convergence maintains shallow water table conditions in all scenarios (Maxwell and Kollet 2008a, Ferguson and Maxwell 2010). Note that as shown in previous studies D_{wt} decreases in scenario I, indicating increasing groundwater storage due to irrigation with imported water.

Local-scale differences in LE are strongly dependent on feedbacks between energy and moisture availability. While the spatially-uniform increase in air temperature in scenarios H, HW and HD drives a uniform increase in potential evapotranspiration, moisture limitations result in decreased LE over portions of the domain in H and more notably in HD (figure 1, H and HD). Increased precipitation in HW increases moisture availability, resulting in increased LE throughout the domain (figure 1, HW). Consistent with previous studies, irrigation increases moisture availability

over agricultural areas, increasing LE from direct canopy evaporation and plant transpiration (figure 1, I (e.g. Lobell *et al* 2009, Ozdogan *et al* 2010, Döll *et al* 2012)); as expected, pumping reduces groundwater levels, decreasing LE in areas where groundwater contributes to moisture availability at the surface (figure 1, P). When pumping and irrigation are combined, irrigation increases LE in agricultural areas, while pumping-induced groundwater declines decrease LE in some adjacent areas.

Changes in local-scale water and energy budgets alter spatially-distributed recharge and runoff processes, which subsequently impact on basin-scale and averaged hydrologic response. Figure 2 shows cumulative evapotranspiration (ET, (mm)) summed spatially over the basin, stream discharge at the basin outlet (Q , (mm)), and net groundwater recharge also summed over the basin (ΔS , (mm)) for CNTRL and each scenario, normalized by basin area (left column), and differences in cumulative ET, cumulative Q , and total

Table 1. Difference in basin-integrated annual ET, stream discharge Q and groundwater storage S_{gw} between CNTRL and scenarios normalized by basin area (mm).

	Scenario					
	H	HD	HW	I	P	PI
ΔET	58.5	−17.7	113.9	34.6	−16.6	26.1
ΔQ	−31.5	−79.7	39.1	40.3	−60.5	−29.8
ΔS_{gw}	−163.8	−572.0	258.9	62.0	−239.9	−167.6

groundwater storage (S_{gw} ; (mm)) between each scenario and CNTRL (scenario − CNTRL; right column). Differences in basin-integrated annual ET, Q and S_{gw} are shown in table 1.

Impacts of climate change and water management on basin-scale cumulative ET exhibit the same order of magnitude but distinct seasonal characteristics. Differences in cumulative ET due to pumping and irrigation, respectively, are monotonic over the water year. That is, moisture availability increases due to irrigation and decreases due to groundwater pumping with no change in atmospheric conditions. This change in soil moisture drives a monotonic increase in cumulative ET for irrigation and a decrease for pumping. Irrigation increases moisture availability throughout the year, which in turns drives a monotonic increase in cumulative ET; conversely, groundwater pumping decreases moisture availability throughout the year, driving a monotonic decrease in cumulative ET. However, differences in basin-integrated ET in scenarios I, P and PI are negligible outside of the growing season, as evidenced by negligible change in cumulative difference from October to June (figure 2(b)). In scenario HW, uniform increases in precipitation and temperature over the year drive an approximately constant, monotonic increase in cumulative ET throughout the year. In scenarios H and HD, however, changes in cumulative ET are not monotonic, again illustrating that dependence of changes in land surface water and energy fluxes on both moisture and energy availability.

Figure 2(d) shows striking similarities between impacts of climate change and water management on stream discharge Q : precipitation-driven increases in Q under scenario HW are approximately equal to irrigation-driven increases under scenario I; temperature-driven reductions under scenario HW are approximately equal to pumping-induced reductions under scenario PI; and combined precipitation and temperature-driven reductions under scenario HD are similar to pumping-induced reductions under scenario P. Uniform climate perturbations over the water year results in relatively constant differences in Q , as evidenced by the predominately linear, monotonic changes in figure 2(d). Differences due to water management are monotonic, but exhibit greatest slopes during the growing season and negligible slopes outside of this period.

Net recharge is characterized by short periods of positive recharge associated with precipitation events followed by gradual losses to ET and baseflow between events. Figure 2(e) shows that net recharge follows a similar pattern in all scenarios at both event and seasonal timescales. Close inspection of figure 2(e) shows, however, that differences in event recharge are generally small and differences in cumulative net recharge are driven primarily by differences

in ET between scenarios. Differences in cumulative net recharge result in large changes in groundwater storage S_{gw} within the basin (figure 2(f)). Whereas changes in Q are nearly equal for climate and water management scenarios (figure 2(d)), changes in S are much greater for climate scenarios. Groundwater depletion is approximately equal in scenarios H and PI, but is substantially greater in scenario HD than scenario P; similarly, increased groundwater storage is substantially greater in scenario HW than scenario I. While figure 1 shows that local-scale changes in water table depth due to irrigation and groundwater pumping are comparable to those due to climate change, these changes are generally localized to agricultural areas within the domain; climate-driven changes in groundwater storage are thus much greater when viewed at the basin scale.

Careful inspection of figure 1 indicates widespread decreases in water table depths under scenario I, as well as isolated areas of decreased water table depth in scenario PI, indicating increased groundwater recharge from irrigation, consistent with other recent studies (e.g. Döll *et al* 2012). Note also that this figure demonstrates that the storage changes for P are less than for H due to the localized nature of pumping (the cones of depression a clearly seen in figure 1) and the total amounts: changes in ET due to changing temperature and temperature yield greater recharge changes than pumping due to water management.

Impacts of climate change and water management practices are likely to differ between regions depending on local climate, geologic and hydrologic conditions, as well as local cropping and irrigation practices. Notably, in addition to changes in annual precipitation amount, impacts of climate change on runoff and recharge are likely to depend on changes in precipitation frequency and intensity. Impacts of irrigation and groundwater pumping are likely to depend on local cropping practices, irrigation scheduling and technology, irrigation source (i.e., groundwater versus local surface water versus imported surface water), and well depth and distribution, along with initial water table depth and distribution. Further analysis of factors affecting watershed response to climate change and water management is beyond the scope of this study.

4. Conclusions

In summary, this study uses a fully-integrated model of groundwater, surface water and land surface processes to evaluate and compare impacts of large-scale climate change and local-scale water management practices on local and

basin-scale water and energy budgets for an agricultural watershed the semi-arid Southern Great Plains, USA. Our results demonstrate, surprisingly, that water management impacts on land surface fluxes and basin-scale surface water and groundwater resources can be comparable to those of climate change. Notably, the effects of climate change and water management on stream discharge and groundwater storage are nearly equivalent for the study area and scenarios evaluated here.

Our results show that changes in climate directly alter local, spatially-distributed surface fluxes throughout the study area, with subsequent feedbacks on surface water and groundwater resources. Conversely, water management practices directly alter water availability and distribution, with feedbacks on land surface fluxes. These results imply that many semi-arid basins worldwide that practice widespread groundwater pumping and irrigation may already be experiencing similar hydrologic impacts as would be expected from a warming climate and underscore the need to account for the hydrologic and land energy impacts of local water management practices in developing climate change projections and adaptation and mitigation strategies for water resources.

These results suggest that feedbacks from large-scale pumping and irrigation, currently omitted from most studies, might exacerbate climate impacts in agricultural watersheds; a topic ripe for future study. Moreover, while it is well known that ET feedbacks from irrigation may propagate in coupled atmospheric simulations (e.g. Lobell *et al* 2009) feedbacks from groundwater depletion have not been thoroughly studied. Our results suggest that management and mitigation strategies for semi-arid regions need be based on an understanding of impacts and feedbacks from changes in both climate and water management.

Global reliance on groundwater to meet agricultural, municipal and industrial water demands has increased significantly over recent decades (Döll *et al* 2012, Scanlon *et al* 2012), and recent studies have shown increasing areas of groundwater overdraft and depletion (e.g. Rodell *et al* 2009). To date, local-scale groundwater use has been largely neglected in climate change impact and risk assessments. Our results suggest that increasing reliance on groundwater pumping is likely to exacerbate the impacts of climate change and lessen the resilience of local communities. These results underscore the importance of accounting for the effects of local water management practices as well as changing climate conditions in assessing climate change impacts on water supplies and in developing local-scale adaptation and mitigation strategies.

In addition to impacts on water supply, our results demonstrate significant feedbacks between water management practices and land energy fluxes. While studies have demonstrated that land energy fluxes play an important role in driving local and regional-scale weather and climate, particularly in semi-arid plains regions where land–atmosphere interactions drive a significant portion of seasonal-to-interannual climate variability, irrigation may also have an important impact on these processes (e.g. DeAngelis *et al* 2010). Current

projections of climate change neglect interactions between groundwater dynamics, shallow soil moisture and land energy fluxes; similarly, effects of water management practices such as groundwater pumping and irrigation are also neglected. Our results suggest that water management practices and local- to basin-scale hydrologic feedbacks significantly affect land energy fluxes and therefore may impact local and regional climate. These results emphasize the need to account for hydrologic and land energy impacts of local water management practices in developing climate change projections and adaptation and mitigation strategies for water resources.

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References

- Anyah R O, Weaver C P, Miguez-Macho G, Fan Y and Robock A 2008 Incorporating water table dynamics in climate modeling: 3. Simulated groundwater influence on coupled land–atmosphere variability *J. Geophys. Res.—Atmos.* **113** D07103
- Ashby S F and Falgout R D 1996 A parallel multigrid preconditioned conjugate gradient algorithm for groundwater flow simulations *Nucl. Sci. Eng.* **124** 145–59
- Bates B, Kundzewicz Z W, Wu S and Palutikof J 2008 Climate change and water *Technical Paper of the Intergovernmental Panel on Climate Change* (Geneva: IPCC Secretariat) pp 210–4
- Christensen J H *et al* 2007 Regional climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press)
- Crosbie R, McCallum J, Walker G and Chiew F 2012 Episodic recharge and climate change in the Murray–Darling Basin, Australia *Hydrogeol. J.* **20** 245–61
- Dai Y J *et al* 2003 The common land model *Bull. Am. Meteorol. Soc.* **84** 1013–23
- DeAngelis A, Dominguez F, Fan Y, Robock A, Kustu M D and Robinson D 2010 Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States *J. Geophys. Res.* **115** 14
- Diffenbaugh N S, Pal J S, Trapp R J and Giorgi F 2005 Fine-scale processes regulate the response of extreme events to global climate change *Proc. Natl Acad. Sci. USA* **102** 15774–8
- Döll P, Hoffmann-Dobrev H, Portmann F T, Siebert S, Eicker A, Rodell M, Strassberg G and Scanlon B R 2012 Impact of water withdrawals from groundwater and surface water on continental water storage variations *J. Geodyn.* **59–60** 143–56
- Eltahir E A B 1998 A soil moisture rainfall feedback mechanism 1. Theory and observations *Water Resour. Res.* **34** 765–76
- Faunt C C (ed) 2009 Groundwater availability of the Central Valley aquifer, California *United States Geological Survey Professional Paper 1766* (Reston, VA: USGS)
- Ferguson I M and Maxwell R M 2010 The role of groundwater in watershed response and land surface feedbacks under climate change *Water Resour. Res.* **46** W00F02

- Ferguson I M and Maxwell R M 2011 Hydrologic and land–energy feedbacks of agricultural water management practices *Environ. Res. Lett.* **6** 014006
- Haddeland I, Skaugen T and Lettenmaier D P 2006 Anthropogenic impacts on continental surface water fluxes *Geophys. Res. Lett.* **33** L08406
- Hong S Y and Kalnay E 2000 Role of sea surface temperature and soil-moisture feedback in the 1998 Oklahoma-Texas drought *Nature* **408** 842–4
- Jones J E and Woodward C S 2001 Newton–Krylov-multigrid solvers for large-scale, highly heterogeneous, variably saturated flow problems *Adv. Water Resour.* **24** 763–74
- Kollet S J and Maxwell R M 2006 Integrated surface–groundwater flow modeling: a free-surface overland flow boundary condition in a parallel groundwater flow model *Adv. Water Resour.* **29** 945–58
- Kollet S J and Maxwell R M 2008 Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model *Water Resour. Res.* **44** W02402
- Kollet S J, Maxwell R M, Woodward C S, Smith S, Vanderborght J, Vereecken H and Simmer C 2010 Proof of concept of regional scale hydrologic simulations at hydrologic resolution utilizing massively parallel computer resources *Water Resour. Res.* **46** W04201
- Koster R D, Suarez M J, Higgins R W and Van den Dool H M 2003 Observational evidence that soil moisture variations affect precipitation *Geophys. Res. Lett.* **30** 1241–4
- Lobell D, Bala G, Mirin A, Phillips T, Maxwell R M and Rotman D 2009 Regional differences in the influence of irrigation on climate *J. Clim.* **22** 2248–55
- Masoner J R, Mladinich C S, Konduris A M and Smith S J 2003 Comparison of irrigation water use estimates calculated from remotely sensed irrigated acres and state reported irrigated acres in the Lake Altus drainage basin, Oklahoma and Texas, 2000 growing season *Water Resources Investigations Report* 03-4155 (Reston, VA: USGS)
- Maxwell R M, Chow F K and Kollet S J 2007 The groundwater–land–surface–atmosphere connection: Soil moisture effects on the atmospheric boundary layer in fully-coupled simulations *Adv. Water Resour.* **30** 2447–66
- Maxwell R M and Kollet S J 2008a Interdependence of groundwater dynamics and land-energy feedbacks under climate change *Nature Geosci.* **1** 665–9
- Maxwell R M and Kollet S J 2008b Quantifying the effects of three-dimensional subsurface heterogeneity on Hortonian runoff processes using a coupled numerical, stochastic approach *Adv. Water Resour.* **31** 807–17
- Maxwell R M and Miller N L 2005 Development of a coupled land surface and groundwater model *J. Hydrometeorol.* **6** 233–47
- McGuire V L 2007 Water-level changes in the High Plains aquifer, predevelopment to 2005 and 2003 to 2005 *United States Geological Survey Scientific Investigations Report* 2006-5324 (Reston, VA: USGS)
- Ozdogan M, Rodell M, Beaudoin H K and Toll D 2010 Simulating the effects of irrigation over the united states in a land surface model based on satellite-derived agricultural data *J. Hydrometeorol.* **11** 171–84
- Patton E G, Sullivan P P and Moeng C H 2005 The influence of idealized heterogeneity on wet and dry planetary boundary layers coupled to the land surface *J. Atmos. Sci.* **62** 2078–97
- Rodell M, Velicogna I and Famiglietti J S 2009 Satellite-based estimates of groundwater depletion in India *Nature* **460** 999–1002
- Scanlon B R, Faunt C C, Longuevergne L, Reedy R C, Alley W M, McGuire V L and McMahon P B 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley *Proc. Natl Acad. Sci.* **109** 9320–5
- Seneviratne S I, Luthi D, Litschi M and Schar C 2006 Land–atmosphere coupling and climate change in Europe *Nature* **443** 205–9
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L (ed) 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
- Sophocleous M 2002 Interactions between groundwater and surface water: the state of the science *Hydrogeol. J.* **10** 52–67
- Trenberth K E, Dai A, Rasmussen R M and Parsons D B 2003 The changing character of precipitation *Bull. Am. Meteorol. Soc.* **84** 1205–17
- Wada Y, van Beek L P H, Sperna Wiland F C, Wu Y-H and Bierkens M F P 2012 Past and future contribution of global groundwater depletion to sea-level rise *Geophys. Res. Lett.* **39** L09402
- Wang E L, Yu Q, Wu D R and Xia J 2008 Climate, agricultural production and hydrological balance in the North China Plain *Int. J. Climatol.* **28** 1959–70