



## RESEARCH LETTER

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## Key Points:

- We quantify Beijing's water balance through time using newly coupled hydrology, biology, and land use models
- We use a crop growth model to simulate irrigation demand and recharge rate on agricultural land
- We demonstrate that land use change in Beijing enhances groundwater recharge, thus reducing the rate of groundwater level decline

## Supporting Information:

- Supporting Information S1

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## Quantifying changes in water use and groundwater availability in a megacity using novel integrated systems modeling

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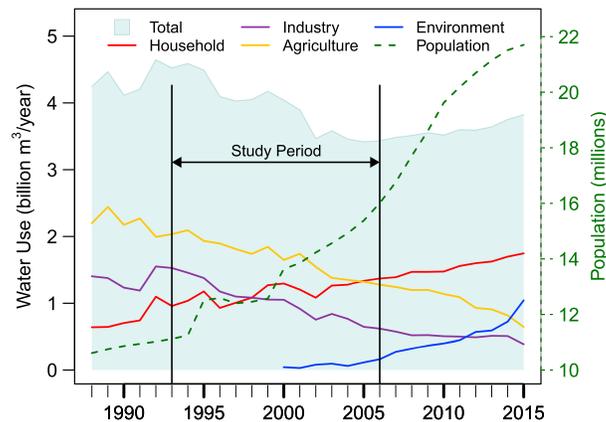
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**Abstract** Water sustainability in megacities is a growing challenge with far-reaching effects. Addressing sustainability requires an integrated, multidisciplinary approach able to capture interactions among hydrology, population growth, and socioeconomic factors and to reflect changes due to climate variability and land use. We developed a new systems modeling framework to quantify the influence of changes in land use, crop growth, and urbanization on groundwater storage for Beijing, China. This framework was then used to understand and quantify causes of observed decreases in groundwater storage from 1993 to 2006, revealing that the expansion of Beijing's urban areas at the expense of croplands has enhanced recharge while reducing water lost to evapotranspiration, partially ameliorating groundwater declines. The results demonstrate the efficacy of such a systems approach to quantify the impacts of changes in climate and land use on water sustainability for megacities, while providing a quantitative framework to improve mitigation and adaptation strategies that can help address future water challenges.

### 1. Introduction

Megacities around the world are experiencing water shortages driven by changes in land use and climate, along with rising population and affluence. Water shortages and their associated impacts extend well beyond the administrative boundaries and catchment areas of megacities because of cascading effects on regional water supplies and the profound influence these cities have globally [Lall, 2014; McDonald et al., 2014; Deines et al., 2016; Liu et al., 2017]. Identifying sustainable trajectories for megacities under global change requires an improved understanding of spatial and temporal dynamics of coupled human and natural systems [Pataki et al., 2011; Liu et al., 2015]. Sustainable water management is challenged by changes in climate, urbanization, economic development, and ecohydrologic constraints; it should thus be supported by modeling efforts that account for the multifaceted interactions among climatic, hydrologic, agronomic, and socioeconomic subsystems [Zhou et al., 2012; Gorelick and Zheng, 2015].

However, most research on megacity water sustainability has been fragmented or has not effectively captured the interactive and synergistic effects of coupled human and natural systems [Yang et al., 2016]. Here we synthesize climate, hydrology, land use, and socioeconomic data with integrated systems models to assess changes in groundwater availability for Beijing, China, a megacity that exemplifies the global water sustainability challenge. Our approach is designed to help policy makers quantify the potential long-term impacts of a range of policy choices by capturing important biophysical and socioeconomic processes and feedbacks that are crucial for effective science-based decision making.



**Figure 1.** Annual water use total and by sector for the Beijing Municipality, along with population data. Modified from *Deines et al.* [2016].

We simulated the interactive impacts of historical land use change and climate variability on groundwater availability across the Beijing region to quantify the key drivers that alter the water balance for this important megacity. We focus on 1993–2006, a period with relatively stable rates of both population growth and water use change. This analysis enhances our understanding of how megacities may respond and adapt to global change. It also continues the development of a coupled human and natural systems approach [*Liu et al.*, 2007] that emphasizes the interactions and feedbacks among system components.

## 2. Site Description

Beijing, the capital of the most populous country in the world, faces serious water sustainability challenges [*Feng et al.*, 2013; *Zhong et al.*, 2009] that have significant implications for China and the rest of the world. It exemplifies the global water shortage problems of megacities worldwide, due to its rapid population growth, land use change, and economic development overlain on a backdrop of climate variability.

The Beijing Municipality covers 16,410 km<sup>2</sup> (24.6% of this area was used to grow crops in 2006), characterized by a humid continental climate with hot, humid summers and cold, dry winters. Long-term average annual precipitation in Beijing is approximately 552 mm [*Xie et al.*, 2007], about 80% of which falls from June to September, making the region highly sensitive to water shortages. The city's population increased from ~11 to ~16 million people from 1993 to 2006 [*Beijing Bureau of Statistics*, 1980–2011]. This growth combined with decreased precipitation during an early 21st century drought resulted in a drastic decline in available per capita water from ~1000 m<sup>3</sup> in 1949 [*Probe International Beijing Group*, 2008] to under 110 m<sup>3</sup> in 2010 [*Zhang et al.*, 2012].

Since the early 1980s, Beijing's economy rapidly shifted toward the service or tertiary sector. From 1993 to 2006, the service sector grew from 47% to 72% of gross domestic product, while agriculture and mining (the primary sector) declined from 6% to 1% and industry, manufacturing, and construction (the secondary sector) declined from 47% to 27% [*Beijing Bureau of Statistics*, 1980–2011]. These economic changes eased water demand since Beijing's primary and secondary sectors are 20 to 40 times more water intensive than its tertiary sectors [*Zhang et al.*, 2012]. Nevertheless, in 2006 the primary and secondary sectors still accounted for 37% and 18% of water use, respectively.

Despite recent demographic and economic growth, Beijing's total water use peaked in 1992 at 4.6 billion m<sup>3</sup> and then declined and leveled off near 3.5 billion m<sup>3</sup> for 2002–2011 (Figure 1), with the decline largely due to reductions in industrial and agricultural uses, offsetting a rise in domestic water use. Average water use from 2000 to 2009 declined by 44% for industry and 30% for agriculture, while domestic use rose 40% relative to the previous decade (Figure 1).

These shifts in water use in part reflect changing water costs. Water prices rose substantially between 1990 and 2009 (by a hundredfold for agricultural groundwater use and tenfold to twentyfold for domestic and industrial uses), motivated in part by the government's desire to limit water use. Water-intensive industries were also moved outside of the municipality [*Probe International Beijing Group*, 2008]. These efforts were strongly supported by water pricing policy: prices for industry, lodging, and restaurants were about 2 to 3 times those of domestic prices over this period with up to 20 times higher prices for certain industrial uses. In 1996 and 1997 sewage processing fees were added to water prices; these have recently risen an order of magnitude. Despite the steady rise in water prices, domestic water in Beijing was less expensive than in other countries [*Organisation for Economic Co-operation and Development*, 2013].

In addition to measures aimed at curbing demand, engineering projects continue to enhance supply. From 1978 to 2009, the rate of wastewater treatment increased from 7.6% to 80.3% [Beijing Water Authority, 2010], and since 2003 there have been at least nine emergency water diversions from lakes and reservoirs in neighboring provinces [Beijing Bureau of Statistics, 1980–2011]. In addition, massive engineering projects designed to capture and divert water from other regions are being planned and developed. For example, the South to North Water Transfer (SNWT) Project, designed to divert water from the Yangtze River to Beijing and several other cities and provinces in northern China, is unprecedented in investment (~\$US79 billion) and has enormous potential socioeconomic and environmental impacts [Liu *et al.*, 2016]. The approach presented here provides a basis to evaluate the likely demand for water from the SNWT and its effects on groundwater recovery under potential climate and land use change scenarios.

Although several regional watersheds contribute to Beijing's water supplies, most large rivers in the region do not flow during the dry season. Since 2015, river restoration projects have been implemented to improve the health of Beijing's watersheds [Meng *et al.*, 2012; Pittock *et al.*, 2009]. Such "environmental flows" accounted for over 10% of total water use in 2011 (Figure 1). Surface water limitations in the Beijing region since the late twentieth century have resulted in significant overexploitation of regional groundwater. By 1980, seven groundwater well fields had been constructed to supply ~1.5 million m<sup>3</sup>/d of groundwater to the city. Additionally, approximately 1800 supply wells provide 1.0 million m<sup>3</sup>/d for industry, and 34,000 shallow wells are used for irrigated agriculture. By 2006, total groundwater extraction reached ~2.2 billion m<sup>3</sup>/yr [Beijing Water Authority, 2010].

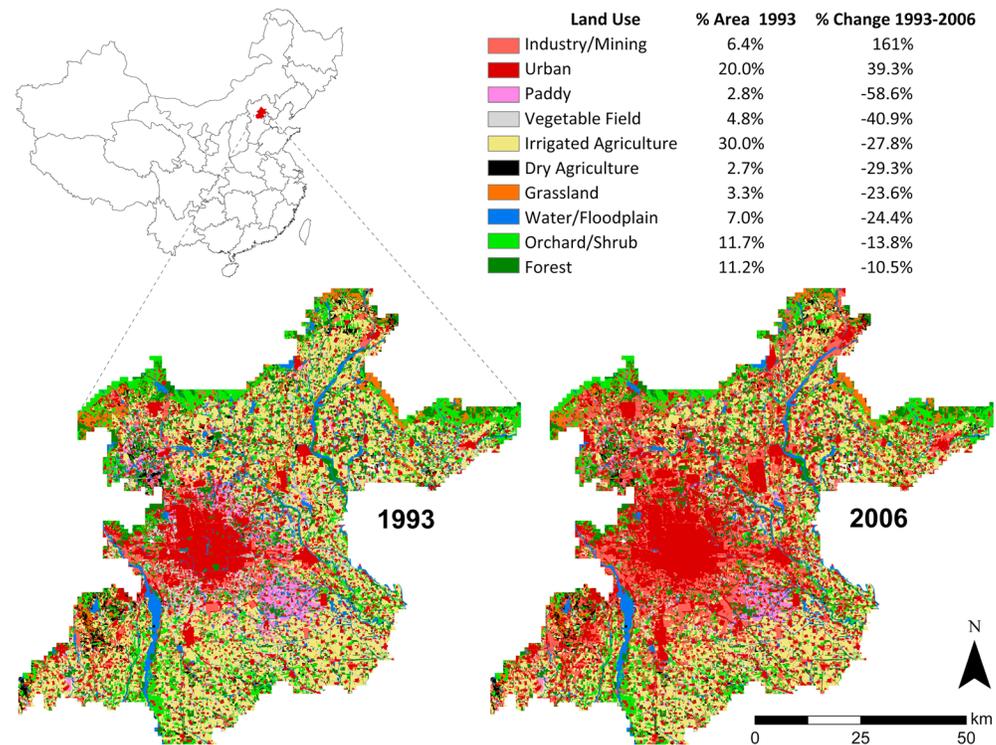
From 1999 to 2006, the watersheds supplying Beijing experienced a severe drought, requiring the construction of six emergency well fields from 2002 to 2004 with a combined capacity of 1.1 million m<sup>3</sup>/d, approximately half of which was pumped from the deep semiconfined aquifer. Groundwater now accounts for over 70% of the total water supply, approximately 60% of which was used for irrigation, 25% for drinking water, and 15% for industrial use [Zheng *et al.*, 2010; Cao *et al.*, 2013]. We chose to simulate this critical transitional period of 1993–2006, during which we had access to sufficient data to drive and validate our integrated systems models (Figure 1).

### 3. Methods

To examine drivers of changing water availability and sustainability in a megacity such as Beijing, we integrated sectoral water use and climate data into coupled land use, crop growth, and hydrology models. Population growth, built infrastructure, landscape physiography, and land cover data were used to simulate annual land use changes. These maps were then combined with climate, soil, and topography data to create inputs for the crop growth model to simulate soil water balances and fluxes. Water fluxes were synthesized into annual groundwater recharge maps and used as primary inputs to a groundwater flow model of the region, which accounted for changes in groundwater storage through time. Domestic, agricultural, and industrial water uses from groundwater were incorporated in our systems model by distributing groundwater pumping from these sectors across the corresponding modeled land use areas for each annual time step. The groundwater model thus served as the basis to develop a spatially and temporally explicit integrated water budget under changes in climate, land use, and water use. The details of each data type and model are described below.

#### 3.1. Land Change Data and Model

Using a fuzzy classification algorithm based on the principle of maximum entropy, we developed a land change model to simulate the growth of built areas at the expense of other land types. Maximum entropy classification algorithms have been used for many purposes, including mapping species distributions [Phillips *et al.*, 2006], aboveground biomass [Saatchi *et al.*, 2011], landslide susceptibility [Felicísimo *et al.*, 2013], and agricultural land use [Viña *et al.*, 2013]. The algorithm was applied to seven "predictor" variables using the software MaxENT [Phillips *et al.*, 2006]. Initial land use was derived from land use maps produced from 2.5 m pan-sharpened SPOT imagery for 1993, 2001, and 2007, resampled to the 30 m predictor variable resolution, while the last three predictor variables were obtained from a digital elevation model [Jarvis *et al.*, 2008]. The maximum entropy model was first calibrated using observed growth in built area between the 1993 and 2001 land use maps. From the resulting probability map, growth in built area from 2001 to 2007 was



**Figure 2.** Modeled land use change in the Beijing Plain. The location of the Beijing Plain study region is shown in the upper left inset map in red. The table beside the legend shows the percent cover of each class in 1993 along with the percent changes by class between 1993 and 2006.

predicted using observed annual rates of built area growth. Pixels are built starting with those that have the highest probability of change and ending when the observed rate of growth was reached.

The model was validated using 10,000 random pixels from 2001 and 2007 observed land use maps to calculate the Area Under the Receiver Operating Characteristic Curves (AUC) [Ray *et al.*, 2012; Hanley and McNeil, 1982], producing AUC scores of 0.897 and 0.637 for the calibration (1993–2001) and validation (2001–2007) periods, respectively. This indicates that the model performed far better than random, which is unusually good for land change models [Pontius *et al.*, 2008]. Most of the projected built areas were immediately adjacent to earlier builtup areas, indicating the typical dominance of spatial “inertia” in land change models [Mertens and Lambin, 2000], with reduced skill projecting “satellite” buildout. In other words, the model assumes stationarity of the buildout process, based on observed changes.

This validated model was then used to produce annual land use maps for the 1993–2006 period by backcasting urbanization from 2007 to the observed urban extent in 1993, replacing urban areas with the earlier observed land covers from the 1993 and 2001 maps (Figure 2). In this process, the map for the previous year was created by replacing the most unsuitable (lowest probability) urban areas with the land use that existed in the earlier observed land cover map.

### 3.2. Climate Data

Gridded daily observations of maximum and minimum temperature and precipitation for 1993–2006 at 0.5° resolution were the primary data employed in the plant growth model. Gridded precipitation data [Xie *et al.*, 2007] were derived from over 2200 stations across East Asia, and gridded temperature data [Xu *et al.*, 2009] were derived from 751 stations in China. Daily solar radiation was obtained from the National Center for Environmental Prediction Climate Forecast System Reanalysis [Saha *et al.*, 2010].

### 3.3. Plant Growth Model

The System Approach to Land Use Sustainability (SALUS) model [Basso and Ritchie, 2012, 2015] was used to simulate daily plant growth and soil water budgets to provide estimates of groundwater recharge across agricultural and natural areas of the Beijing Plain region (Figure 2) during the study period. The water balance in each cell accounts for surface runoff, infiltration, soil evaporation, plant transpiration, soil water storage, vertical soil water flow, and drainage to the saturated zone (recharge). Plant development and primary productivity are simulated as functions of the interaction between the daily environmental conditions (temperature, solar radiation and precipitation) soil properties, genotypes and agronomic management. Potential rates of plant growth are tempered by nutrient and water limitations. SALUS grows roots in a manner similar to the well-known CERES model [Ritchie and Otter, 1985], but with numerous improvements. It has been tested globally for climate variability impact on yield [Rosenzweig *et al.*, 2013; Asseng *et al.*, 2013, 2015; Bassu *et al.*, 2014], water use efficiency [Basso and Ritchie, 2012; Ritchie and Basso, 2008], and crop yields [Albarenque *et al.*, 2016; Basso *et al.*, 2016a]. A comprehensive testing of model algorithms is reported in Basso *et al.* [2016b].

Eight land use types were modeled across the Beijing Plain: paddy rice; dryland wheat; irrigated wheat; forest; vegetables; prairie, grasslands, and clear cut; shrubland and orchard; and bare soil. Soil data from the Soil Database of China [Shi *et al.*, 2004] were combined into three classes based on textural similarities: cinnamon [Gong *et al.*, 2003], fluvo-aquic [Xu *et al.*, 2005], and skeletal [Corti *et al.*, 2002]. In rice paddy fields, a fourth soil type was used to allow surface ponding and runoff as a function of slope. Two classes were created to account for slope: low slope ( $<10^\circ$ ), which dominated the study area, and high slope ( $\geq 10^\circ$ ) based on calculations from a Digital Elevation Model. These four input types (land use, soil type, slope class, and climate) were fully crossed, and each unique, existing combination was modeled with SALUS over the study period, resulting in 42 simulation scenarios. Modeled variables of interest included daily groundwater recharge, evapotranspiration, and optimal irrigation, which we aggregated to annual time steps for input to the groundwater model. Daily irrigation was modeled using an automated irrigation scheme that applies water when soil moisture drops below 30% of plant-available water up to 80% of that capacity. In effect, this approach estimates optimal irrigation and consumptive use of irrigation water lost to plant transpiration and soil evaporation.

### 3.4. Groundwater Model

The groundwater model domain covers the Beijing Plain region (Figure 2), which was formed by alluvial fans of the Chaobai River, Yongding River, and several small rivers. The thickness of Quaternary deposits ranges from 10 to  $>500$  m in the modeled region [Zhou *et al.*, 2012]. The shallow ( $\sim 50$  m deep) groundwater bearing layers are considered to be the shallow aquifer, which is mostly unconfined. Most agricultural water use was extracted from this shallow aquifer, and some groundwater drinking well fields are located on the upstream parts of the alluvial fans with coarse sediments. Deep aquifer units, which are the primary supply for industrial use, are semiconfined by low-permeability interbedded layers of fine sediments and receive leakage from the shallow aquifer. The primary source of water to the groundwater system is recharge, while the primary sink below the root zone is pumping from groundwater.

The groundwater model is built using MODFLOW-2005 [Harbaugh, 2005], with a horizontally uniform finite difference grid with  $1 \times 1$  km cells. The model has three layers, a top unconfined layer representing the shallow aquifer, a second low-permeability confining layer, and a bottom layer corresponding to the deep aquifer. Two types of lateral boundary conditions were applied: (1) the west, north, and northwest boundaries along the mountain fronts received lateral flux from the mountainous terrain, represented by specified flux boundaries and (2) the south, east, and southeast boundaries were represented by regional head-dependent flux boundaries with levels adjusted annually based on a regional groundwater flow model for the North China Plain [Cao *et al.*, 2013].

The initial water levels for the model were estimated by interpolating water levels observed at the beginning of 1993 from 102 monitoring wells. The annual water budget was then approximated using the model to account for pumping and average annual recharge across the region from 1993 to 2006. The groundwater flow model was calibrated to annual average observed water levels at monitoring wells using least squares regression (see Text S3 supporting information).

### 3.5. Model Integration and Simulations

This section briefly describes how the submodels were integrated to simulate changes in water balance across the modeled domain (see Texts S1–S4 in supporting information). Annual groundwater extraction was spatially defined in the groundwater model based on socioeconomic data and output from the land use and SALUS models. Socioeconomic data included annual urban and industrial groundwater use [Yang *et al.*, 2016], combined with their spatial extent from the land use model. Pumping for the industrial and urban sectors was distributed proportionally across the region based on land cover type because spatial variations in pumping by these sectors are not known. In addition, annual pumping volumes for Beijing were distributed among the known well fields. SALUS outputs for annual irrigation water applied for each land use-soil-slope-climate combination and the summed total volume for each grid cell were used to calculate the consumptive agricultural pumping. Wells were assumed to be in the centroid of each model grid cell containing irrigated agriculture to specify the annual, cell-specific amount of consumptive irrigation water extracted using SALUS.

For those land types modeled in SALUS, annual groundwater recharge maps were produced for input into the groundwater model by annually aggregating the SALUS model daily output to the 1 km groundwater model grid using spatially weighted averages of land cover types. Agricultural water use from both surface water and groundwater sources in excess of SALUS-calculated consumptive water use was added to the recharge map. We assume that recharge in water bodies (lakes, rivers, and reservoirs) is proportional to annual precipitation. Recharge from urban and industrial areas was calculated as a combination of pipe leakage, precipitation (assumed to percolate through pervious areas), storm water harvest facilities, and channels that accumulate overland flow. Pipe leakage was calculated as a fraction of annual urban water use; this was then distributed across the annual urban area from the MaxENT model. Because urban areas were not simulated by SALUS, we assume that a fraction of the annual precipitation in those areas exceeding a calibrated threshold becomes recharge to groundwater. In the calibration process, we estimated the water body recharge proportion, the fraction of urban water supply as pipe leakage, and the fraction and threshold of precipitation infiltration along with four hydrogeologic properties of the simulated aquifers (see Text S3 supporting information). This led to a parsimonious parameterization, without sacrificing representation of spatiotemporal variations in recharge.

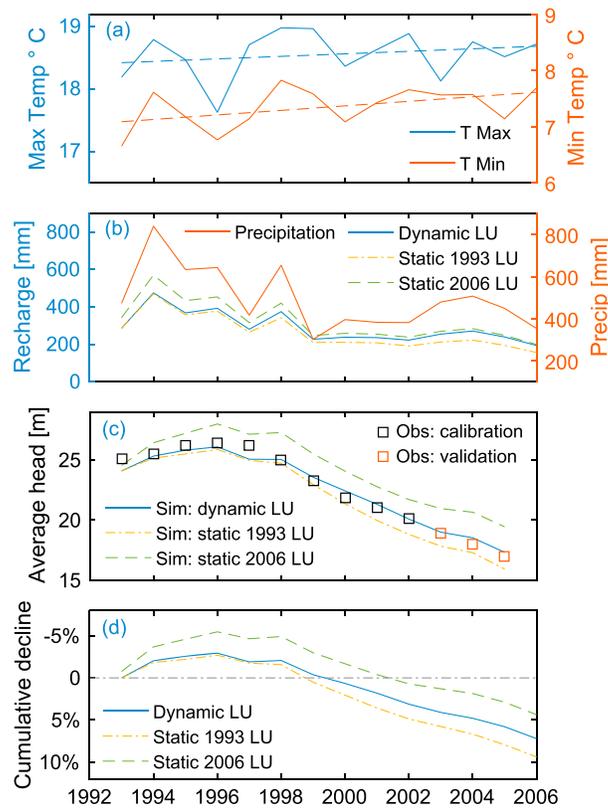
To demonstrate how our coupled modeling approach improves inference about changes in Beijing's hydrogeological system, we ran three sets of simulations. First, we ran the linked model using the simulated annual land use maps to generate annual recharge and pumping inputs ("dynamic land use"). We then ran two "static land use" simulations in which we maintained annual variations in the water budget but used static land use maps from 1993 or 2006 to produce the annual recharge and pumping inputs. We then compared the simulated and observed groundwater head data to evaluate the importance of dynamic land use in this system relative to the observed water level changes.

## 4. Results and Discussion

Land use changed dramatically across the Beijing plain from 1993 to 2006, with 39% growth of urban uses and 161% growth of industrial uses. These expansions were offset by reductions in other land uses, notably a 28% reduction in irrigated agriculture (Figure 2).

Analysis of the climate data shows that from 1993 to 2006, Beijing's maximum temperatures remained relatively stable (+0.26°C per decade,  $p = 0.4$ ), while the minimum temperature increased by 0.52°C per decade ( $p = 0.09$ ), based on a linear trend analysis (Figure 3a). Meanwhile, there was significant variability in precipitation, including a drought from 1999 to 2006 when annual precipitation was 37% lower than the average for the previous two decades (Figure 3b). Both the temperature and precipitation variability pose challenges for water sustainability in the region because evapotranspiration increases with higher temperatures, and recharge was greatly reduced during periods of low precipitation (Figure 3b).

To assess regional groundwater sustainability, the groundwater flow model was calibrated to match the observed groundwater levels at monitoring wells. The model provides a reasonable representation of spatial and temporal storage dynamics (Figure 3c). However, it underestimates the magnitude of the cone of depression in the central eastern part of the domain (see Figures S3–S4 supporting information), likely because spatial variations in self-supplied pumping are not well known nor are the well depths or the distribution of pumping volumes across municipal wellfields. Our calibrated systems model showed that from 1993 to



**Figure 3.** Temporal changes in climate, recharge, and groundwater storage. (a) Annual average daily maximum and minimum temperatures for the Beijing municipality based on daily observations [Xu et al., 2009]. (b) Recharge for the three simulations (dynamic simulated land use (LU), static land use from 1993 and 2006) and observed annual precipitation [Xie et al., 2007]. (c) Simulated and observed groundwater head of the shallow aquifer, averaged over the monitoring well locations. (d) Simulated cumulative decline in groundwater storage in the shallow aquifer as a percentage of 1993 levels.

the groundwater model for urban recharge, as we were able to simulate nonurban recharge with no calibration through the SALUS biophysics model. However, simulated increases in recharge due to land use change only partially offset declines in storage. Completion of the South-to-North Water Transfer Project will increase the amount of water diverted to Beijing and will likely further alleviate stress on the groundwater system [Hao et al., 2014; Yang et al., 2016].

The simulated storage declines under the three model scenarios highlight the importance of including annual land use dynamics when simulating rapidly urbanizing areas, especially megacities. Compared to the dynamic land use scenario that matches both the water table increases during wet years before 1998 and the decline rate during the subsequent drought, the static 1993 land use scenario overestimated groundwater storage decline due to a lack of urban and industrial growth and the accompanying increase in recharge. In contrast, the static 2006 land use scenario underestimated groundwater storage decline due to the enhanced urban recharge and pipe leakage in the artificially inflated industrial and urban areas, particularly in the early years of the simulation.

### 5. Discussion and Conclusions

We present a novel integrated modeling system to quantify how various human activities have altered Beijing's water sustainability pathway and to demonstrate how this approach can model complex biophysical interactions among the atmosphere, plants, and water resources of coupled systems. This model

2006, groundwater storage in the shallow unconfined aquifer declined by approximately 7.2% (Figure 3d). From 1996 (when water level peaked) to 2006, water levels in monitoring wells declined by 8.7 m on average for the available monitoring wells (Figure 3c).

Notably, we found that urbanization between 1993 and 2006 enhanced annual recharge by 22.4% by the end of this 13 year period relative to the recharge that would have occurred if land use had remained static since 1993 (Figure 3b). Indeed, the annual average recharge in the static 2006 land use (LU) simulation was 26% higher than that in the static 1993 LU simulation. This was due to the conversion of irrigated agricultural areas (within which the model simulates ~27% consumptive use of total irrigation water compared to water use statistics) to urban areas with little evapotranspiration, concentrated runoff into permeable channels, pipe leakage, and storm water retention and recharge structures in the urban core. Although others have recognized increased recharge in urban areas [e.g., Lerner, 2002] and in Beijing specifically [Zhang and Kennedy, 2006], our approach enabled us to optimize

provides process-based estimates of annual recharge that account for human induced feedbacks via simulated land use changes. A unique feature of the study is the use of the SALUS plant growth model to estimate recharge for a regional groundwater flow model. Through this linkage, recharge was calculated using SALUS simulations based on daily climate inputs to simulate plant growth dynamics, which are crucial for simulating water budgets. Thus, the only remaining recharge parameters to estimate are related to urban and industrial areas. This resulted in a more parsimonious model with fewer parameters to be estimated, reduced calibration efforts, and improved parameter specificity, all while retaining a good overall model fit.

This systems modeling effort provides insights not otherwise obtainable. For example, we quantified the influence of urbanizing agricultural areas in terms of reduced demand for irrigation water and thus less consumptive loss of water through evapotranspiration. The simulation results also indicate that Beijing's urbanization enhanced groundwater recharge, mainly through leaking water distribution systems and increased runoff from impermeable areas. Although overland flow across impervious surfaces is a significant concern in most municipalities, it can provide a useful source of water if it can be managed appropriately to enhance groundwater recharge in settings where large declines in groundwater level have been observed. However, the poor quality of recharge water from both urban storm water and sewage reclamation may pose significant challenges for cities such as Beijing.

Our systems model, which is based on detailed climate, soil, and land use inputs, generally captured the observed variations in groundwater storage. This demonstrates the ability to use such integrated models to help explain how a coupled system changes in time and space and the results of such changes on the states of the system, including groundwater levels and storage. Integrating time-variable land use, as simulated by MaxENT, provides a better overall fit to the observed data, matching both the period of water table increases during a wet interval and the declining rate during the subsequent drought. The integrated model provides a good fit between simulated and measured mean water levels, indicating that the simulation reasonably quantifies the overall groundwater budget of the modeled domain. The simulated water budget is subject to uncertainties including the lack of hydrologic information to determine lateral fluxes from the northwestern boundary, estimation of recharge, and uncertain pumping information (rates and locations). Further constraining the parameters and uncertainties would require additional detailed data.

This study demonstrates the efficacy of linking land use, dynamic vegetation/water budget, and groundwater systems models to quantify the impacts of historical climate trends and variability and the importance of accounting for changes in land use. A systems model framework can also incorporate a wider range of factors influencing water sustainability in megacities such as Beijing, adding submodels to account for socioeconomics, landscape hydrology, and projected climate change, along with feedbacks among model components. Given proper modifications, this approach is broadly applicable to other megacities around the world facing similar sustainable water supply challenges.

Due to lack of contemporaneous data, the coupled models simulation is restricted to a historical period. For many megacities and other large urban areas facing critical water sustainability issues, development of systems models will face limitations due to data availability and quality, as well as modeling uncertainties that are similar to those we faced for our Beijing model. Despite these limitations, this study demonstrates that significant insights into the variables controlling water availability in Beijing can be gained using a systems approach that can be readily applied to other megacities across the globe.

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