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Impact of land use on distributed hydrological processes in the semi-arid wetland ecosystem of Western Jilin

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Abstract:

In especially arid/semi-arid regions, wetlands are steadily destroyed or converted into other forms of land use due mainly to population and socio-economic growth. The accurate estimation of catchment hydrological processes is therefore vital not only for sustainable land/water resources management in these regions, but also for the adequate preservation of wetland ecosystems. In this study, distributed recharge, runoff and evapotranspiration (ET) are simulated for the wetland-based ecosystem of Western Jilin using WetSpass (Water and Energy Transfer between Soil, Plants and the Atmosphere under quasi-Steady-State), extended with MODFLOW. Comparisons of hydrophysiographic conditions of 1930 and 2000 show good agreements between the model-simulated fluxes and long-term field-measurement data, all with R^2 above 0.8. About 21% of the wetlands have been converted into primarily farmlands. Water quality is also deteriorating due to land use change and accompanying increase in ET against decreasing recharge. While ET is highest for open water surfaces, it mostly originates from vegetated land surfaces. Recharge is not only highest, but also mainly originates from vegetated land surfaces. Similarly, runoff is highest and largely originates from bare land surfaces. Whereas ET is influenced mainly by land use, recharge and runoff are variously influenced by land use, soil type and topographic slope. Changes in the hydrophysiographic conditions pose a considerable threat to wetland ecosystems in the study area. As ET is the predominant mode of water loss, ET-limiting land/water resources management strategies are critical for environmental sustainability and for long-term restoration and conservation of the fragile wetland-based ecosystem.

KEY WORDS Western Jilin; land use; wetland ecosystem; evapotranspiration; groundwater recharge; surface runoff

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INTRODUCTION

There is steady depletion of water resources in especially arid/semi-arid regions due mainly to population growth and related expansions in farming activity. The area of land under arid/semi-arid conditions is also increasing as a result of population growth, intensive farming and adverse climatic conditions (Wheater and Al-weshah, 2002). Changes in land use due to deforestation, urbanization and reclamation of wetlands for farming variously impact catchment hydrology. The hydrological processes most affected by land use are evapotranspiration (ET), recharge and runoff (Batelaan *et al.*, 2003). These hydrological processes are critical for the sustainable development and preservation of (valuable) wetland ecosystems (Ming *et al.*, 2007).

Not much has remained of indigenous land cover across the globe (Dams *et al.*, 2008), yet hydrological impacts of land use on wetland ecosystems remain poorly understood (Batelaan *et al.*, 2003). Wetlands are ecological systems with dynamic and complex groundwater/surface water interactions beyond surface water boundaries of the wetlands (Ming *et al.*, 2007). Wetlands are important biodiversity and regulation systems of global carbon circulation through sequestration (Chen and Lu, 2003; Wang *et al.*, 2006). Despite their importance, however, wetlands are increasingly destroyed or converted into other forms of land use (Dams *et al.*, 2008).

Groundwater, an important source of water for especially groundwater-dependent wetland ecosystems, is scarce and unsustainable in arid/semi-arid regions (Moiwo *et al.*, 2009). With intensive groundwater exploitation (above replenishment rate) in these regions, groundwater-dependent wetland ecosystems have deteriorated or sometimes entirely disappeared (Pan *et al.*, 2003). Water resources development and management strategies should therefore focus on integrated land use practices that can support and preserve (valuable) wetlands.

One such strategy is connecting recharge and discharge areas via hydrological modelling (e.g. Batelaan *et al.*, 2003). Landscape physiographic features can also be used to delineate groundwater recharge and discharge areas (Batelaan *et al.*, 2000; Scanlon *et al.*, 2006). Vegetation mapping, hydrochemical analysis and groundwater modelling are other viable strategies for protecting ecologically valuable wetlands (Batelaan *et al.*, 2003;

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Batelaan and De Smedt, 2007). Geographic information system (GIS) and Remote Sensing (RS) technologies are suitable platforms for distributed ecological and hydrological modelling. WetSpass (Water and Energy Transfer between Soil, Plants and the Atmosphere under quasi-Steady-State) is a GIS/RS-based model that is integrated with MODFLOW (Asefa *et al*., 2000). WetSpass-MODFLOW integration allows detailed spatial analysis of catchment hydrological processes. In this study, the integrated WetSpass-MODFLOW model is used to simulate the impact of land use on the hydrology and wetlands of Western Jilin.

Western Jilin is the largest and one of the most important wetland ecosystems in Songhua River Basin (Pan *et al*., 2006). Land reclamation for farming poses a considerable threat to this valuable wetland-based ecosystem (Pan *et al*., 2003; Moiwo, 2006). This study therefore aims to explain the causes of wetland degradation in the region and the need for tangible and sustainable countermeasures. The findings of the study will contribute to relevant scientific literature for developing future land/water resources management strategies to preserve wetland ecosystems in the region and beyond.

MATERIALS AND METHOD

The study area

Western Jilin lies between 43°59′N–46°18′N and 121°38′E–126°12′E (Figure 1). It has a population of ≈4·73 million within an average area of 46 895 km^2 (Moiwo, 2006). In Western Jilin, springs are moderately dry, summers humid warm, autumns windy and winters clod dry, with over 150 days of frost (Pan *et al*., 2003). Precipitation is low and varies in space and time, with annual average precipitation of 350 mm in the west and 420 mm in the east. Average winter temperature is −16 °C while that of summer is 23 °C. Winds are generally moderate all the year round, averaging 3–6 m/s (Pan *et al*., 2003; Moiwo, 2006).

Surface elevation in the east, south and west of the study area is high, while the central floodplain and northwest regions are low (Figure 1). The average land surface elevation is 159 m, with an average slope of 0·43%. The main physiographic features of the study area are inland depressions, lakes, ponds, shoals, lowlands and wetlands. Natural land cover is predominantly steppe, flooded grassland, coniferous forest and meadow (Pan *et al*., 2006). Though surface waters are largely fresh (some brackish), salt concentrations are increasing; driven mainly by high ET and large-scale water diversion for agricultural, industrial and domestic use (Zhang *et al*., 2003).

About 26% of the soils are sandy-loam, 21% loam and 12% clay-loam, and the soil distribution generally corresponds with vegetation zones (Zhang *et al*., 2003). The main rivers of the surface drainage are the Nen, Songhua, Er'songhua, and the tributary rivers of Tao'er and Lalin (Figure 2). Flows in the rivers are dwindling due to surface water development.

Land use

Wetlands and meadows are the predominant natural land cover for 1930. Since then, there is extensive degradation of especially the fragile wetlands due mainly to over-exploitation of the land and water resources (Pan *et al*., 2003, 2006). In analysing the effect of land use on the hydrological processes and wetlands of the study area, land use data, lithological data and hydrogeological data are used. The land use and soil maps of the study area are obtained from China Natural Resources Database (CNRD; Li, 2002). Topographic maps of China (produced at a map scale of 1 : 100 000 by Japan before and during World War II) are used to reconstruct the land use map

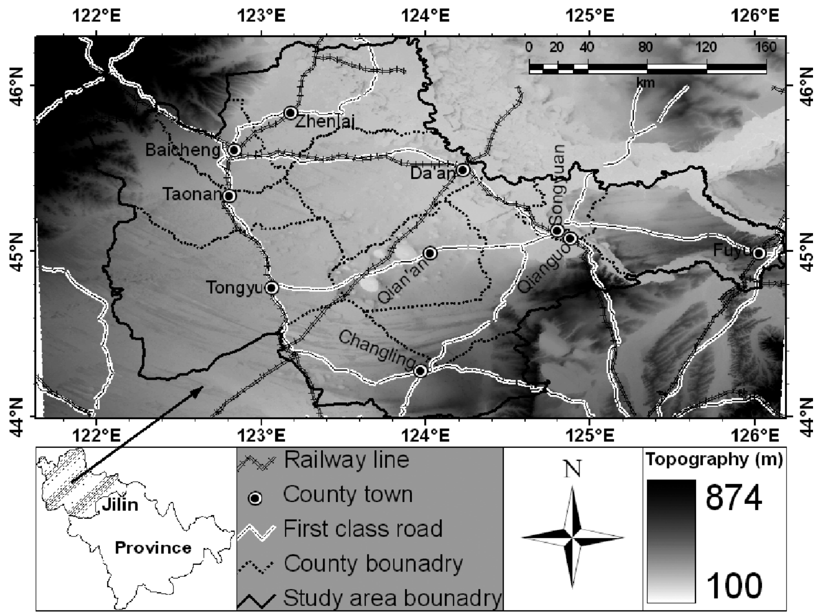

Figure 1. Location of Western Jilin study area showing administrative counties, main road network and ambient topography

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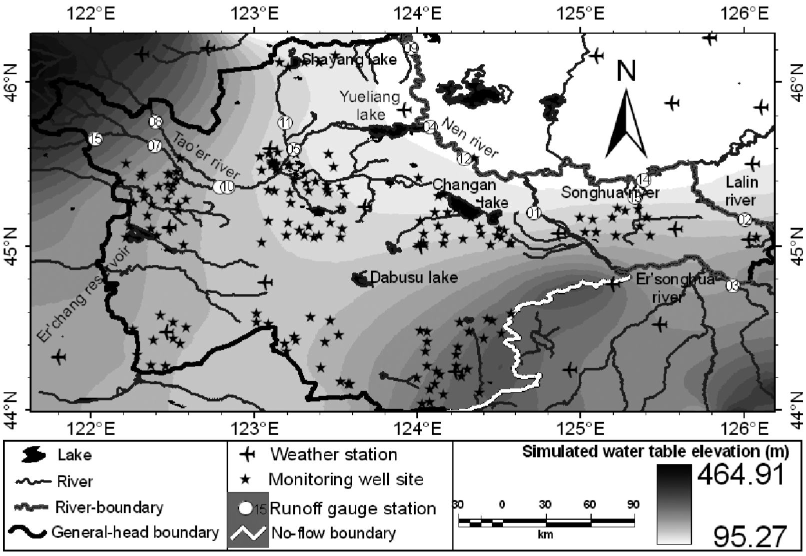

Figure 2. Main drainage system, groundwater monitoring wells, weather and runoff gauge stations, boundary conditions and simulated water table elevation for 2000

for 1930—see Himiyama (1998, 2001) for details on the data collection and processing. For the land use map of 2000, satellite images (Landsat TM), along with agricultural and other ground-truth data are used to construct the maps at a map scale of 1 : 100 000. Details on the data collection and processing are given by Wu and Guo (1994) and Liu *et al*., (2002).

Because the pixel size of the land use map for 1930 is 2×2 km (Himiyama, 1998) and that for 2000 is 30×30 m (Liu *et al*., 2002), the density of information in the maps are different. Hence, the land use for 1930 is readjusted for selected land use types including settlements and open water systems that are reasonably known to exist since the 1930s and not represented on the map (JPB/HPB-GM, 1985). Then the impact of land use on the hydrological processes of ET, recharge and runoff, the water quality and wetland ecosystems is quantified by comparing the hydrophysiographic conditions for 1930 (pre-development period) with those for 2000 (post-development period).

Hydrogeological setting

There are generally two aquifer systems in the study area—the shallow phreatic and deep confined aquifer systems. The phreatic aquifers consist of fluvo-alluvial deposits of the early Quaternary Baitushan and Tertiary Taikong origin (Zhang *et al*., 2003). The formations of the deep aquifer system predate the Quaternary epoch and consist of much coarser deposits of silt and sand. The riverine and lacustrine deposits in the floodplains are poorly drained and saline.

The gravelly deposits in the west, east and piedmont regions form the main groundwater recharge area (Pan *et al*., 2003). Groundwater flow is generally driven by topographic slope from the piedmont regions to the floodplains. Once in the floodplains, flow considerably weakens due to gentle slopes and loess-like fluvo-lacustrine deposits (Moiwo, 2006).

The hydrogeological boundaries of the study area are defined based on piezometric data and natural physiographic features like rivers and groundwater-divide obtained from Jilin Province Geometeorological Bureau (JPB/HPB-GM, 1985). No-flow boundary conditions are defined along the groundwater-divide on the southeast border of the study area. Cross-formational flows from the mountain regions in the south, southwest, north and east are assigned general-head boundary (GHB) conditions. River-boundary conditions are defined along the Nen, Songhua, Er'songhua and Lalin Rivers to represent surface water/aquifer interaction on the east and southeast borders of the study area (Figure 2). While the land surface elevation forms the model upper limit, it is limited at the bottom by sheets of clay deposit.

Since significant groundwater use only started after 1956 (also the time when hydrogeologic data logging started in the region), the hydrologic conditions of 1956 are defined in place of that of 1930. Then areal recharge is simulated by WetSpass using the land use maps of 1930 and 2000, and the respective water table positions interactively updated by MODFLOW. WetSpass-MODFLOW interaction enhances estimation of ET from an updated water table position. Since considerable interaction exists between the phreatic and deep aquifer systems (Moiwo, 2006), a single-layered finite-difference model with a grid size of 500 m $\times$ 500 m in 518 rows and 702 columns (i.e. a total of 363 636 grid-cells, of which 187 579 are active) was constructed. One additional reason for setting up a single-layer model is that wetlands and surface water systems are predominantly influenced by water table levels in phreatic aquifers (Batelaan *et al*., 2003).

WetSpass-MODFLOW model

WetSpass is loosely integrated with GIS (Asefa *et. al*., 2000), and is widely used in the simulation of distributed hydrological processes (Batelaan and De Smedt, 2007;

Dams *et al*., 2008). WetSpass takes advantage of multi-resolution RS classification to sub-divide each grid-cell into vegetated, bare soil, open water and impervious surface fractions where independent water balances are maintained. Water balance for the various fractions of the raster grid-cell is seasonally defined as follows:

$$P = ET_{\mathrm{vboi}} + S_{\mathrm{vboi}} + R_{\mathrm{vboi}} \tag{1}$$

where P is precipitation (l); ET is evapotranspiration (l); S is surface runoff (l); R is groundwater recharge (l); and the subscripts v, b, o and i respectively represent vegetated, bare land, open water and impervious fractions of the raster grid-cell. For a given season, the different components of the water balance are aggregated for the various fractions of the raster grid-cell as follows:

$$nET = n_{\mathrm{v}}ET_{\mathrm{v}} + n_{\mathrm{b}}E_{\mathrm{b}} + n_{\mathrm{o}}E_{\mathrm{o}} + n_{\mathrm{i}}E_{\mathrm{i}} \tag{2}$$

$$nS = n_{\mathrm{v}}S_{\mathrm{v}} + n_{\mathrm{b}}S_{\mathrm{b}} + n_{\mathrm{o}}S_{\mathrm{o}} + n_{\mathrm{i}}S_{\mathrm{i}} \tag{3}$$

$$nR = n_{\mathrm{v}}R_{\mathrm{v}} + n_{\mathrm{b}}R_{\mathrm{b}} + n_{\mathrm{o}}R_{\mathrm{o}} + n_{\mathrm{i}}R_{\mathrm{i}} \tag{4}$$

where n is the nth raster cell and the subscripts are as defined in equation (1). WetSpass uses USDA (1951) soil classification system in which soil clay and sand fractions are used to classify the soil into 12 textures.

Where as WetSpass simulates recharge, MODFLOW uses WetSpass-generated recharge to simulate the sub-surface hydrogeological processes as follows (Harbaugh, 2005):

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right) + W = Ss\frac{\partial h}{\partial t} \tag{5}$$

where *Kxx, Kyy* and *Kzz* are values of hydraulic conductivity along the x, y and z coordinate axes (l t^{-1}); h is potentiometric head (l); W is volumetric flux (source/sink) per unit volume (t^{-1}); Ss is specific storage of the porous material (l^{-1}); and t is time (t). In this study, WetSpass and MODFLOW-2005v1.5 are used to simulate distributed hydrological processes of ET, recharge and runoff.

WetSpass database

An important feature of WetSpass is its ability to link each grid-cell feature with adaptable land use, soil type and runoff database. A successful application of WetSpass is therefore contingent on the degree of representation of field conditions in the database table (Table I). The database is defined based on published and field-measured data on land use (Wang *et al*., 2007), soil type (JPB/HPB-GM, 1985; Wang *et al*., 2006) and runoff (USDA-NRCS, 1972; Ren *et al*., 2002). The WetSpass-MODFLOW model is validated with field-measured data (1956 and 2000) from 15 hydrological, 19 meteorological and 71 groundwater monitoring stations (Figure 2). Hydrographs of the validation analysis are presented in Figure 3.

RESULTS AND DISCUSSION

Calibration analysis and limitation

Several methods exist for calibrating catchment water balance components. While isotopes and geochemical tracers are used to verify runoff, baseflows are determined from low flow discharges. Following Volker and Chris (2001), the lowest monthly discharge for 1956 and 2000 are used to isolate baseflow (which is representative of long-term mean recharge in the study area).

ET is calibrated using literature values (Moiwo, 2006; Shi *et al*., 2008) and estimates from the FAO56-Penman-Monteith equation (Allen *et al*., 1998). The MODFLOW model is calibrated using water table data from 71 monitoring wells. The goodness of fit of the calibration analysis (Figure 3) is measured by both R^2 (>0·8) and RMSE—which is 2·07 m^3 (10%) of average recharge, 5·42 m^3 (9%) of average discharge, 28·72 mm (6%) of average ET and 5·66 m (4%) of average water table elevation. Despite the good agreements, some discrepancies exist in the calibration analysis. These are attributed to instrument/measurement errors, disturbances from artificial water transfer and exploitation, and differences in the nature of the field data (point-based) and model outputs (spatially continuous).

Land use/land cover pattern (1930 and 2000)

The land use maps for 1930 and 2000 are shown in Figure 4 while a detail breakup of the land use types is listed in Table II. Whereas much of the study area is under grassland and wetland for 1930, about 44% of the region is under agricultural land use, with bottomland, marshland and grassland accounting for only 1, 7 and 18% respectively for 2000. High land demand due to rapid population and socio-economic growth is the main drive for wetland reclamation and destruction in the study area.

Table I. Average range of selected parameters defined in WetSpass database table for Western Jilin study area

Land use	Soil type	Runoff
Land use type (21)	Soil type (12)	Percent slope (0–13%)
Root depth (0·3–3·6 m)	Field capacity (0·19–0·47)	Runoff coefficient (0·09–1)
Leaf area index (0·2–10·8)	Wilting point (0·03–0·21)	Vegetation type (default)
Vegetation height (0·04–23 m)	Plant available water (0·16–0·26)	Soil type (default)
Interception percentage (12–42%)	Evapotranspiration depth (0·34–0·62 m)	Slope type (default)

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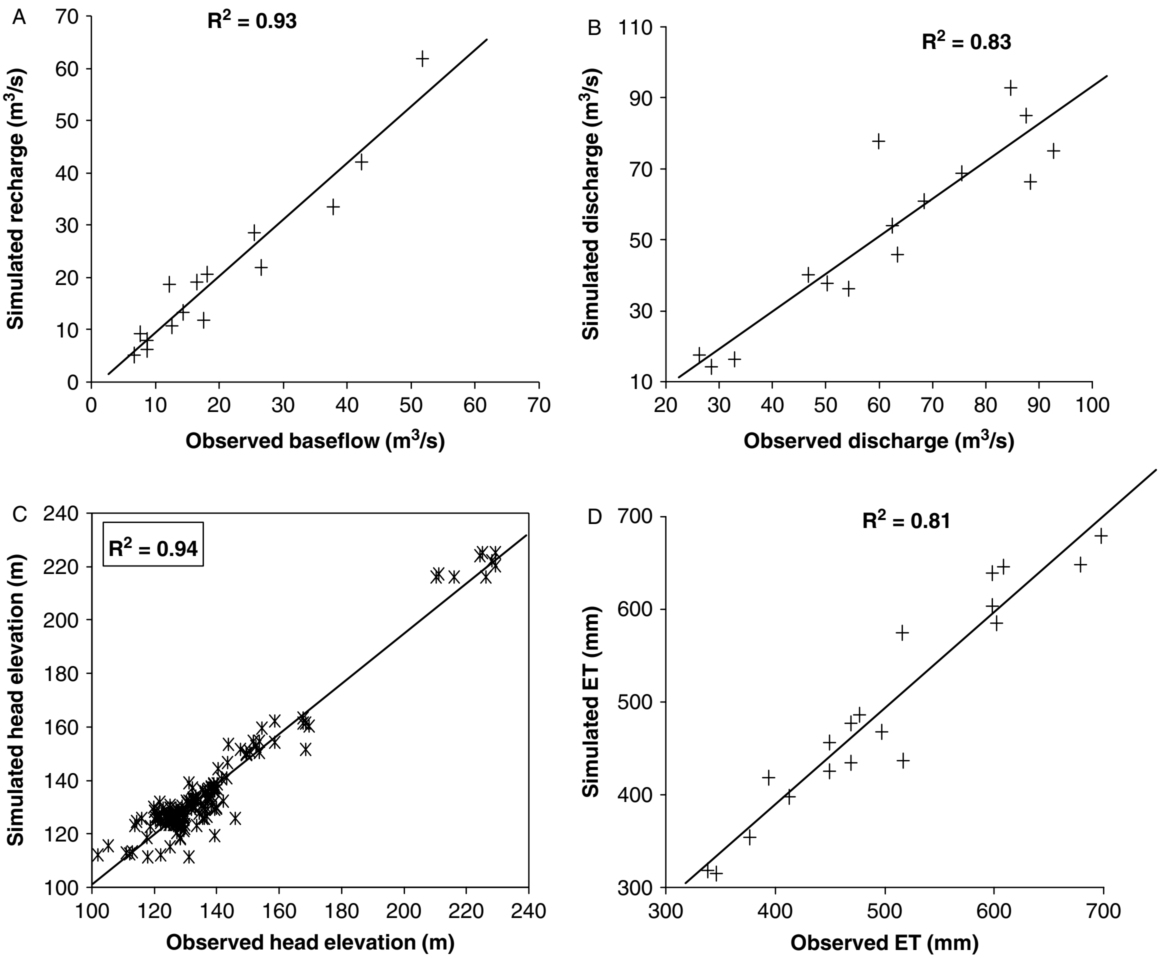

Figure 3. Hydrographs of calibration analysis of WetSpass-MODFLOW model for Western Jilin study area

Hydrological effect of land use change

Differences in the hydrological processes of ET, recharge and runoff for the land use conditions of 1930 and 2000 are plotted in Figure 5. The negative values in the figure denote decreasing trends in the hydrological processes and vice versa. As noted, the error bars (which represent the minima and maxima of the hydrological processes), are much more pronounced. Nearly all the ET minima are negative, indicating lower ET in 2000. This could be due to the disproportional fraction of farmlands that are largely barren in winter. Low temperatures (below −23 °C) and high humidity (above 80%) also limit water loss to the atmosphere in winter. The high ET for open water and saline land surfaces could be due to high land exposure via farming. In the study area, most of the saline lands are in the floodplains, which like open water surfaces sustain high ET when exposed. On the average, however, ET has increased in the 70-year period from 1930 to 2000 (Figure 6). While the overall increase in ET could be attributed to such factors as warming temperature, intensive irrigation increases soil moisture thereby increasing potential water loss via ET (see Pan *et al*., 2003; Moiwo, 2006).

Unlike wood lands, shrubs and saline lands, there is low recharge for sandlots and bottomlands (Figure 5). Most of the sandlots and indeed bottomlands have evolved from marshlands—an important source of groundwater replenishment (Chen and Lu, 2003). Hence the conversion of this land use type into other forms of land use limits groundwater recharge. Similarly, most of the shrubs have evolved from forest lands. Forest trees penetrate deep into the aquifer systems and therefore can sustain high water loss via ET (Wang *et al*., 2007). It is therefore possible for shrubs to have higher recharge than forests. However, average recharge is decreasing in the study area (Figure 6), which could be attributed to high ET triggered by extensive irrigation and land exposure. The thickness of the zone of soil moisture is increasing due to high irrigation pumping and corresponding groundwater drawdown. With increasing soil moisture zone thickness, the volume of water held as soil moisture increases and the potential for groundwater recharge decreases accordingly. Much of the water held as soil moisture is eventually lost to the atmosphere via ET.

Interestingly, however, average runoff for 1930 is not substantially different from that for 2000 (Figure 6). But for specific land use types like sandlot, flat-paddy and low-dry field (all of which have evolved from marshlands), there exists a slight increase in runoff. Similarly, higher runoff is observed for designated land use types like rural settlement—most of which once belonged to natural forests. Runoff for wood lands and

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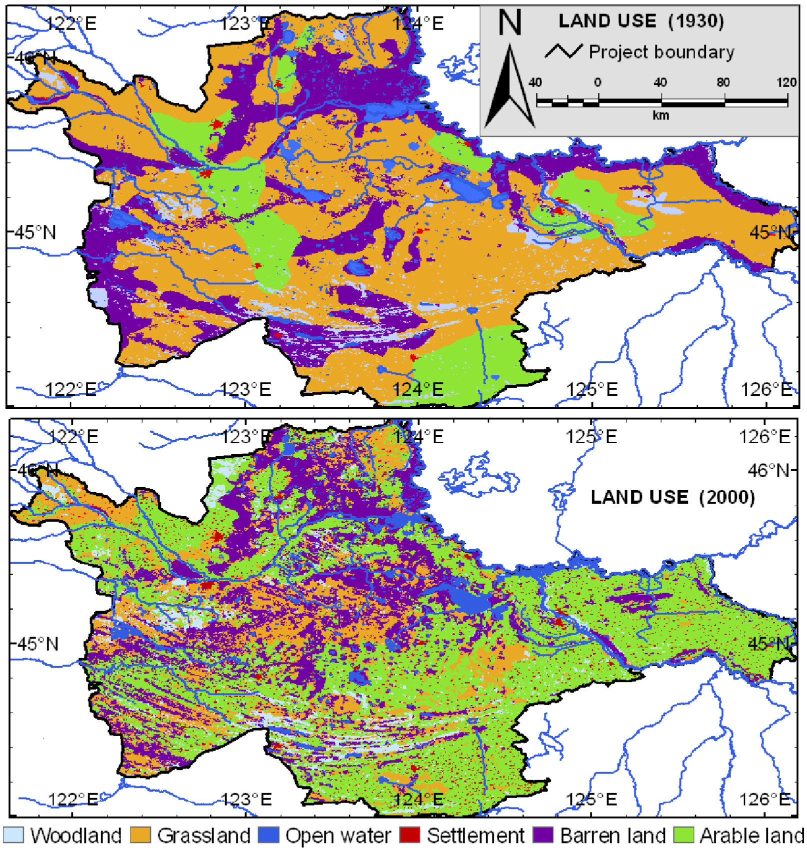

Figure 4. Spatial distribution of land use in Western Jilin for 1930 and 2000; modified after Himiyama (1998, 2001), Liu *et al.* (2002) and Li (2002)

rivers is also low (Figure 5). For especially vegetated lands, runoff and river flow generally decrease with decreasing precipitation (Wang *et al.*, 2007).

Hydrological effect of combined land use and soil type

In the study area, sandy soils generally occur along drainage courses. The coarse nature of the soils and their proximity to water lead to high ET, low recharge and runoff. Clay soils are made up of fine particles that firmly hold onto soil water, hence high potential for water logging. They therefore have low recharge and ET, and generally high runoff. Sand and clay are the two soil types with the most contrast in terms of textural and hydrologic properties. A number of studies show that soil (Gill *et al.*, 2004), land cover (Batelaan and De Smedt, 2007) and topographic slope (Cheng *et al.*, 2008) significantly influence catchment hydrology. Hence the combined effect of land use and soil type on the hydrological processes of ET, recharge and runoff are analysed and the results presented in Figure 7.

Under the land use conditions of 2000, unique combinations are identified for four soil types (sand, silt, loam and clay) and seven land use (open water, wetland, wood plant, grassland, bare land, settlement and agriculture) types. Irrespective of the soil type, ET is highest for open water surfaces, followed by wetlands. It is lowest for agricultural lands. This implies that ET is more a function of land cover (especially open water body), than is of soil type (also see Batelaan and De Smedt, 2007). On the other hand, recharge and runoff are variously influenced by soil and land cover types. Recharge is lowest for bare land surfaces and highest for agricultural lands. The high recharge for farmlands could be induced by irrigation return-flow. As most of the bare land surfaces (which are largely saline) occur along rivers and lakes, ET is potentially high, hence the negative recharge. Whereas runoff is lowest for wood lands, it is highest for bare land surfaces. This could imply that having lands under vegetation cover is an effective soil conservation measure.

One other physiographic factor with a vital influence on recharge and runoff is topographic slope. Slope analysis shows that recharge generally decreases with increasing steepness in slope (Figure 8). However, the effect of slope on recharge can also be moderated by such other factors as soil type and vegetation. Cheng *et al.* (2008) observed that while coarse soils increase the potential for recharge in even steep slopes, fine soils, on the other hand, reduce recharge in even gentle slopes. Though variously influenced by land use and soil type, runoff generally increases with increasing steepness in slope. The decreasing runoff for the steep (11-13%) slope areas is likely the moderating effect of vegetation (Figure 8). Terracing or levelling of land surfaces could therefore be an effective soil/water management strategy for cultivated lands.

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Table II. Area and percent fraction of land under different land use types for 1930 and 2000 in the Western Jilin study area

Land use type		Land use code	Area (10^6 m^2)		Fraction (%)	
			1930	2000	1930	2000
Woodland						
Dense forest		21	2553·75	480·00	5·45	1·02
Sparse forest		22		481·50		1·03
Shurb/bush		23		1022·75		2·18
Wood plant		24		659·50		1·41
	Sub total		2553·75	2643·75	5·45	5·64
Pasture						
Tall grass		31	24 913	3702·75	53·13	7·90
Medium grass		32		4287·25		9·14
Short grass		33		496·50		1·06
	Subtotal		24 913	8486·50	53·13	18·10
Open-water						
River		41		189·50		0·40
Lake		42	1673·75	1555·75	3·57	3·32
Reservoir/pond		43		118·00		0·25
Bottomland		46		357·25		0·76
	Sub total		1673·75	2220·50	3·57	4·74
Settlement						
Urban/city/town		51	155·00	155·00	0·33	0·33
Village		52		1409·25		3·01
Others		53		13·50		0·03
	Sub total		155·00	1577·75	0·33	3·36
Barren land						
Sandlot		61		47·75		0·10
Salineland		63		7021·50		14·97
Marshland		64	11447·25	3463·25	24·41	7·39
Bareland		65		5·00		0·01
	Sub total		11447·25	10537·50	24·41	22·47
Cultivated land						
Flat paddy		113		942·25		2·01
Flat-dry field		122		22·25		0·05
Low-dry field		123	6152·00	20464·25	13·12	43·64
	Sub total		6152·00	21428·75	13·12	45·70
	Grand total		46894·75	46894·75	100	100

Origin of the water balance components

Analysis of the raster grid-cells explains the origin of the water balance components in the study area. Based on the land use conditions for 2000, ET is highest for open water surfaces, followed by bare land, impervious land and vegetated land surfaces (Figure 9A). Ready availability of water induces high ET in open water surfaces. In the study area, most farmlands and deciduous forests are barren in winter. As bare lands also commonly occur along drainage courses in the area, they sustain sufficient soil moisture and hence the moderately high ET. There is direct evaporation of precipitation over impervious surfaces whereas vegetation limits water loss in vegetated land surfaces.

There is considerable recharge in winter during which period the lands are barren or crop covers very thin. It is therefore important to take into account ET from vegetated and bare land surfaces when recharge is estimated via soil water balance. In the study area, recharge is highest for vegetated land surfaces, followed by bare land and impervious land surfaces (Figure 9A). Vegetation retards surface runoff, thereby enhancing infiltration and recharge. Furthermore, most of the vegetated surfaces are irrigated farmlands where irrigation return-flow contributes to recharge. Whereas bare lands with coarse soils do sustain sufficient recharge, infiltration in impervious surfaces is highly limited. As evaporation is generally far in excess of recharge on open water surfaces, WetSpass ignores recharge for the open water surface fraction of the raster grid-cell (Batelaan *et al.*, 2003).

Over 60% of the areal runoff is on bare land surfaces, followed by impervious and vegetated land surfaces (Figure 9A). Whereas there is little mechanical obstruction to runoff on bare land and impervious land surfaces, vegetation considerably limits runoff (even on steep slope surfaces).

Figure 9B depicts the trends of the water balance components in relation to the percent average area of the land use types. Though ET is highest for open water surfaces and least for vegetated land surfaces,

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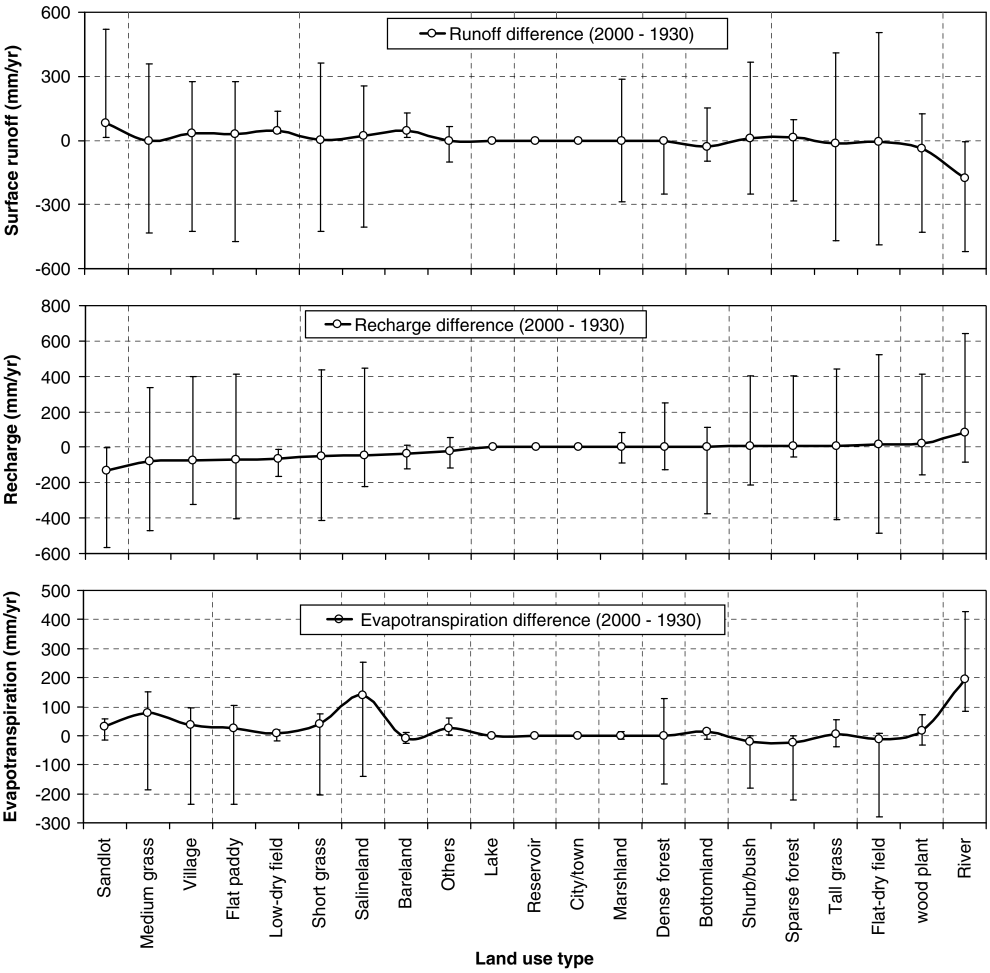

Figure 5. Differences in evapotranspiration, groundwater recharge and surface runoff (averaged per land use type) for the land use conditions of 1930 and 2000 in Western Jilin study area; error bars are measures of minimum and maximum values

most of the ET actually originates from vegetated land surfaces. This is because vegetated land is the largest land use in the study area, especially in summer. Similarly, most of the recharge originates from vegetated land surfaces. Since farmlands (the largest land use) are largely barren in winter and bare lands have little resistance to surface runoff, most of the runoff originates from the bare land surfaces in the study area (Figure 9B).

Effect of land use on wetland ecosystem

The impact of land use change on the wetlands of Western Jilin is quantitatively analysed and the results presented in Figure 10. Based on the analysis, an average of ≈21·4% of the wetlands has been converted into other forms of land use since 1930. Of this fraction, settlements, bare lands, open waters, forests, saline lands, grasslands and farmlands respectively account for 0·1, 0·7, 1·0, 2·0, 2·9, 4·8 and 9·9%—also see Wang *et al.* (2006). It is important to note that a considerable portion of the saline- and short grass-lands has evolved from the exhaustion of reclaimed wetlands through continuous farming. As such, most of the wetlands are primarily converted into farmlands in the study area. Rapid population and socio-economic growth is the primary force driving wetland reclamation in the area. In the study area, population has grown from $6·5 \times 10^5$ in 1932 to $4·75 \times 10^6$ in 2000 (Wang *et al.*, 2006). More importantly, over 70% of the population is directly engaged in farming (Pan *et al.*, 2003).

In their struggle to increase production for the staggering population, farmers have increasingly become reliant on groundwater irrigation. Excessive groundwater pumping has myriad negative implications for especially groundwater-dependent wetland ecosystem (Batelaan *et al.*, 2003; Ming *et al.*, 2007). For instance, dissolved salts in groundwater are pumped to the land surface during irrigation, which could lead to land salinization following evapotranspiration. Saline lands support limited or only salt-tolerant crops, and are generally unproductive (Pan *et al.*, 2006). High salt concentrations in especially inland freshwater wetlands could destroy the natural mix of wetlands, limiting or distorting eco-biodiversity and related ecological functions of wetlands (Ming *et al.*, 2007). Groundwater irrigation also depletes saturated storage, leading to the degradation of groundwater-dependent wetlands (Batelaan *et al.*, 2003). Conversely, head loss in wetland-dependent aquifers could cause wetland degradation via accelerated leakage (Chen and Lu, 2003).

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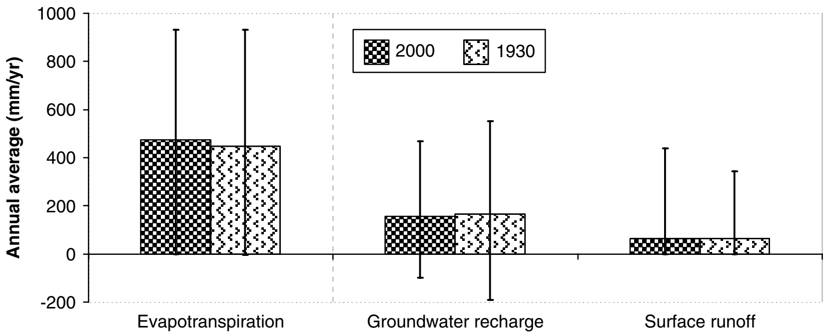

Figure 6. Comparisons of average evapotranspiration, groundwater recharge and surface runoff for the land use conditions of 1930 and 2000; error bars are measures of minimum and maximum values

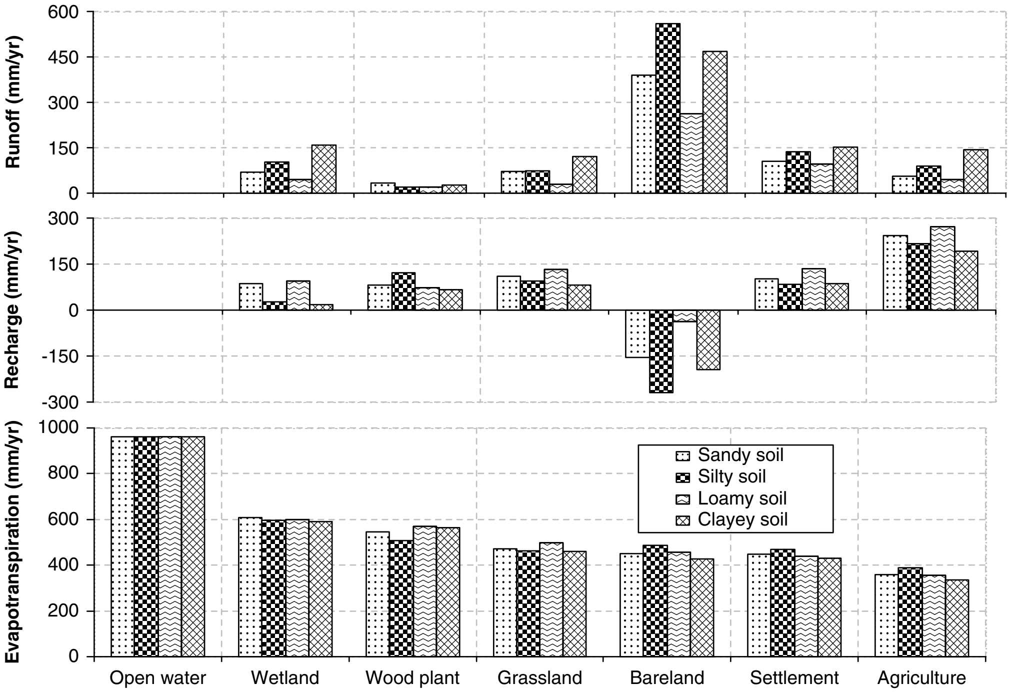

Figure 7. Evapotranspiration, groundwater recharge and surface runoff for 2000 (A) averaged per unique land use/soil type combination, (B) normalized by percent average area of land use type

As wetlands naturally occur in areas that favour ponding, they are easily targeted for reservoir construction and urban water supply. As shown in Figure 10, the current mode of land reclamation or development is destructive of the wetland ecosystem. With predicted population growth (Wang *et al.*, 2006), there is a high possibility that the remaining wetlands in the study area could be targeted for farming. Tangible countermeasures are therefore needed to preserve wetland ecosystems in the region. This can be achieved via sustainable integration, development and management of land, water and wetland ecosystems in the study area.

Effect of land use on water quality

There is increasing salt concentration in the soils and waters of Western Jilin as a result of the changes in land use. About 27% of the land area was saline in 1958, 33% in 1984 and 46% in 2001 (Pan *et al.*, 2003). Field measurements of dissolved oxygen (DO) and carbon oxygen demand (COD), two common indictors of water quality, also show increasing trends in most of the surface water systems in the study area (ADB, 2005).

Soil/water quality deterioration in the region is driven by natural as well as anthropogenic factors. For instance, the rivers generally originate from those mountains with abundant deposits of andesites, liparites, basalts, tuffs and granites. MgO, CaO, Na_2O and K_2O salts etched from these deposits by flowing rivers are deposited in the sluggish-flow areas in the floodplains, leading to salinization. The fragile hydrologic and semi-arid climate conditions also induce high ET, leaving behind deposited salts in the floodplains.

Anthropogenic factors such as overgrazing, clearing of wetlands for farming, irrigation pumping of groundwater and cropland fertilization variously affect salt concentration in the soils and waters of the region. Surface water eutrophication and groundwater deterioration (due to leaching and deposition of excess phosphates and nitrates) are other vital soil/water quality issues in the region (Zhang *et al.*, 2003; ADB, 2005). Surface water

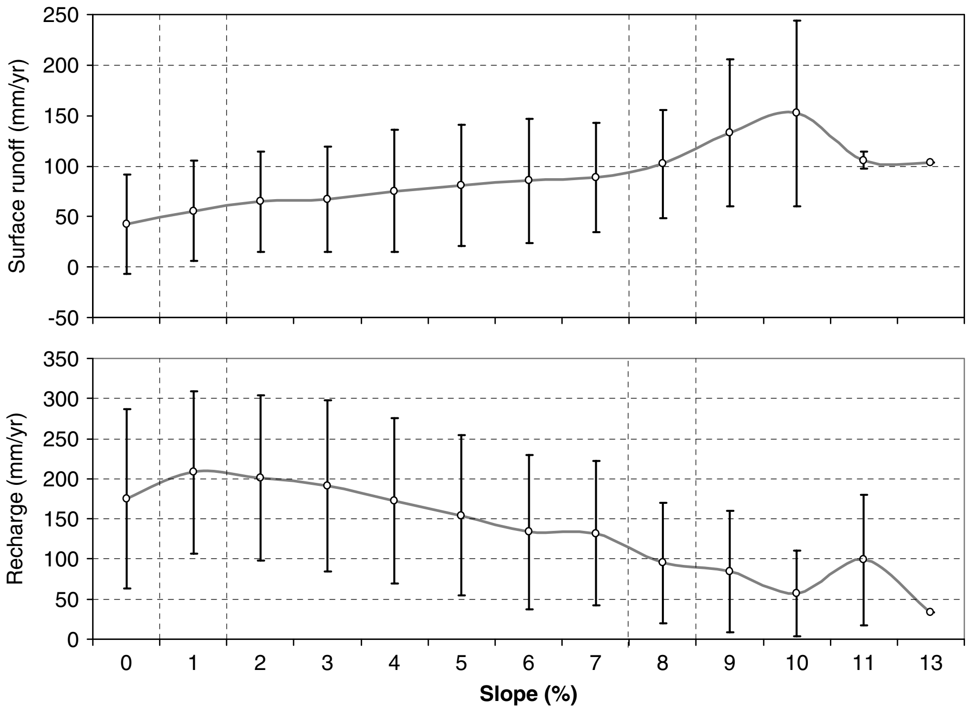

Figure 8. Average groundwater recharge and surface runoff (for 2000) for different percent slopes in the study area; error bars denote ± standard deviation

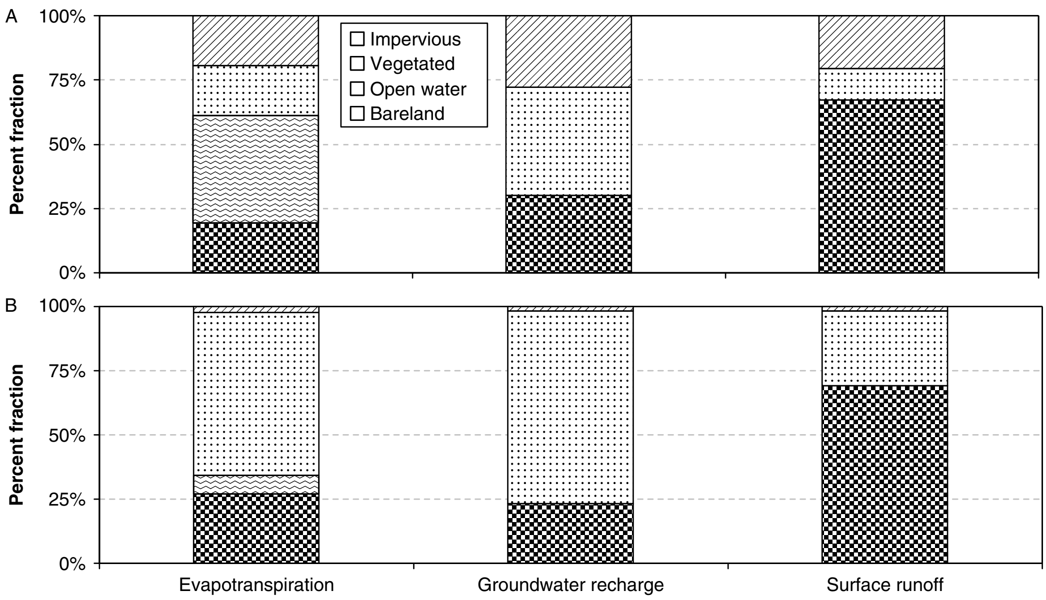

Figure 9. Percent fractions of WetSpass-simulated evapotranspiration, groundwater recharge and surface runoff for 2000 (A) averaged for the individual fractions of the raster grid-cell, (B) normalized by percent average area of the land use type

development distorts not only natural flows, but also delicate balances of the ecosystems. Currently, there is hardly sufficient fresh water flow or rainfall to dissolve accumulated salts in the floodplains (Pan *et al.*, 2003, 2006).

SUMMARY AND CONCLUSION

Accurate estimation of catchment hydrological processes is vital for sustainable land use planning and protection of wetland ecosystems in especially arid/semi-arid regions. In this study, WetSpass, extended with MODFLOW, is used to successfully simulate the water balance components of distributed recharge, runoff and ET in the wetland-based ecosystem of Western Jilin. Hydrophysiographic conditions of 1930 and 2000 are used in the simulation, and the calibrated model fluxes correspond favorably with field-measured hydrometeorological data.

Quantitative analysis reveals substantial changes in land use in the 70-year period from 1930 to 2000. About 21% of the wetlands have been converted into other forms of land use. The wetlands are primarily converted into farmlands due to increasing land pressure from rapid

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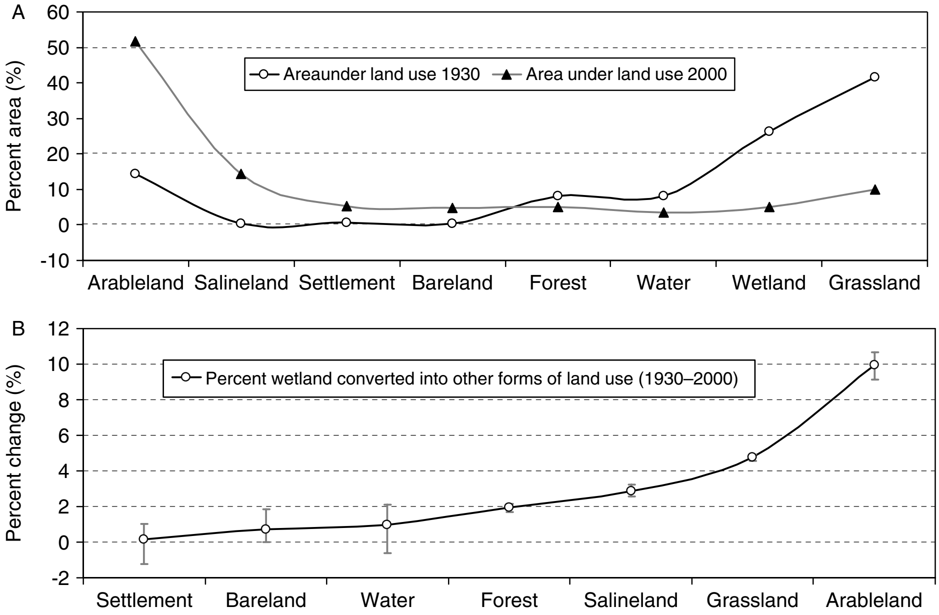

Figure 10. Plots of percent (A) land use/land cover change, and (B) converted wetland into other forms of land use for 1930–2000 in Western Jilin study area; error bars denote ± standard deviation

population and socio-economic growth. Whereas ET is increasing, recharge and saturated storage are decreasing. Water resources are therefore dwindling in the study area, having a destructive effect on the wetland ecosystem. Raster grid-cell analysis based on the land use conditions of 2000 shows that ET is highest for open water surfaces. However, most of the ET originates from vegetated land surfaces. Recharge is not only highest for vegetated land surfaces as well, but mostly originates from these land surfaces. Runoff is highest, and largely originates from bare land surfaces. The hydrological components of ET, recharge and runoff are highest in summer—the precipitation/irrigation season in the study area. Whereas water availability is the primary factor influencing ET, recharge and runoff are variously influenced by topographic slope, land use and soil type. Because of the semi-arid climate and extensive irrigation, recharge can easily be negative in especially the arable lands of the study area. Furthermore, the quality of land/water resources is deteriorating due mainly to the indiscriminate development of these resources. In WetSpass hydrology, net recharge is the residual term of precipitation, ET and runoff. Negative recharge (implying excess ET) is therefore only sustained by evapotranspiration of shallow groundwater or deep groundwater hauled to land surface for irrigation. Therefore, ET-limiting land use/water resources management strategies are critical not only for environmental sustainability, but also for the efficient restoration and preservation of the wetland-based ecosystem of Western Jilin.

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