

# Impact of Land-use Patterns on Distributed Groundwater Recharge and Discharge

## — A Case Study of Western Jilin, China

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**Abstract:** The impact of land-use on distributed groundwater recharge and discharge in the western Jilin (WJ) was analyzed in this study. WJ is a transitional, semi-arid zone with a fragile, hydrological closed ecosystem in the Songhua River Basin (SRB). The research tool includes a seamlessly linked MODFLOW, WetSpa, the Seepage packages, and ArcGIS. The model calibration showed good agreement between simulated water table elevation and measured water table depths, while predicted groundwater discharge zones showed strong correlations with field occurrences of drainage systems and wetlands. Simulated averages for distributed recharge, water table elevation and groundwater drawdown were 377.42mm/yr, 194.43m, and 0.18m respectively. Forest vegetation showed the highest recharge, followed by agricultural farmlands, while open-water and other drainage systems constituted groundwater exit zones. When present land-use conditions were compared with the hypothetical natural pre-development scenario, an overall loss of groundwater recharge (24.09mm/yr) was observed, which for the project area is  $18.05 \times 10^8 \text{ m}^3$ . Groundwater abstraction seemed to be the cause of water table drawdown, especially in the immediate vicinities of the supply wells. An important issue of the findings was the ability of the hypothetical forest vegetation to protect, and hence sustain aquifer reserves and dependent ecosystems. The profound data capture capability of ArcGIS makes it particularly useful in spatio-temporal hydroecological modeling.

**Keywords:** land-use; ecosystem; groundwater; recharge; discharge; Western Jilin

### 1 Introduction

Studying the impact of land-use on groundwater is a key issue in setting up a sound land-use planning project. Many studies have shown that land-use planning is fundamental for the reliable protection of ecologically valuable wetlands. Thus special attention should be given to the effect of land-use on the hydrologic cycle and the protection of groundwater systems, especially recharge and discharge (Boeye and Verheyen, 1992; Bernáldez et al., 1993; Pucci and Pope, 1995; Batelaan et al., 2003). It has been estimated that global land-use impact on the hydrologic cycle surpasses that of recent climate change (Vorosmarty et al., 2004). Thus the impacts of land-use on the atmospheric components of the hydrologic cycle (regional and global) are increasingly being recognized, though those on the subsurface components of the hydrologic cycle, particularly groundwater recharge are not equally known.

Many recharge studies have been conducted in natural ecosystems (Cook et al., 1989; Phillips, 1994; Tyler et al., 1996; Izbicki, 2002), however, replacing natural ecosystems with agricultural farmlands alters almost every groundwater recharge parameter, including climate, soil,

and vegetation. For instance, large-scale irrigation leads to increased evapotranspiration that may alter regional climate through precipitation recycling (Moore and Rojstaczer, 2002; Adegoke et al., 2003). Surface water irrigation increases the amount of water applied to the geologic system, generally enhancing recharge (Roark and Healy, 1998; McMahon et al., 2003). Tillage affects recharge by changing soil structure (Leduc et al., 2001).

In the western Jilin Province (WJ), remarkable changes in land-use have taken place since the 1930s as a result of agricultural expansion (Himiyama et al., 1995). As linkages between vegetation and hydrology are the central foci of the emerging field of ecohydrology (Rodríguez-Iturbe, 2000; Newman et al., 2003), such linkages are often time complex due to the spatial and temporal nature of hydro-geologic materials and thus require combined methodologies including groundwater modeling, vegetation mapping, GIS and remote sensing; as demonstrated in the works of Batelaan et al. (Batelaan and De, 1998; 2001; Batelaan et al., 1996; 1998; 2003). The objective of this study is to investigate the impact of land-use on distributed groundwater recharge and discharge, with reference to WJ ecosystem. In particular the extent and magnitude of the groundwater

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recharge, water table dropdown and the identification of probable discharge zones are investigated in the study. Such results can be used in locating ecosystems most sensitive to land-use change and protecting such ecosystems.

## 2 Study Area

The study area is located on the western tip of Jilin Province ( $43^{\circ}59' - 46^{\circ}18' \text{ N}$ ,  $121^{\circ}38' - 126^{\circ}12' \text{ E}$ ), in the Songnen Plain with an area of  $46,897 \text{ km}^2$ . It includes two prefecture-level cities—Baicheng and Songyuan. Baicheng City has jurisdiction over Taonan and Da'an cities, Tongyu and Zhenlai counties and Taobei District; and Songyuan over Fuyu and Qian Gorlos cities, Qian'an and Changling counties and Ningjiang District. Annual temperature variations are distinct with winter and summer averages of  $-16^{\circ}\text{C}$  and  $23^{\circ}\text{C}$  respectively. There is a short frost period in the winter season. Recorded average annual precipitation ranges from 400 to 620 mm/yr and open-water evaporation is strong, especially in summer, averaging 1945 mm/yr with average wind velocities of 4 m/s. The study area has a population of  $4.73 \times 10^6$ , accounting for 17% of the provincial total. There also exist plenty of resources and excellent road network including railways (Fig. 1).

WJ is topographically high in the east, south and west, but low in the central and north zones, forming a bowl-shaped hydrologic basin. It is 130–550 m above sea level (a.s.l.) with an average slope of 0.12%. There is a topographic and corresponding groundwater divide on the southern border at an elevation of about 200 m a.s.l. Geologically, the Songnen Plain has well developed Mesozoic formations and the late Tectonic movements of the Cenozoic era prolonged into the Mesozoic eon. Thus the geomorphology of the modern Songnen Plain mimics the geologic profile of the Cenozoic epoch.

Vegetation, especially phreatic plants, is vital in the delineation of recharge and discharge areas (Batelaan et al., 2003). Grassland vegetation is widespread in the basin, 70% of which is cultivated. In the western hillock and plateau regions, sand dunes with low organic matter are dominant land features. A simplified land-use analysis in the study area shows that 5.63% is forest, 18.12% pasture, 4.83% open-water, 3.39% residential/settlement, 22.43% barren-land and 45.60% arable land, mostly under paddy rice cultivation.

## 3 Material and Methods

Due to extensive data requirement in environmental research and complex interactions of geo-ecological proc-

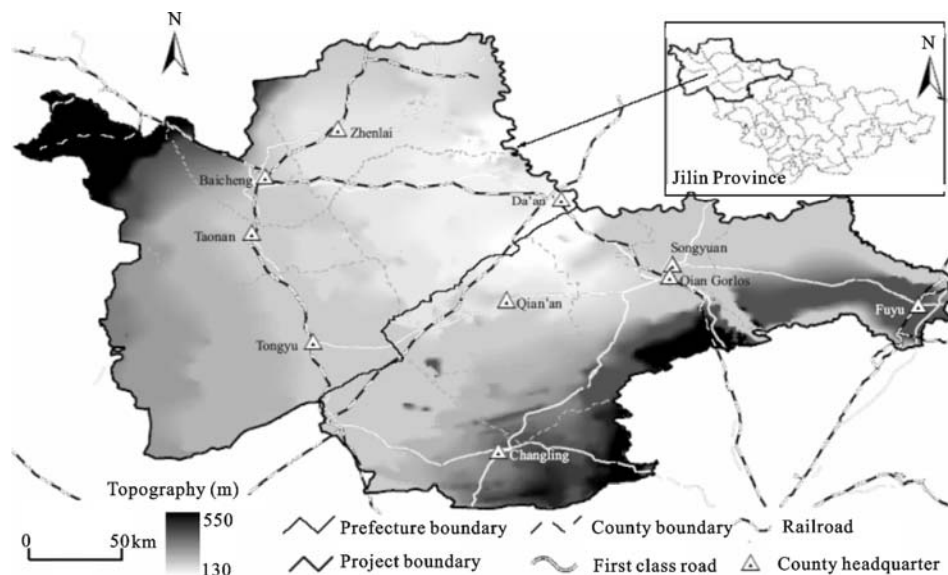


Fig. 1 Map of the study area

esses like land-use, soil type, slope, temperature, precipitation, wind, and topography coupled with spatio-temporal variations in distributed recharge and discharge, Batelaan and De Smedt (2001) developed the "WetSpa" model. It is a physically based model in which the long-term averages of spatially distributed water balance components of the vegetated soil, bare soil, open-water and impervious parts of a raster cell are calculated.

### 3.1 Theory and conceptual model

The purpose of conceptual models is to describe the nature and scope of data and determine the suitability of mathematical models. An integrated MODFLOW, SEEPAGE and WETSPASS with ArcGIS was used in the study, which is well documented in various literatures including Vandewiele et al. (1991), Wang et al. (1997) and De Smedt et al. (2000). The conceptual model was converted into a suitable mesh of grids in ArcMap (Fels and Matson,

1996). The WetSpass model has been fully integrated with ArcView (Batelaan et al., 1996) and Arc/Info (Asefa et al., 1999) and loosely linked with MODFLOW. Output results are readily imported back into GIS ArcView for visualization.

The MODFLOW groundwater flow equation (Harbaugh, 2005) can be vividly described in a three dimensional, constant density state as follows:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \quad (1)$$

where  $t$  is time [T];  $h$  is potentiometric head [L];  $W$  is source/sink [ $T^{-1}$ ] with  $W < 0$  for flow out of the system and  $W > 0$  for flow into the system;  $K$  is hydraulic conductivity [ $LT^{-1}$ ],  $xx$ ,  $yy$  and  $zz$  are hydraulic conductivities along the  $x$ ,  $y$  and  $z$  axis respectively;  $S_s$  specific yield for [ $L^3T^{-1}$ ]. The seepage package (Batelaan and De Smedt, 1998) that takes into account the short-falls in MODFLOW drain package (Harbaugh and McDonald, 1996) simulates groundwater discharge as:

$$\nabla(T\nabla h) + R - D \pm Q = 0 \quad (2)$$

where  $\nabla$  is the divergence or gradient operator [ $L^{-1}$ ];  $h$ , the groundwater head [L];  $T$ , the transmissivity [ $L^2T^{-1}$ ], which depends upon  $h$ ;  $R$ , the recharge [ $LT^{-1}$ ];  $D$ , the groundwater discharge [ $LT^{-1}$ ]; and  $Q$ , interactions with the underlying groundwater aquifers or effects of pumping wells [ $L^3T^{-1}L^{-2}$ ].

Then water balance for the vegetated soil, bare soil, open-water and impervious components of the model domain in the 'WetSpass package' (Batelaan and De Smedt, 2001) can be given as:

$$P = ET + S + R \quad (3)$$

where  $P$  is the average seasonal precipitation [ $LT^{-1}$ ];  $ET$  is the total evapotranspiration including interception [ $LT^{-1}$ ];  $S$  is the surface runoff [ $LT^{-1}$ ]; and  $R$  is the groundwater recharge [ $LT^{-1}$ ].

### 3.2 Boundary conditions

Alluvial aquifers in WJ are bounded at the top by water table, laterally by alluvial valley walls, and at the base by bedrocks. The boundaries therefore include rivers, potentiometric surfaces, pumping wells, and study area frontiers. The boundary types were simulated either as specified-head (Dirichlet boundary type), specified-flow (Neumann boundary type), head-dependent flow (Cauchy boundary type) boundary conditions, or a free-surface boundary (Franke et al., 1984).

### 3.3 Data sources

A numerical model of 357 columns and 257 rows with a resolution of  $1000m^2$  was built from the conceptual model. The PCG2 solver was used with a head and residual convergence criteria of 0.1 in a finite difference, steady-state simulation. Land-use and soil DTM from 2000 remotely sensed data were used. Also DEM of topography depicting slope and drainage was obtained from the Provincial Bureau of Lands and Water Resources. Data for water table depth, precipitation, air temperature and wind speed were 10-year averages (1995–2004). The water table data were collected from 171 monitoring wells while the meteorological data were from 10 meteorological stations in the project area. The point data were converted into point shape-files and the Kriging function in ArcMap (Fels and Matson, 1996) was used to build layers of raster grids for water table depth, temperature, precipitation and wind speed at a projected scale of 1:2,000,000.

## 4 Results and Analyses

### 4.1 Groundwater recharge

There are different modes of recharge in the project area including precipitation recharge, surface water (stream, lake, pond, etc.) and irrigation returns. Recharge is mainly from precipitation, thus the only one simulated for. The simulation result for recharge under the present land-use conditions is given in Fig. 2.

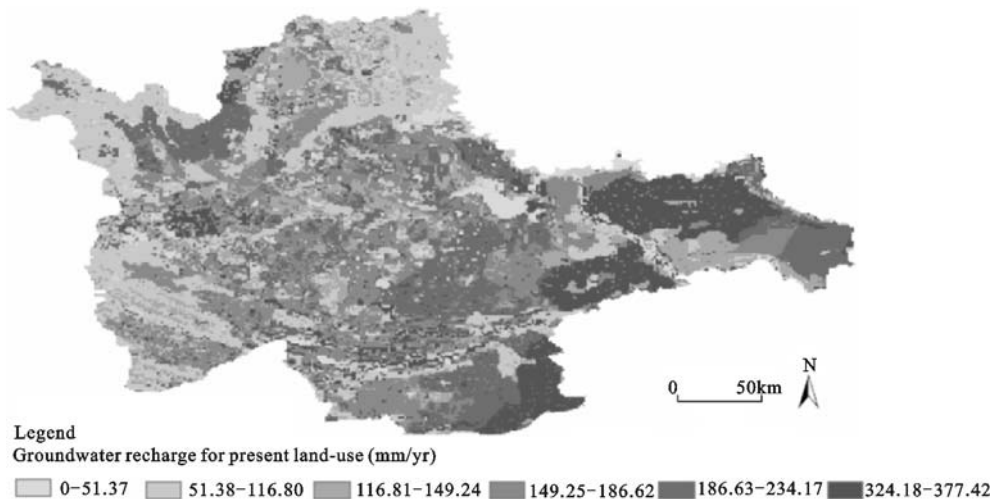


Fig. 2 Simulated groundwater recharge under present land-use management in study area

The simulation annual recharge varies from 0 to 377.42mm/yr, at an average of 159.79mm/yr and standard deviation of 63.44mm/yr, which is 37.36% of measured annual average precipitation. Low recharge was noted over open-water systems—rivers, lakes, reservoirs, or near-surface water table zones, including swamplands and floodplains or overflow lands. Low recharge in these groundwater exit zones can be explained in terms of high transpiration and/or evaporation. Recharge is low for settlement areas, especially the urban or near-urban settlements. It varies with the level of urbanization, that is, the more urbanized a settlement, the less recharge. The variation of groundwater recharge in the settlement zones is influenced by imperviousness from surface pavements and infrastructure. Recharge is highest under forest covers, a natural or near-natural landform. This emphasizes the importance of forest vegetation and/or the impact of human activities on groundwater recharge and dependent ecosystems in the study area.

In order to analyze the impact of the various land uses on the groundwater recharge, average recharge was determined for each land-use type and the result is given in Fig. 3. It is explicit from the curve in Fig. 3 that groundwater recharge very strongly depends upon land-use type. However, to determine the impact of the present land-use on the recharge system, the WetSpss model rerun was performed for a hypothetical natural forest land-use. Under this scenario, it was assumed that dense wood forest existed everywhere in the basin, except for the natural drainage systems—natural lakes, rivers and streams, but not man-made reservoirs. Under this condition, the predicted average groundwater recharge is 262.76mm/yr, or 61.43% of the total precipitation. This is 24.09% (which for the project area is  $1.805 \times 10^9 \text{ m}^3$ ) higher than the present conditions, an indication of strong land-use impact on the recharge system in the project basin due to human activities.

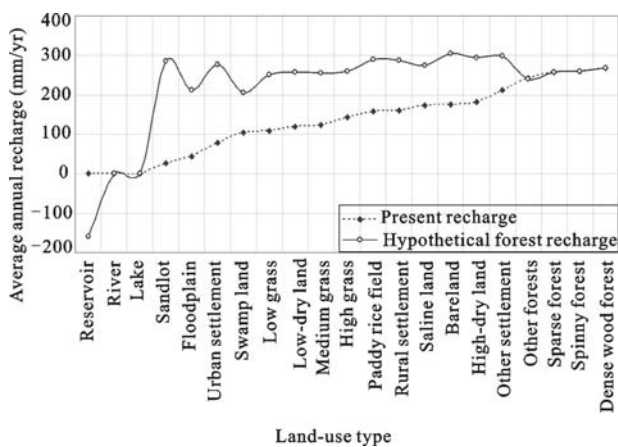


Fig. 3 WetSpss simulated annual groundwater recharge curves under the present and hypothetical forest condition

The impact of the present land-use on groundwater

recharge was determined by taking the difference between the hypothetical natural forest scenario and the present land-use management. Fig. 4 shows the average difference in recharge and standard deviations for present land-use types in the basin, classified from the low to the high. The calculated recharge difference ranges from -236.50 to 316.24mm/yr, with an average value of 102.94mm/yr; 64.42% of the present mean recharge, which far surpasses the present annual total groundwater withdrawal ( $1.228 \times 10^9 \text{ m}^3$ ) in the basin. Hence decline of recharge due to present land-use management has resulted in groundwater loss in aquifer reserves at magnitudes higher than the combined groundwater withdrawal for industrial, agricultural and domestic drinking waters. Small losses in recharge were seen for the forest vegetation; dense wood forest -0.04mm/yr, spinney forest -0.04mm/yr, sparse forest -0.06mm/yr, and other forests -0.07mm/yr in that order. The largest loss in recharge (-157.10mm/yr) occurred over the reservoir systems, which were treated as man-made, discharging water through strong evaporation. However, the established hypothetical natural forest form of land management reversed the strong evaporation phenomenon.

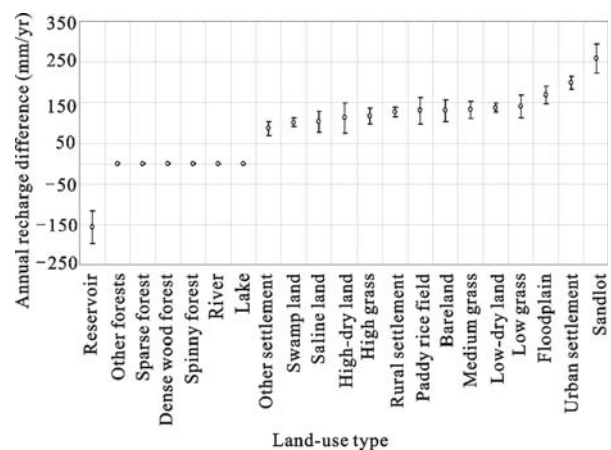


Fig. 4 Average recharge difference between the present and hypothetical forest conditions

#### 4.2 Groundwater table, discharge and drawdown

King (1899), as cited in Domenico and Schwartz (1993), observed that water table is a reduced replica of the topography, especially in humid regions. It is the saturated surface below which all soil/rock pores are completely filled with water. The simulated water table in Fig. 5 somewhat mimics the topography, conforming to the observations of King (1899). It differs from the topography in that the water table gradient is much gentle. Groundwater discharge was simulated with the integrated WetSpss-MODFLOW model for the present conditions. In this paper, discharge areas are defined as areas where groundwater recharge is zero or negative. Discharge occurs mainly along the drainage systems and wetland zones including streams, lakes, swamplands and floodplains/overflow lands (Fig. 5).

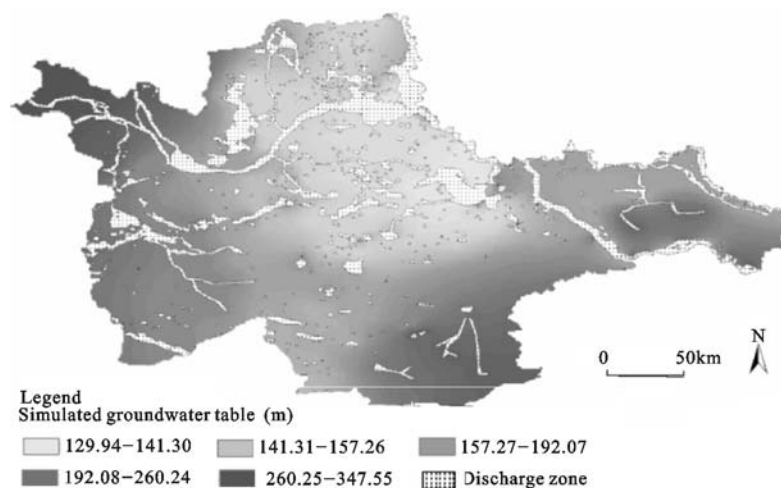


Fig. 5 Simulated water table and groundwater discharge zones in the study area

Water table for the present land-use management was determined in the first step. A rerun was carried out with all 171 pumping wells activated (extracting a total of  $1.228 \times 10^9 \text{ m}^3$ ), and the water table noted. In the third and final step, the two water tables for the pre- and post-pumping events were interpolated in ArcMap to obtain yearly water table drawdown. In Fig. 6, water table drop is highest ( $>2.98\text{m}$ ) in the immediate vicinities of the pumping/supply wells with more gentle drawdown cones in the upstream zones of the groundwater flow system. This shows that well recovery predominantly comes from the upstream areas of the groundwater flow system. The water table drawdown deepens with higher well density and the sphere of influence of the drawdown cones decreases with distance away from the wells. Decreasing water tables have various implications for dependent ecosystems, discussed in the next section of this paper.

The model was calibrated by means of a distributive curve of measured versus simulated groundwater heads in the study area. The curve showed a good agreement between the two heads with a correlation coefficient of the 'line of goodness of fit' of 0.89, root-mean-square error of 0.43, and an absolute mean error of 0.23. These figures reflect a high degree of accuracy of the study by the strong correlation between the simulated and measured groundwater heads.

## 5 Discussion

The study has shown some of effects of land-use through human activities on groundwater recharge. By analyzing the recharge difference between the present land-use and the hypothetical natural forest scenario, it has been shown that for the study area, groundwater recharge is very much dependent upon land-use types.

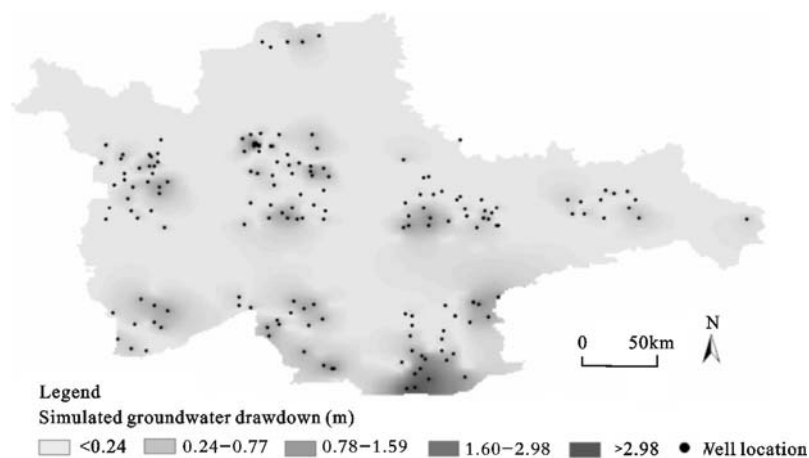


Fig. 6 Simulated groundwater drawdown from current withdrawal in the study area

Recharge generally decreases when vegetated forests deteriorate to be other landforms (bush, grassland or bare-land), either by human activity or natural phenomena such as desertification, forest fires. It was equally

noted that groundwater abstraction for agricultural, industrial or domestic uses was the principal cause of groundwater drawdown in the study area.

Analysis of the recharge difference in relation to the

present and hypothetical forest land-uses, summarized in Fig. 3 can be divided into Lost Recharge, Neutral Recharge and Gained Recharge. About 66.67% of all the land-use types gained recharge (85.97–258.53mm/yr), 9.52% showed no change in recharge (neutral), while another 23.81% lost recharge (–0.04 to –157.10mm/yr).

Agricultural lands, settlements and barren lands gained considerable amount of recharge in the hypothetical forest state. These land-uses have the largest impact on the recharge system in the study area.

Neutral recharge occurs mostly in the natural drainage belts, where the pre-development and the present situations are the same, thus no change in recharge is observed over these areas.

In the areas with lost recharge, minor recharge losses (–0.04 to –0.07mm/yr) are noted over some forms of the forest vegetation, probably from high evapotranspiration. The largest recharge loss is observed over the reservoir system. The reservoir systems were considered to be man-made and were therefore converted into forest under the hypothetical forest condition. This phenomenon changed the reservoir systems from the discharge state to recharge one. This probably is the driving force behind the high negative recharge, normally explained as evapotranspirative discharge.

The loss constitutes considerable loss for the groundwater systems, estimated at 24.09% ( $1.805 \times 10^9 \text{ m}^3$ ) of the present mean recharge. Because agriculture constitutes 43.54% of the land-use in the basin, direct link is thus obvious. This is developing water stress in the aquifer systems, a condition that is worsened by groundwater abstraction. This could be contributing factor for expanding desertification and the basin ecosystem degradation.

## 6 Conclusion

The impact of land-use on groundwater recharge was investigated for the project area of the western Jilin Province, where land-use is very much influenced by agriculture to the extent that desertification now poses significant threat to the fragile ecosystem. Importance in that respect was groundwater drawdown, since increasing drawdown influences the aquifer water reserve and its sustainable use.

The WetSpss-MODFLOW model was used to establish distributed recharge and discharge in the study area. The results were compared with a hypothetical natural forest scenario where the land was assumed to be under dense wood forest. The results showed substantial reduction in groundwater recharge especially over bareland and settlement land-use types. Mean groundwater recharge for the present conditions was 159.79mm/yr, accounting for 37.36% of annual average precipitation in the area, but the bare-land and settlement land-use types yielded much lower recharge rates, averaging 26.24mm/yr and 78.63mm/yr, respectively. Under hypothetical natural conditions, the model predicted an

average groundwater recharge of 262.76mm/yr, 61.43% of the total precipitation.

All bareland and settlement land-use types showed considerable losses in groundwater recharge, were 258.93mm/yr and 194.60mm/yr. For agricultural land-use, recharge trend was similar to those for bareland and settlement, but with less magnitude. Other land-uses as broad-leaf forest, wood forest, sparse forest, and other forms of forest yielded small losses in recharge, but their total effect was negligible as they are not abundant. For the natural drainage systems—lakes and rivers, there was no change in recharge. These areas were treated to be natural under both the present and hypothetical conditions and no variance was detected. For the reservoir systems, a large negative recharge was noted. This was because reservoirs were treated as man-made systems and therefore converted into forest in the hypothetical scenario.

Concentrated production wells were observed in most urban settlements with high groundwater abstractions and the MODFLOW simulation results showed large water table drawdown in those areas. The dropping water tables reduce groundwater discharge to wetlands, especially during base-flow periods, which may lead to (negative) chain-disorders and destroying the buffer capacities of dependent ecosystems.

In conclusion thus, all indicators showed that urbanization and agriculture are main causes of significant reduction in recharge in the study area.

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