

Groundwater recharge and discharge analysis for land use conditions suitable for the hydrology and ecology of semiarid regions

Juana Paul Moiwo and Fulu Tao

ABSTRACT

Land use is critical for the hydrology of arid/semiarid regions with fragile/valuable ecosystems. Using Western Jilin as proxy for arid/semiarid, four land use conditions were investigated for the sustainability of fragile/valuable ecosystems – land use conditions for 1930 (pre-development), 2010 (post-development), forestland and grassland. For forestland/grassland, barren/bare-lands and land surfaces with $\geq 10\%$ slope in 2010 were replaced with grass and forest. Error analysis showed good agreements among the model-simulated and field-measured values, with average error $< 10\%$. Shifting from 1930 to 2010 land use condition decreased annual recharge and discharge by 17.09% (21.46 mm/yr or $1.01 \times 10^9 \text{ m}^3$) and 34.14% (10.03 mm/yr or $4.70 \times 10^8 \text{ m}^3$), respectively, in the $4.69 \times 10^{10} \text{ m}^2$ study area. Rehabilitating 2010 land use with forest increased recharge and discharge, respectively, by 6.25% (6.51 mm/yr or $3.05 \times 10^8 \text{ m}^3$) and 12.82% (2.88 mm/yr or $1.16 \times 10^8 \text{ m}^3$). Replacing the forest with grass increased recharge and discharge, respectively, by 15.22% (15.85 mm/yr or $7.43 \times 10^8 \text{ m}^3$) and 35.85% (6.93 mm/yr or $3.25 \times 10^8 \text{ m}^3$). Although pre-development land use condition was most conducive, grass performed better than forest in the study area. Rehabilitation with grass little affects food production in the region, and is thus applicable to other arid/semiarid regions.

Key words | arid/semiarid hydrology, forestland, fragile/valuable ecosystem, grassland, land use

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INTRODUCTION

Land use is the modification of land cover systems to meet the needs of society and to sustainably preserve the ecosystem and environment (Herold *et al.* 2006). Extensive land use started about a century ago (Junkermann *et al.* 2009) and little now remains of natural land cover systems (Pan *et al.* 2003; Yu *et al.* 2006; Li *et al.* 2008). The intensive exploitation of land resources with increasing industrialization sometimes results in undesirable outcomes (Bahremand *et al.* 2006; Tian & Yang 2009). This necessitates the need for land use analysis in terms of the driving factors and negative effects of land use (Rodell *et al.* 2009; Moiwo *et al.* 2011).

Whereas recharge is important for groundwater storage, discharge is critical for the sustainability of groundwater-

dependent ecosystems (Dams *et al.* 2008). While recharge largely occurs in high-elevation areas, discharge is mostly associated with low-elevation areas (De Smedt & Batelaan 2001). Irrespectively, the dynamic interactions of local and regional flows with surface water and groundwater systems could cause recharge and discharge to occur in the same area (Batelaan *et al.* 2003). Recharge–discharge areas, the so-called intermediate zones, have conditions that generally favor valuable wetlands and ecosystems. In especially arid/semiarid regions where water is critical for food production and ecological sustainability (Li *et al.* 2008; Gao & Liu 2009), there is the need for efficient water management strategies (Batelaan & De Smedt 2007; Moiwo *et al.* 2010a, b; Yasuda *et al.* 2013).

Land use could adversely change air composition and suppress precipitation (Junkermann *et al.* 2009) and runoff (Yang & Tian 2009). Anthropogenic activities and climate change could also suppress runoff (Fan *et al.* 2010). Excessive logging could cause low net primary productivity of mountain forests (Zhao *et al.* 2010). Irrigation, which is a land use-related activity, is one of the main causes of groundwater depletion across the globe (Rodell *et al.* 2009; Moiwo *et al.* 2012). Groundwater modeling, vegetation mapping, hydro-geochemical and climatic/land physiographic analysis or different combinations of these approaches in a GIS (geographical information system) can be used to assess the effects of land use on the ecosystem (Asefa *et al.* 1999; Woldeamlak *et al.* 2007).

The integration of RS (remote sensing) and GIS can serve as a powerful platform for processing distributed data at various spatial and temporal scales (Rodell *et al.* 2004; Gowda *et al.* 2007). WetSpas (Water and Energy Transfer between Soil, Plants and the Atmosphere under quasi-Steady State) is a physically based and spatially distributed model which uses remote sensing data to simulate hydrological processes driven by land-physiography (Asefa *et al.* 1999; Batelaan *et al.* 2003). Firmly integrated in GIS, WetSpas is loosely linked with MODFLOW to interactively simulate hydrological processes based on land use and update groundwater levels (Asefa *et al.* 1999; Batelaan & Woldeamlak 2004).

Batelaan *et al.* (2003) successfully used the WetSpas model with a Seepage-Package to quantify distributed recharge and discharge in the Grote-Nete Basin, Belgium. Pokojska (2004) used WetSpas to simulate groundwater recharge in the Rega River Basin, Poland. Aish *et al.* (2010) applied the model in the simulation of treated sewage groundwater recharge mounds in Gaza, Palestine. WetSpas has also been applied in land use and hydrological analyses under various agro-climatic conditions (Yu *et al.* 2006; Batelaan & De Smedt 2007; Moiwo *et al.* 2010a, b).

Arid/semiarid regions constitute some 30% of the global terrestrial area (Dregne 1991). These regions are generally characterized by low precipitation, frequent droughts, sparse vegetation, over-grazing, soil salinization, desertification, land degradation, and storage depletion (Scanlon *et al.* 2006; Yasuda *et al.* 2013). Despite the inherent fragility, arid/semiarid regions constitute valuable ecosystems and biodiversity (Pan *et al.* 2006) that need active preservation to

ensure sustainability (Tian & Yang 2009). This implies that the high population pressures and intensive land uses in arid/semiarid regions require management strategies which consistently ensure hydrological and ecological sustainability.

This study aimed to identify the land use conditions that are suitable for the sustainability and preservation of fragile/valuable wetlands/ecosystems in arid/semiarid regions. The study used Western Jilin (a semiarid region in northeast China with large expanses of wetlands), as a proxy for arid/semiarid regions. It analyzed groundwater recharge and discharge for four land use conditions – forestland, grassland, and land use conditions of 2010 (post-development) and 1930 (pre-development). While grassland is a typical semiarid vegetation (Tian & Yang 2009), forestland and grassland conditions are among the most investigated forms of land use (Junkermann *et al.* 2009; Abu-Saleem *et al.* 2010). The findings of this study could further deepen our knowledge on land/water resources management strategies in arid/semiarid regions. This is critical for the preservation and sustainability of not only fragile/valuable wetlands, ecosystems, and biodiversity, but also for the livelihoods of the millions of people in these regions and beyond.

RECHARGE–DISCHARGE MODEL

Groundwater recharge and discharge could occur at various scales of the watershed. Here, in this study, groundwater recharge is defined as water reaching the saturated zone through the water table. Then, discharge is water flowing from saturated storage towards the land surface under hydraulic gradient and/or capillary suction. In the study, WetSpas simulated recharge while MODFLOW Drain Package simulated discharge (Asefa *et al.* 1999; Batelaan & Woldeamlak 2004). WetSpas uses RS/GIS multi-resolution features to split the raster grid-cell into a cascade of vegetated, bare-land, open-water, and impervious surfaces where independent water balances are maintained (Batelaan & De Smedt 2007).

WetSpas and MODFLOW raster grid cells match a perfect overlay for the interactive simulation of distributed hydrological processes based on land-physiographic

characteristics. WetSpss uses editable database tables of land-physiographic features, such as land use, surface slope, and soil texture to simulate groundwater recharge as the residual of raster grid cell water balance as (Batelaan & Woldeamlak 2004):

$$R_{\text{tot}} = n(P_{ibov} - S_{ibov} - ET_{ibov} - I_{ibov}) \quad (1)$$

where R_{tot} is total groundwater recharge [LT^{-1}]; P is precipitation [LT^{-1}]; S is surface runoff [LT^{-1}]; ET is evapotranspiration [LT^{-1}]; I is interception [LT^{-1}]; n is the number of raster grid cells in the model domain raster layer [-]; and the subscripts i , b , o , and v , respectively, denote impervious, bare-land, open-water, and vegetated surface fractions of the raster grid cell [-]. Note that Equation (1) separately computes the hydrological processes in each fraction of the raster grid cell before aggregation on a seasonal or annual basis (Batelaan & De Smedt 2007).

MODFLOW simulates three-dimensional groundwater flow in heterogeneous, anisotropic porous media under constant water density state as (Harbaugh 2005):

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = Ss \frac{\partial h}{\partial t} \quad (2)$$

where t is time [T]; h is hydraulic head [L]; W is source/sink flux [T^{-1}] with $W < 0$ for outflow and $W > 0$ for inflow; Ss is specific storage [L^3T^{-1}]; and K_{xx} , K_{yy} , and K_{zz} are hydraulic conductivities, respectively, along the x -axis, y -axis, and z -axis [LT^{-1}].

The MODFLOW Drain Package adapts hydraulic conductivity to model local conditions to limit the effects of vertical discretization and numerical instability (Batelaan *et al.* 2003). The Drain Package simulates groundwater discharge as (Harbaugh 2005):

$$\begin{aligned} D &= C(h - dl) & \text{for } h > dl \\ D &= 0 & \text{for } h \leq dl \end{aligned} \quad (3)$$

where D is groundwater discharge [LT^{-1}]; h is hydraulic head [L]; C is drain conductance coefficient [L^2T^{-1}]; and dl is drain level [L]. The drain conductance coefficient relates the drainage head to the resulting flux in a lumped

way (Batelaan *et al.* 2003). The Drain Package interactively uses the WetSpss-simulated groundwater-level dependent recharge to simulate discharge. Further details on the interaction processes of WetSpss, MODFLOW, and the Drain Package are documented by Batelaan & De Smedt (2007).

MODEL APPLICATION

Case study

The hydrological model was applied to the Western Jilin ecosystem – a vast expanse of fragile/valuable wetlands in the semiarid northeast China region. The case study area lies between longitudes $121^{\circ}38' - 126^{\circ}12'$ E and latitudes $43^{\circ}59' - 46^{\circ}18'N$ (Figure 1). The $\sim 47,000 \text{ km}^2$ region accounts for 60% of the wetlands in the Songhua River Basin and is inhabited by over five million people (Yu *et al.* 2006; Tian & Yang 2009). The wetland ecosystem is under intense pressure due to farming and other land use activities in the region (Pan *et al.* 2006; Li *et al.* 2008).

The prevailing semiarid monsoon climate is dry in spring, rainy in summer, windy in autumn, and cold in winter (Zhang *et al.* 2003). The annual temperature (average of 10.3°C) has high seasonal (4.0°C to 14.3°C) and diurnal (30.0°C to 31.8°C) variations (Gao & Liu 2009). There are 130–165 frost-free days and the soils freeze in November through April. In the study area, open-water evaporation ($\sim 1,973 \text{ mm/yr}$) far exceeds annual precipitation ($\sim 458 \text{ mm/yr}$). Like ET, over 80% of the precipitation occurs in the summer months of June through August. Average annual humidity, radiant energy, and wind speed are respectively 66.8%, $5 \times 10^{12} \text{ J/m}^2$, and 6.7 m/s (Pan *et al.* 2003; Li *et al.* 2008).

Hydro-climatic conditions and site discretization

Underneath the Western Jilin ecosystem lie the Mesozoic/Cenozoic continental lacustrine deposits of the Songhua Basin. The aquifer systems comprise various mixes of sand, sandstone, silt, shale, clay, and volcanic coal layers (Zhang *et al.* 2003; Pan *et al.* 2006; Yang *et al.* 2009). There are also widespread water storage depletion and soil/environmental degradation in the region due to the

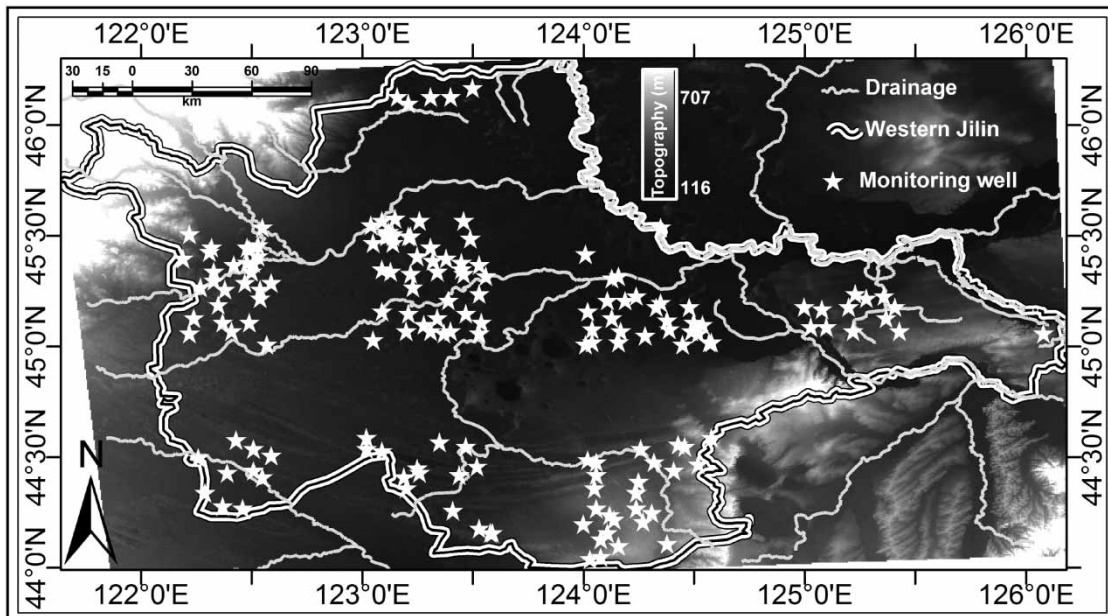


Figure 1 | A map of Western Jilin depicting the study area, drainage system, groundwater monitoring wells, and background topography.

intensive exploitation of land/water resources (Zhang *et al.* 2003; Pan *et al.* 2006; Yang *et al.* 2009). The near-endorheic basin is over 70% bounded by groundwater divide. To various extents, land physiographic features, groundwater divides, and pumping bore wells make up the flow boundary conditions. Also, the model domain is bounded at the top by the land surface and at the bottom by impervious clay/rock layers (Zhang *et al.* 2003; Moiwu *et al.* 2012).

Flux-dependent riverbed conductance was used to simulate river-aquifer interactions in the study area. The model was discretized into a 500 m × 500 m grid cell resolution, resulting in a total of 518 rows, 702 columns, and 363,636 grid cells for the ~47,000 km² study area. The study focused mainly on land surface systems (e.g., wetlands along with recharge and discharge areas) most influenced by phreatic groundwater conditions. The hydro-climatic data were interpolated in GIS (using the natural neighbor interpolation) to get the distributed input data required by the model.

Land use conditions

Before 1949, over 57% of the study area was under grassland vegetation (Himiyama 2001). This has since dropped to below 20% due to pressures mainly from population growth and intensive land use (Liu *et al.* 2002; Tian &

Yang 2009). Currently, grassland vegetation is largely limited to land surfaces that are barren or with significant sand dunes (Gao & Liu 2009). Details of the land use types for the 1930 and 2010 conditions (Himiyama 2001; Liu *et al.* 2002) are listed in Table 1. Based on the land use conditions of 1930/2010, 7.6%/5.3% of the study area is forest, 57.4%/18.1% pasture, 9.1%/4.0% open-water, 0.3%/3.4% settlement, 8.2%/2.4% wetland, 4.2%/15.0% barren land and 13.1%/51.9% farmland (Table 1). In this study, pre-development land use is the land use condition before 1979 when over 70% of the land use was forest/grass cover.

Scenario of land use conditions

In China, significant hydrological development started in 1979. This also marked the start of intensive land use as farmers resumed full responsibility for their allotted portions of farmlands (Yang & Tian 2009). Thus in determining the impact of the land use on groundwater recharge and discharge, the pre- and post-development land use conditions were first simulated. The land use of 1930 represented the pre-development condition while that of 2010 the post-development condition. As change in land use over a short period is generally insignificant (Herold *et al.* 2006), the land use conditions of 1930 and 2010 were considered to

Table 1 | A detailed list of the 1930 pre-development and 2010 post-development land use conditions in the Western Jilin study area

| Land use class | | 1930 | | 2010 | |
|--------------------|-------------|--|--------|--|--------|
| | | Area (10 ⁹ m ²) | % | Area (10 ⁹ m ²) | % |
| Dense forest | Forest | 3.55 | 7.57 | 2.46 | 5.25 |
| Spine forest | | | | | |
| Sparse forest | | | | | |
| Other forest types | | | | | |
| High grass | Pasture | 26.91 | 57.39 | 8.50 | 18.13 |
| Medium grass | | | | | |
| Low grass | | | | | |
| River | Open-water | 4.28 | 9.13 | 1.87 | 3.99 |
| Lake | | | | | |
| Reservoir/pond | | | | | |
| Urban settlement | Settlement | 0.16 | 0.34 | 1.59 | 3.39 |
| Rural settlement | | | | | |
| Other settlements | | | | | |
| Bottomland | Wetland | 3.86 | 8.23 | 1.10 | 2.35 |
| Marshland | | | | | |
| Sandlot | Barren-land | 1.98 | 4.22 | 7.03 | 14.99 |
| Saline land | | | | | |
| Bare-land | | | | | |
| Paddy field | Farmland | 6.15 | 13.12 | 24.34 | 51.91 |
| High dry-land | | | | | |
| Low dry-land | | | | | |
| Total | | 46.89 | 100.00 | 46.89 | 100.00 |

sufficiently represent the pre- (before 1979) and post- (after 1979) development land use conditions in the study area (Gao & Liu 2009).

Next, forest and grassland conditions were simulated as alternative land rehabilitation measures to enhance groundwater recharge/discharge and the preservation/sustainability of valuable/fragile wetlands/ecosystems in the study area. For the forestland and grassland conditions, all land surfaces under the post-development land use condition of 2010 with barren/degraded lands and surface slopes $\geq 10\%$ were respectively replaced with forest and grass. Forestlands and grasslands are among the most investigated forms of vegetation (Scanlon *et al.* 2006; Yang *et al.* 2009; Moiwo *et al.* 2012). In fact, in the study area, grassland was the dominant vegetation in the pre-development period (Himiyama 2001). The forest/grass rehabilitation analysis

was used to isolate the land use with suitable recharge and discharge conditions for the preservation and sustainability of fragile/valuable wetlands/ecosystems in the study area.

Calibration and validation

The model was calibrated using (1998–2007) groundwater level data (Batelaan *et al.* 2003) from 176 monitoring wells – see Figure 1 for the well locations. It was then validated using recharge and discharge values (Volker & Chris 2001; Gebert *et al.* 2011) from long-term (1972–1997) streamflow records in a gauge station downstream of the study area (Moiwo *et al.* 2010a). Figure 2 plots the calibration and validation results with good agreement in both cases. The coefficient of determination (R^2) for the calibration analysis was 0.92 with root mean square error (RMSE) of 2.87 m and

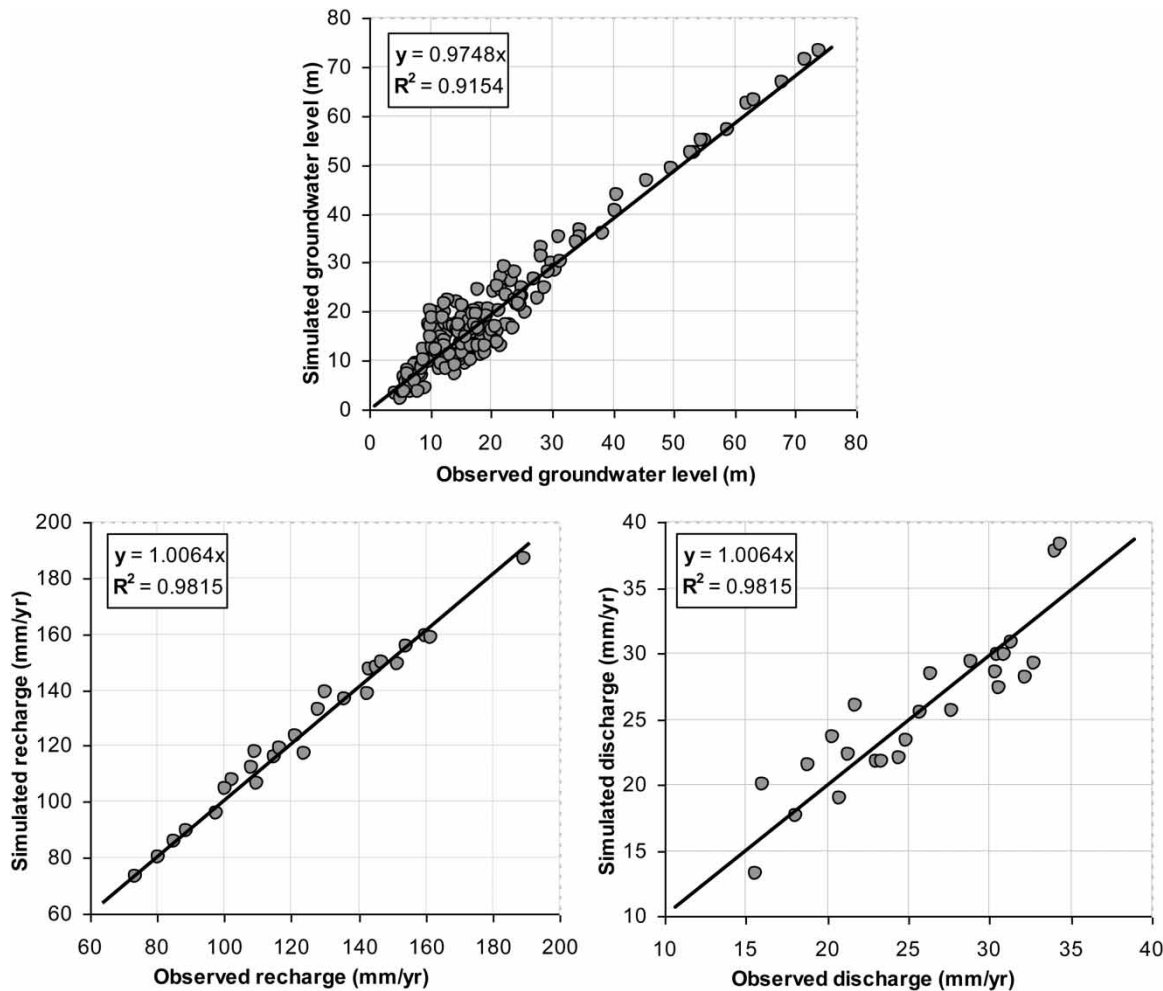


Figure 2 | Plots of the results of the model calibration analysis for groundwater level (top panel) and validation analysis for recharge (bottom left panel) and discharge (bottom right panel) in the Western Jilin study area.

mean absolute error (MAE) of 1.67 m. Then R^2 for the validation analysis was 0.98 for both recharge and discharge. The RMSE and MAE were 9.73 mm and 6.83 mm for recharge and 2.01 mm and 1.54 mm for discharge.

All the tests indicated strong agreement among the model-simulated and field-measured values with average error of <10%. Recharge in the study area was generally higher than discharge. It is important to note that rather than enhancing storage, the general storage depletion suggested that a significant fraction of the water regime was lost through ET (which included ET driven by irrigation from groundwater pumping). In fact, putting together the average discharge (24.21 mm/yr) and ET (478.67 mm/yr) resulted in a total discharge that was almost three times

the average annual recharge (115.05 mm/yr). This explained the steady depletion of water storage in the study area.

RESULTS AND DISCUSSION

Hydro-climatic characteristics

Analysis of the long-term (1953–2008) climatic data suggested that while the trends in temperature and open-water evaporation increased, that in precipitation decreased. Precipitation, temperature, and ET were also highest in the summer months of June through August. Peak agricultural activities (e.g., irrigation) were in summer, which also

influenced the dynamics of ET in the study area. The increasing trend in open-water evaporation could be due to the rising temperatures as a result of climate change (Lee *et al.* 2008; Moiwo *et al.* 2010b). Like land use change, climate change could suppress precipitation (Junkermann *et al.* 2009). The increase in open-water evaporation and decrease in precipitation generally cause water storage loss. This condition could have negative implications not only for groundwater recharge/discharge, but also for fragile/valuable wetlands/ecosystems in the study area.

Groundwater recharge

Groundwater recharge in the study area under the land use conditions of 1930 and 2010 are plotted along with those of the forestland and grassland conditions in Figure 3. The WetSpss-simulated recharge increased from open-water to farmland surfaces and was generally higher under the land use condition of 1930 than of 2010. Recharge was substantially higher for marshland and grassland surfaces under the 1930 than the 2010 land use condition. However, the reverse was the case for farmland surfaces. In terms of area, these were the land use types which shrank the most since 1930 due to land development in the study area.

Farmland surfaces not only increased, but were also heavily irrigated in the study area. Scanlon *et al.* (2006) noted similar trends in a global synthesis of groundwater recharge in arid/semiarid regions. For the average precipitation of 458.20 mm/yr, recharge under the land use conditions of 1930 and 2010 was 125.59 mm/yr and 104.12 mm/yr, respectively. It was 114.63 mm/yr and 119.98 mm/yr, respectively, for forestland and grassland conditions (Figure 3, bottom panel).

As the land use shifted from the 1930 condition to that of 2010, recharge in general dropped by 17.09% or 21.46 mm/yr. However, the shift from the land use condition of 2010 to forestland and grassland conditions increased recharge respectively by 6.25% (6.51 mm/yr) and 15.22% (15.85 mm/yr). The increased recharge conditions could increase groundwater storage and subsequent discharge to wetlands in the study area. Recharge was better under the land use condition of 1930 than under grassland condition, which was in turn better than that under the other land use conditions in the region.

Under the land use condition of 1930, recharge was 27.41% of the average annual precipitation. It was 22.72%, 25.02%, and 26.18%, respectively, under the 2010 forestland and grassland conditions. This further suggested that

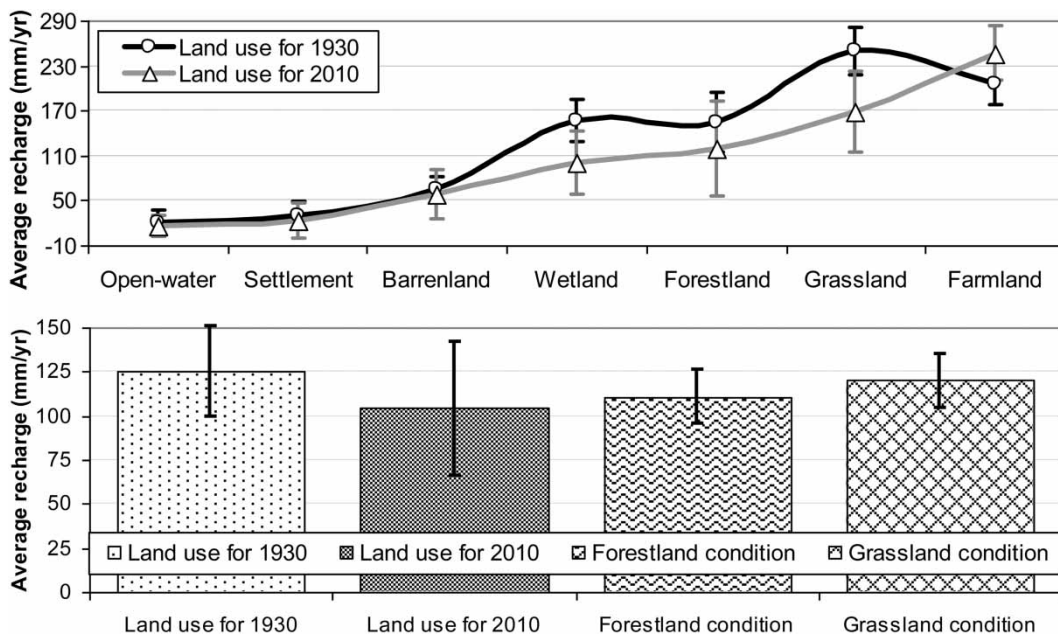


Figure 3 | Model-simulated recharge for the land use conditions of 1930 and 2010 (top panel) along with average recharge for the simulated four land use conditions (bottom panel) in the Western Jilin study area. Error bars denote \pm standard deviation.

rehabilitation of barren/bare-lands and land surfaces with $\geq 10\%$ surface slope with grass vegetation better enhanced hydrological conditions in the study area. Because grass is a shallow-rooted plant, it uses less groundwater than forest (deep-rooted plant), which factor in turn limits ET loss in arid/semiarid regions (Hornbeck *et al.* 1993).

In temperate zones, it has been almost consistently noted that deforestation increases base-flow (Hornbeck *et al.* 1993). An assessment of the impact of reforestation on watershed hydrology showed that 50% increase in forest area resulted in 12% decline in peak discharge (Bahremand *et al.* 2006). With deeper root penetration into groundwater systems, forests sustain high water loss through ET. Also high interception storage under forest condition limits recharge in the study area (Moiwo *et al.* 2010a). Under the land use condition of 2010, over 45% of the region is cultivated and irrigated. Irrigation triggers high ET in semiarid regions, resulting in storage depletion (Yasuda *et al.* 2013). Figure 3 (bottom plate) further shows better recharge under grassland than forestland conditions. This further showed the suitability of grassland over the 2010 and forestland use conditions in terms of the hydrology and hence the sustainability of valuable ecosystems in arid/semiarid regions. In fact, before intensive land development, grassland was the dominant natural vegetation ($>57\%$) in the study area (Himiyama 2001).

Groundwater discharge

The groundwater discharge under the land use conditions of 1930 and 2010 are plotted along with that for forestland and grassland conditions in Figure 4 (top panel). The simulated discharge was highest (29.39 mm/yr) for the land use condition of 1930, followed by grassland (26.28 mm/yr), forestland (21.82 mm/yr) and then 2010 (19.34 mm/yr) land use conditions. Discharge was mainly along drainage courses and in lowland areas like wetlands and marshlands. The shift from the land use condition of 1930 to that of 2010 resulted in annual discharge loss of 34.14% (10.03 mm/yr). However, the shift from the land use condition of 2010 to forestland and grassland conditions respectively increased discharge by 12.82% (2.48 mm/yr) and 35.85% (6.93 mm/yr).

Figure 4 (bottom panel) depicts the percent change in recharge and discharge with the shift from one land use to

the other in the study area. Both recharge and discharge dropped with the shift from the land use condition of 1930 to that of 2010, forestland and grassland. However, recharge and discharge increased with the shift from the land use condition of 2010 to forestland and grassland conditions. While the increase was higher with the shift from the 2010 land use to grassland than to forestland condition, the decrease was highest with the shift from the 1930 to the 2010 land use conditions. The plausible pathway of recharge loss under the land use condition of 2010 was irrigation-driven ET. Also, forest plant roots penetrate deep into the groundwater systems beneath the land surface, triggering high storage loss via ET under forestland condition. However, the short-root nature of grass limited water loss to ET, favoring groundwater storage under grassland condition. The higher storage under grassland condition was conducive for the preservation and sustainability of groundwater-dependent ecosystems, wetlands and biodiversity in the study area.

The results suggested that compared with the land use of 2010 and forestland, grassland presented more favorable recharge and discharge conditions in the semiarid region. In fact, grass is the dominant natural form of vegetation in arid/semiarid regions (Himiyama 2001; Li *et al.* 2008). However, significantly large portions of grasslands in arid/semiarid regions have been converted into other forms of land use, such as farmland (Yu *et al.* 2006; Junkermann *et al.* 2009; Yasuda *et al.* 2013). Thus, the rehabilitation of sloppy and barren/bare-land surfaces with grass vegetation not only enhances the hydrology, but also the sustainability and preservation of valuable/fragile ecosystems, wetlands and biodiversity of arid/semiarid regions. Details of several different vegetation-based rehabilitation strategies for arid/semiarid regions are discussed by Gao & Liu (2009).

Fragile/valuable ecosystems

An ecosystem, as the smallest unit of the biosphere with characteristics to sustain life, is fragile when it loses the ability to resile due to changes in undesirable ways. In other words, the degree of disturbance (external or internal) in excess of the level of tolerance of an ecosystem makes it fragile. For instance, a rainforest becomes fragile when the concurrence of drought and wildfire reduces it to a sparse and low-diversity bush. Also the endangerment of a

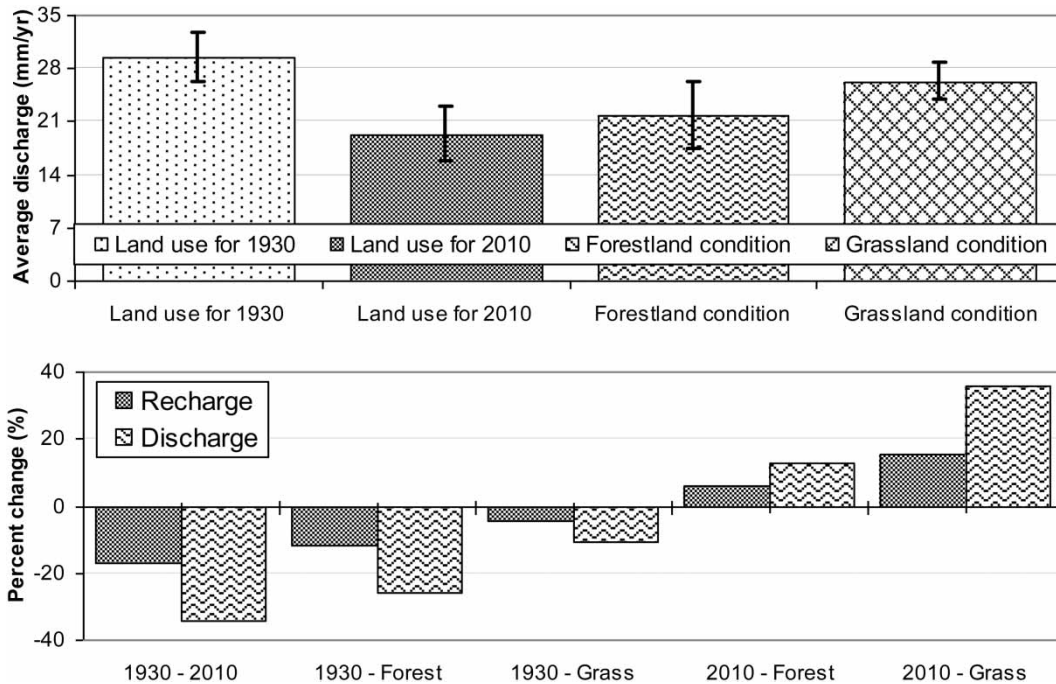


Figure 4 | Model-simulated average discharge for the four simulated land use conditions (top panel) along with percent changes in recharge and discharge due to the shift from one land use condition to another (bottom panel) in the Western Jilin study area. Error bars denote \pm standard deviation.

well-functioning ecosystem by one-in-hundred floods, droughts, or bushfires makes it fragile. An ecosystem is valuable when it is biologically diverse, when it provides wildlife corridors/linkages, recreations and economic benefits and when it supports live-learning/serves legacies for future generations. This implies that ecosystems are inherently fragile, which recognition is critical for the understanding, management, and preservation of earth ecosystems.

Fragility and resilience are the basis for ecological biodiversity because the removal or addition of species could significantly change ecological equilibrium. Industrialization, modernization, and high-quality life drives could induce disturbances that substantially change the balance of natural ecosystems. Man is now the greatest geomorphic agent of change in earth surface systems. Human attributes like population growth, industrialization, urbanization, resource exploitation, and large-scale agriculture have considerably endangered valuable ecological biodiversity in unprecedented ways. Inland/coastal wetlands, freshwater/marine estuaries, reefs, montane landscapes, rainforests, and other forms of ecosystem have all become vulnerable to human activity. Fragile ecosystems usually support

valuable living histories and habitats for at-risk biodiversity. Thus by promoting sustainable land use decisions, this study would enhance the preservation of rare, fragile, and valuable ecosystems.

CONCLUSIONS

This study analyzed the effects of land use on the hydrological processes of groundwater recharge and discharge. The study determined the land use with suitable conditions for the preservation and sustainability of fragile/valuable ecosystems in arid/semiarid regions. For the analysis, an integrated recharge–discharge model driven by WetSpa, MODFLOW, and a Drain Package in GIS environment was used. Western Jilin, a typical semiarid area in northeast China with vast expanses of wetlands and biodiversity, was used as proxy for arid/semiarid hydrology and ecology. In the study, four land use conditions were analyzed – land use condition of 1930 (pre-development condition), that of 2010 (post-development condition) and forestland and grassland conditions (rehabilitation conditions). For the

grassland and forestland rehabilitation conditions, barren/bare-lands and land surfaces with $\geq 10\%$ surface slope in the study area were respectively re-vegetated with high-grass and woodforest. Results of the model calibration and validation analysis were in good agreement with field-measured values, with an average error of $< 10\%$.

The results suggested that grassland condition was more suitable for groundwater recharge and discharge in semiarid wetland ecosystems. High recharge and discharge conditions favored the preservation and sustainability of groundwater-dependent ecosystems and various biodiversity in the area. Because the roots of forest plants penetrate deep into groundwater systems and sustain high water loss through ET, forests were depletive of water resources in the semiarid region. This implied that forest condition was not conducive for the preservation and sustainability of the hydrology and ecology of arid/semiarid regions. The post-development land use condition of 2010 was also not suitable for the hydrology and ecology of the study area. Although recharge and discharge conditions were best under the land use of 1930, reverting to this pre-development land use condition could not be feasible due to modern land use demands and arrangements.

The shift from the pre-development land use condition of 1930 to the post-development land use condition of 2010 respectively resulted in annual recharge and discharge loss of $1.01 \times 10^9 \text{ m}^3$ and $4.70 \times 10^8 \text{ m}^3$ in the $4.69 \times 10^{10} \text{ m}^2$ study area. Also, the shift from the land use condition of 1930 to the forestland and grassland conditions resulted in annual recharge/discharge loss of $7.01 \times 10^8 \text{ m}^3/3.54 \times 10^8 \text{ m}^3$ and $2.63 \times 10^8 \text{ m}^3/1.45 \times 10^8 \text{ m}^3$, respectively. However, the shift from the land use condition of 2010 to the forestland/grassland conditions respectively increased annual recharge by $3.05 \times 10^8 \text{ m}^3/7.43 \times 10^8 \text{ m}^3$ and discharge by $1.16 \times 10^8 \text{ m}^3/3.25 \times 10^8 \text{ m}^3$. Barren/bare-lands (which constituted some 15% of the study area in 2010) are degraded lands due to unsustainable land use practices. Barren/bare-land and land surfaces with $\geq 10\%$ slope together accounted for some 16% ($750 \times 10^8 \text{ m}^2$) of the study area in 2010. This suggested that re-vegetation of only 16% of the study area with grass increased recharge by 15.85 mm/yr ($7.43 \times 10^8 \text{ m}^3$) and discharge by 6.93 mm/yr ($3.25 \times 10^8 \text{ m}^3$). This was efficient in terms of hydrological and ecological sustainability of the study area.

The results suggested that grassland vegetation was sustainable in terms of the preservation and sustainability of arid/semiarid regions with fragile/valuable wetlands and ecosystems. As only barren/bare-lands and land surfaces with $\geq 10\%$ slope were targeted, the re-vegetation strategy could little affect food production/security in the study area. Maintaining grassland condition in otherwise abandoned land surfaces could be broadly acceptable by farmers, decision-makers, and other stakeholders given the perceived hydrological and ecological benefits. The proposed rehabilitation strategy is also easily transferable to other arid/semiarid regions where fragile/valuable ecosystems and biodiversity are endangered by unreasonable land use conditions.

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