Modelling water yield with the InVEST model in a data scarce region of northwest China

Xu Yang, Ruishan Chen, Michael E. Meadows, Guangxing Ji and Jianhua Xu

ABSTRACT

The Bosten Lake basin is an important arid region of northwest China, and has exhibited a declining trend in both lake area and level of water during recent decades. Reliable information on water yield, an important attribute of available water resources in a region, is vital to assess the potential for socio-economic development. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is applied here to simulate water yield in the Bosten Lake basin. The spatial and temporal dynamics of water yield, and the response of water yield to land use and precipitation change, are analysed for the period 1985 to 2015. The results show that, overall, water yield increased during 1985–2015, and that the magnitude of change was greater in the eastern part of the region. The water yield capacity, positively correlated with precipitation, is highest under grassland vegetation and lowest in cultivated and unused land. The paper demonstrates that statistical downscaling and climate reanalysis data can be used in the InVEST model to improve the accuracy of simulated water yield in data scarce regions.

Key words | Bosten Lake Basin, InVEST model, statistical downscaling, water yield

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INTRODUCTION

Water is a crucial natural resource, especially in arid and sem-arid regions of the world, such as northwest China, as it is vital to balancing socio-economic development and ecological security and is therefore a core issue for water resources management. Water resources supplied by precipitation and snowmelt in the region are highly variable and vulnerable to a range of influences, including climate change (Xu *et al.* 2018).

Water yield assessment is a key issue in the field of hydrology and watershed management (Terrado *et al.* 2014). Many mathematical methods are currently available to assess water yield (Taylor *et al.* 2019), although the water balance method is most commonly applied as the outputs are known to align well with the actual situation (Long *et al.* 2014). Although many studies on water resources have been carried out in northwest China (Bao & Fang 2007; Geng *et al.* 2015), these have focused on runoff, water demand, water conservation or water supply, and not specifically considered water yield. Bosten Lake is the main water source for industry, agriculture and life in the Bayingol League Autonomous Prefecture. Moreover, none of the previous studies deal with the water yield in the Bosten Lake and its catchment. With the development of geographic information systems (GIS) and remote sensing (RS), more sophisticated spatial models have been proposed to simulate

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hydrological processes, for example, the Soil and Water Assessment Tool (SWAT) (Jayakrishnan *et al.* 2005), the Precipitation Runoff Modeling System (PRMS) (Markstrom *et al.* 2008) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Zhang *et al.* 2012). The InVEST model is more widely used, and has proved especially suitable for establishing ecosystem services, including water yield, nutrient retention, crop pollination, sediment retention, etc. in areas with sparse data (Hamel *et al.* 2015; Outeiro *et al.* 2015; Groff *et al.* 2016; Posner *et al.* 2016; Redhead *et al.* 2018). Water yield in the InVEST model is defined as the amount of water from precipitation remaining after evapotranspiration and groundwater recharge, and has been employed in water resource studies (Zhang *et al.* 2012; Bangash *et al.* 2013; Redhead *et al.* 2016), but until now there has been no published research on water yield in the Bosten Lake basin.

This study simulates and analyzes water yield during 1985–2015 in a typical arid basin in northwest China. Through spatio-temporal analysis of precipitation and land use change, as well as correlation analysis of precipitation and land use change on water yield, the major objectives were to determine: (1) whether the InVEST model is not only suitable for a data scarce region in northwest China, but also suitable for other similar areas; (2) if a statistical downscaling method can contribute to simulated accuracy; and (3) how precipitation and land use change have an impact on water yield. The combination of a statistical downscaling method and the InVEST model in this study provides a new research idea for data scarce regions, and makes up for the gap in the studies on water yield in an arid region of northwest China.

METHODS

Study region

The Bosten Lake basin is located on the southern flank of the Tianshan Mountains in Xinjiang Uyghur Autonomous Region of China. The surrounding mountains form a barrier to moist air so that the climate is characterized as temperate continental arid.

Statistical downscaling of reanalysis precipitation and temperature data

There are too few meteorological stations in the study region, and the interpolation method is not a better method to obtain precipitation and temperature data. Although the reanalysis data are available, the accuracy is too rough to meet the needs of the study region, so the statistical downscaling method is appropriate for reanalysis data. Spatial variability in precipitation and temperature are strongly influenced by factors such as altitude. In combination with the terrain data, the regional space-time climate characteristics can be revealed by downscaling the reanalysis data (Georgakakos *et al.* 2014). An improved downscaling method which dynamically adjusts terrain parameters (Wang *et al.* 2017) was applied to downscale the reanalysis data. The downscaling method includes three steps: simulation of precipitation gradients and temperature lapse rates, downscaling of reanalysis climate data, and calculation of high-resolution precipitation and temperature data.

Mean monthly precipitation p_i and temperature t_i were initially calculated to reduce the impact of parameter error on downscaling:

$$p_i = \sum_{j=1}^{12} p_{m\,ij}/12 \tag{1}$$

$$t_i = \sum_{j=1}^{12} t_{m\,ij}/12 \tag{2}$$

where $p_{m\,ij}$ is monthly precipitation in ith year and jth month, $t_{m\,ij}$ is the monthly temperature in ith year and jth month.

Previous studies in northwest China have revealed that temperature and precipitation are related to altitude and that the relationship between these variables may be quadratic polynomial or linear (Fu *et al.* 2013; Wang *et al.* 2017). We applied both a quadratic polynomial equation $p = ah^2 + bh + c$ and a linear equation $t = mh + n$ to downscale the reanalyzed precipitation and temperature data. The parameter p is precipitation, t is temperature, and h is altitude. The parameters m, n, a, b, c are coefficients for the equations and were estimated from meteorological observations.

We then calculated the precipitation gradient dp/dh and temperature lapse rate dt/dh by calculating the derivative of the fitting functions:

$$\frac{dp}{dh} = 2ah + b \tag{3}$$

$$\frac{dt}{dh} = m \tag{4}$$

Firstly, based on the altitude of the ASTER GDEM (Global Digital Elevation Map) h_s and using a bilinear interpolation resampling method, the elevation of the reanalysis data h_r was calculated. To facilitate operating the matrix with different grid sizes, the reanalysis precipitation data p_r and h_r, and the reanalysis temperature data t_r and h_r, were resampled to the same grid size as h_s by bilinear interpolation. Downscaled monthly precipitation p_d and temperature t_d with a spatial resolution of 30 m at elevation h_s were then obtained by Equations (5) and (6):

$$p_d = p_r + (h_s - h_r) \cdot \left(\frac{dp}{dh_s} + \frac{dp}{dh_r}\right)/2 \tag{5}$$

$$t_d = t_r + (h_s - h_r) \cdot \left(\frac{dt}{dh_s} + \frac{dt}{dh_r}\right)/2 \tag{6}$$

where $(h_s - h_r)$ is the difference in elevation, $\left(\frac{dp}{dh_s} + \frac{dp}{dh_r}\right)/2$ is the mean precipitation gradient between elevation h_s and h_r, $\left(\frac{dt}{dh_s} + \frac{dt}{dh_r}\right)/2$ is the mean temperature lapse rate between elevation h_s and h_r.

The downscaling equations, Equations (7) and (8), are as follows:

$$p_d = p_r + (h_s - h_r) \cdot [a(h_s + h_r) + b] \tag{7}$$

$$t_d = t_r + (h_s - h_r) \cdot m \tag{8}$$

Calculating water yield in the InVEST model

The water yield component of the InVEST model is designed to map the spatial distribution of water across a river basin, and estimates the quantity of water yield from each subwatershed in the area of interest. InVEST calculates the total water production of the ecosystem, *viz.* precipitation minus the fraction that undergoes evapotranspiration. The model does not differentiate between surface, subsurface, and baseflow, but assumes that all water yield from a pixel reaches the point in question via one of these pathways. This model then sums and averages water yield to the subwatershed level.

The water yield model is based on the Budyko curve and annual average precipitation. Annual water yield Y(x) for each pixel on the landscape x was determined with Equation (9) as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x) \tag{9}$$

where AET(x) is the annual actual evapotranspiration for pixel x, and P(x) is the annual precipitation for pixel x.

Validation method

Due to the availability of only very limited data for the Bosten Lake basin, we selected a part of the catchment, the Kaidu River upstream of the Dashankou hydrological station, to perform the verification. Since the cross-sectional runoff data cannot accurately reflect natural runoff in the entire basin (Wei & Zhang 2010), it is difficult to use hydrological station data directly to verify the model. The simulated results include surface water and groundwater, so the water yield value is used to compare the actual and simulated results (Redhead *et al.* 2016). The equation of water yield value, Equation (10) is as follows:

$$Y = \frac{W}{A} \tag{10}$$

where Y is the water yield value, W is water volume (m^3) which includes runoff, groundwater and snowmelt, and A is the catchment area (km^2).

Analysis method

ArcGIS software was selected to assist with the analysis. Precipitation data were processed using a reclassification tool to obtain different precipitation intervals. The zonal tool was used to analyze the relationships between water yield and precipitation, and land use.

RESULTS

Distribution and change of land use from 1985 to 2015

Land use in the Bosten Lake basin includes cultivated land (CL), forest land (FL), grassland (GL), water areas (WA), built-up areas (BA), and unused land (UL). Cultivated land includes paddy fields and dry land. Forest land includes dense woodland, shrubs, sparse woodland, and other woodlands (nurseries, gardens, etc.). Grassland includes high coverage, medium coverage and low coverage. Water areas include rivers, lakes, reservoirs, glaciers and snow, and wetlands. Built-up areas include urban, rural, and construction land. Unused land includes sand, the Gobi Desert, saline land, marshes, bare land, bare rocky gravel, other (alpine desert, tundra, etc.).

Land use in the catchment is spatially heterogeneous (Figure 1). Cultivated land and built-up areas are distributed mainly in the vicinity of the lake itself. There is limited forest land and this is scattered across the basin. Grassland, and the various land types classified as unused land, are widely distributed in the basin, with grassland predominating in the west, and unused land mainly in the east, where unused land is dominated by the Gobi Desert and bare rocky gravel. Water bodies are widely distributed, with snow in the mountains and lakes on the plains, while rivers are widely distributed.

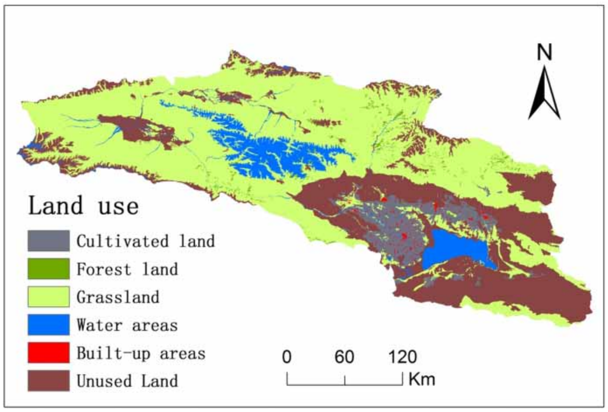

Figure 1 | The distribution of land use in Bosten Lake basin.

Figure 2 shows that cultivated land, built-up areas and grassland have increased over time, while forest land and unused land have generally decreased. The areas occupied by the various categories of water have decreased since 1985 by more than 7%. Rapid population growth and economic development in recent decades has led to the significant expansion of cultivated land and built-up areas in China (Liu *et al.* 2004; Bai *et al.* 2012). Typically, this leads to loss of forest and grassland areas but, in the case of the Bosten Lake basin, grassland and forest areas have not been cleared for cultivation, which has increased in area through the drainage of water bodies and conversion of unused land. The decline of the area occupied by water bodies (which includes snow cover here) relates also to increased snow melt due to higher temperatures (Xie *et al.* 2018; Zhang *et al.* 2019).

Precipitation changes from 1985 to 2015

The mean annual precipitation of the whole Bosten Lake basin fluctuated between 181 mm/m^2 and 500 mm/m^2 from 1985 to 2015 (Figure 3). Following a decreasing trend between 2000 and 2010, precipitation increased after 2010 (Yao *et al.* 2018; Mo *et al.* 2019). The observed pattern of precipitation change is consistent with other records from the region, which suggest that both total precipitation and the number of extreme rainfall events have increased in northwest China (Chen *et al.* 2017). Given the complex topography and scarcity of meteorological stations in the basin, statistical downscaling was used to improve the resolution of precipitation data for the period 1985 to 2015. Precipitation in the Bosten Lake basin decreases from northwest to southeast, and the area that receives less than 100 mm annually has consistently declined since 1985 (Figure 4).

The impacts of land use and precipitation change on water yield

Water in the Bosten Lake basin is sourced from a combination of precipitation and snowmelt, while evaporation and land use types influence the water yield. However, the model only considers the water produced by precipitation. The precipitation to evaporation ratio in northwest China

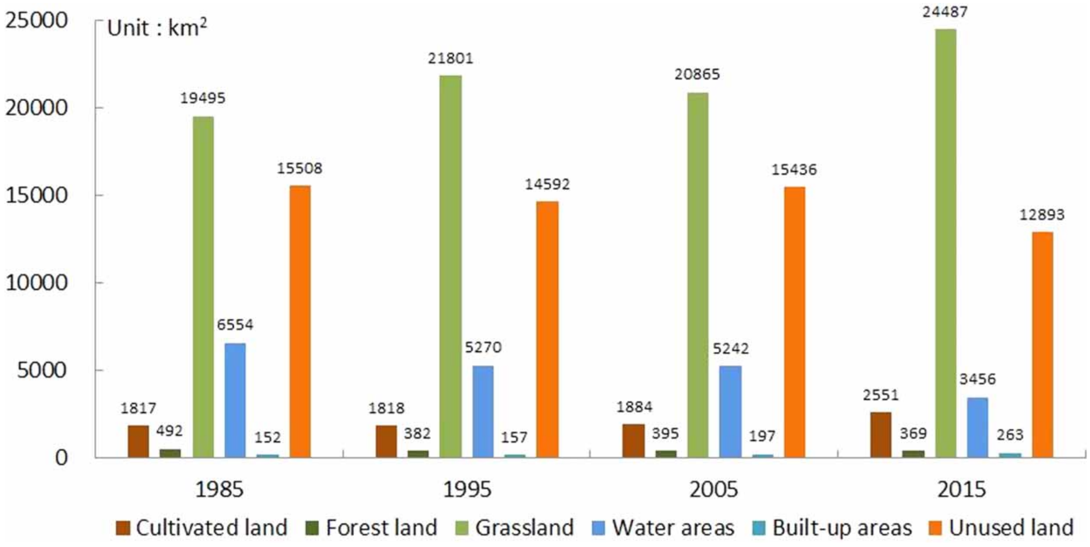

Figure 2 | Land use area of Bosten Lake basin in 1985,1995, 2005 and 2015.

is low and inevitably this results in low water yield in the Bosten Lake basin. Zhu *et al.* (2015) showed that water resources declined during 1972–1990, increased during 1990–2002 and continued to decrease during 2002–2010. Given that precipitation during the period 1995–2015 has increased, the decline in water resources must be related to land use change.

The water yield of different land use types is shown in Figure 5. The area occupied by the various land use types has varied over time, so we use the mean water yield to reflect the amount of water yield on different land use types. Figure 5 shows that the mean water yield of grassland was the highest, and the mean water yield of unused land was the lowest from 1985 to 2015. It can be seen that the water yield capacity of different land use types decreased in turn from grassland, water areas, forest land, built-up areas, cultivated land, to unused land.

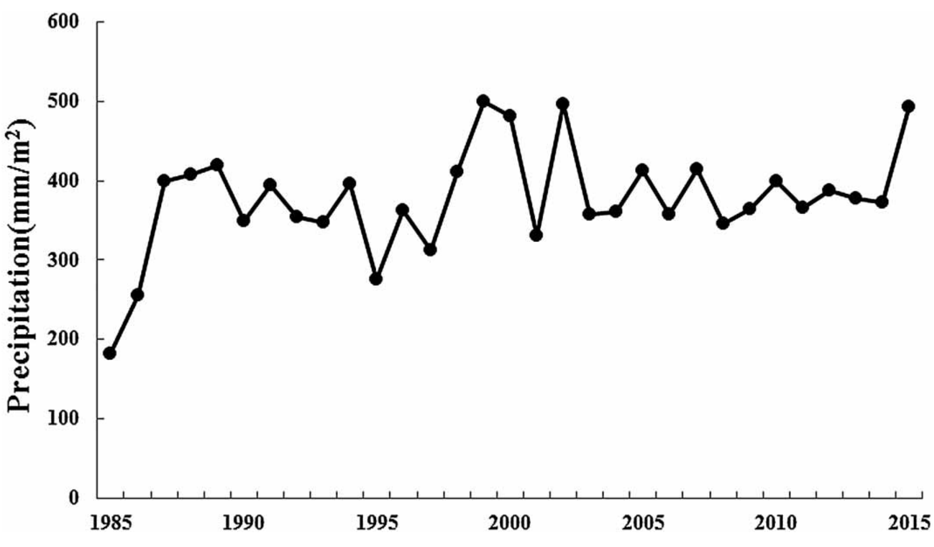

Figure 3 | The average annual precipitation (mm·m^{-2}) of Bosten Lake basin between 1985 and 2015, these data were calculated by statistical downscaling precipitation data.

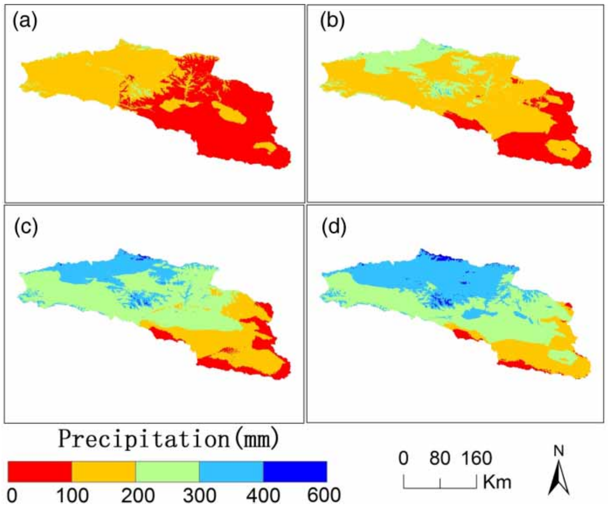

Figure 4 | The precipitation of Bosten Lake basin in 1985 (a), 1995 (b), 2005 (c), 2015 (d), these precipitation data are obtained from climate reanalysis data using the statistical downscaling method.

Precipitation was classified into five categories, *viz.* 0–100 mm, 100–200 mm, 200–300 mm, 300–400 mm, and 400–600 mm.

From 1985 to 2015, the mean water yield was greater in areas with high precipitation than those where precipitation was lowest (Figure 6). The difference in water yield is caused by the difference in precipitation and evaporation between mountainous areas and lowland areas. The precipitation in mountainous areas is greater than that in lowland areas, while the opposite is true for evaporation.

Spatio-temporal distribution of water yield

From 1985 to 2015, the water yield in the Bosten Lake basin increased by 0.32×10^8 m^3 (Table 1). The destruction of soil and vegetation has reduced infiltration and evapo transpiration, and increased the impervious surface, resulting in an increase in water yield. Due to lack of water consumption for human activities, the trend of the water yield is inconsistent with the decline in water resources obtained by Zhu *et al.* (2015).

Figure 7 shows the spatial changes in water yield during the period from 1985 to 2015 within the Bosten Lake basin. There has been more change in water yield in the 30 year period in the mountainous areas, where precipitation and evaporation are highly variable, and in the plains around the lake itself due to the expansion of cultivated land and built-up areas (Liu *et al.* 2004).

DISCUSSION

Proposed modelling approach

Northwest China is geomorphologically complex. On the basis of the 1:1,000,000 digital geomorphological map of China (Zhou *et al.* 2009), the Bosten Lake basin can be classified into (a) plains (elevation: 1,000–1,500 m, relief: 0–150 m) and (b) mountainous areas (elevation:

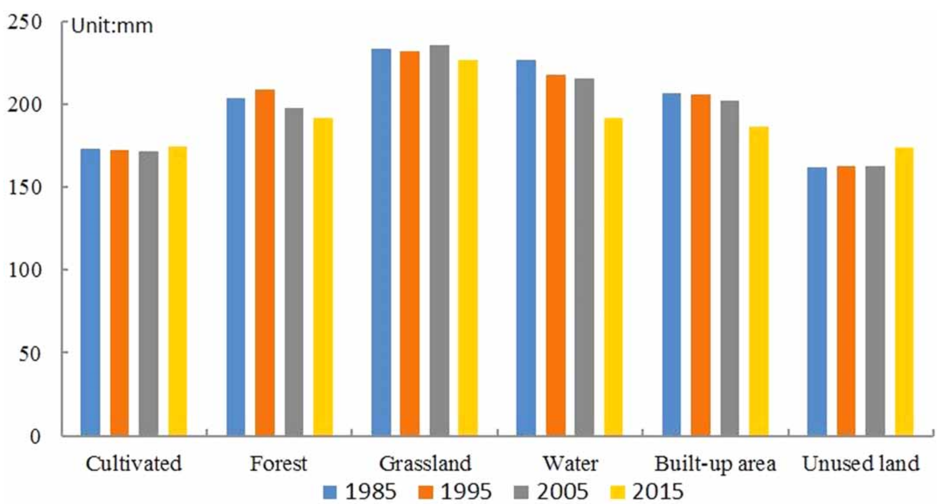

Figure 5 | Mean water yield for different land use types in 1985, 1995, 2005 and 2015.

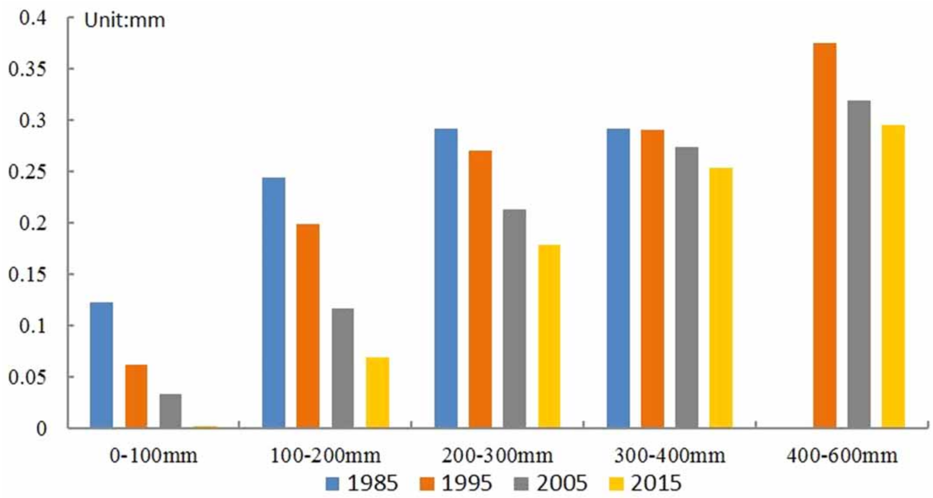

Figure 6 | Mean water yield under different precipitation amounts in 1985, 1995, 2005 and 2015.

1,500–5,000 m, relief: >150 m); permanent snow cover occurs at elevations above 3,900 m. Figure 8 is a three-dimensional conceptual diagram of the Bosten Lake basin that illustrates the spatial distribution of these geomorphological zones and how they contribute to water yield, as calculated using the simplified water balance method.

Temporal trend in water yield

While water in the Bosten Lake basin is indeed derived mainly from precipitation, the model only considers the water yield from precipitation and does not include the proportion from snowmelt and glaciers. Water from snowmelt is, however, taken into account in the verification. As noted in the validation method, the actual water yield is calculated for the catchment area based on the DEM, annual average runoff (Xiang *et al.* 2018), annual average snowmelt (Xiang *et al.* 2018), and annual average groundwater (Li *et al.* 2003). The seasonal factor (Z) can be adjusted in the model: when $Z = 30$, the simulated water yield (Table 2) approximates the actual water yield with a difference of 5.68%. The error arises from the fact that the interchange between surface water and groundwater is not accounted for, which, coupled with the absence of water consumption data, results in the simulated water yield being greater than the actual value.

In Table 3, the correlation coefficients of precipitation and water yield on land use types are different, and the correlation coefficient test is significant positive correlation at

Table 1 | Water yield of Bosten Lake basin in 1985, 1995, 2005 and 2015

Year	Water yield (m^3)
1985	147.93×10^8
1995	148.00×10^8
2005	148.01×10^8
2015	148.25×10^8

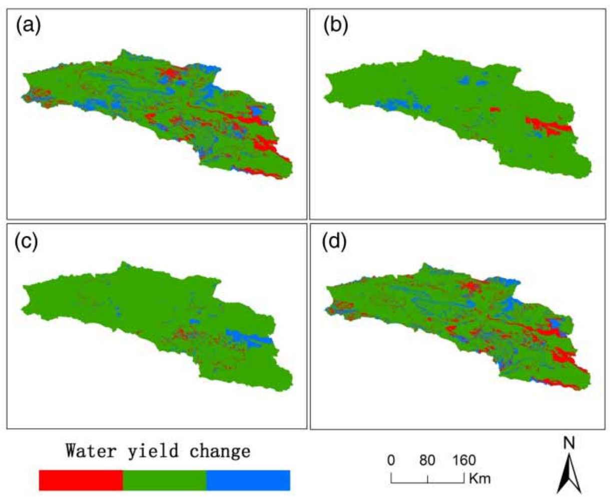

Figure 7 | The change trend of the water yield of Bosten Lake basin in 1985–2015 (a), 1985–1995 (b), 1995–2005 (c), 2005–2015 (d), the dark grey (blue) areas indicate an increasing trend of water yield during the study period, the mid-grey (red) areas indicate a decreasing trend of water yield during the study period, and the light grey (green) areas indicate no change in the water yield during the study period. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2020.026.

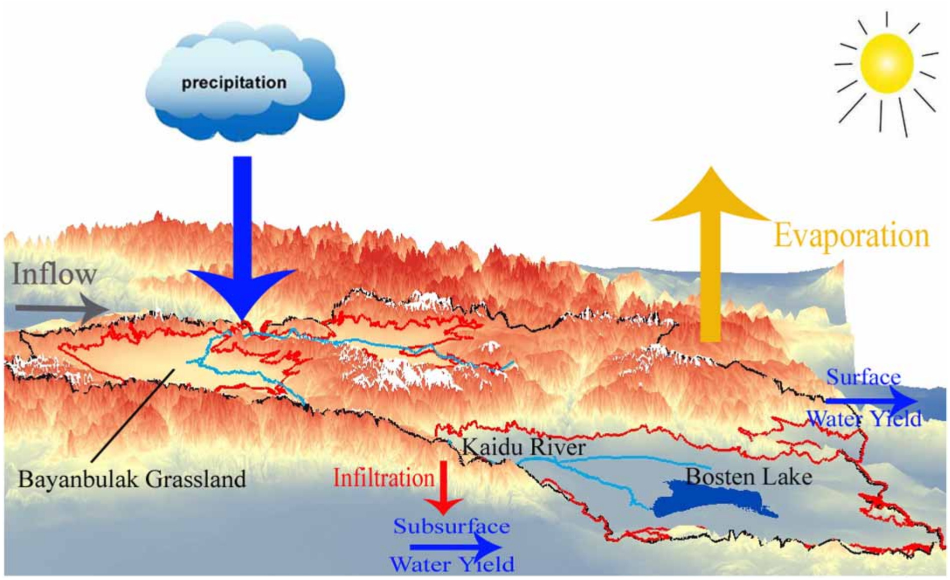

Figure 8 | Conceptual diagram of the simplified water balance method used in the annual water yield model in the Bosten Lake basin. Areas shaded in stippled grey (color) are included in the model, while those that are shaded in solid grey are not. The study area demarcated by the black line is the Bosten Lake basin; the plain areas are demarcated by the grey (red) line; areas of permanent snow are white. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2020.026.

Table 2 | Actual and simulated results of the Kaidu River basin above Dashankou hydrological station

Results	Catchment area (km^2)	Annual average runoff (m^3)	Annual average groundwater (m^3)	Annual average snowmelt (m^3)	Water yield value (m^3/km^2)
Actual results	18,532.66	35.15×10^8	13.00×10^8	5.08×10^8	23.24×10^4
Simulated results			45.66×10^8	–	24.64×10^4

Table 3 | The correlation coefficient of precipitation and water yield on different land use types

	Correlation coefficient			
Land use type	1985	1995	2005	2015
Cultivated land	0.9042	0.9822	0.9826	0.9348
Forest land	0.5936	0.7720	0.7269	0.5833
Grassland	0.7800	0.8364	0.8356	0.8355
Water areas	0.4490	0.4301	0.4950	0.3741
Built-up areas	0.8801	0.9522	0.9969	0.9558
Unused land	0.9115	0.9507	0.9553	0.9022

the 95% and 99.9% levels. The different correlation coefficients are closely related to the distribution of precipitation, evaporation and land use.

The Bosten Lake basin is typical of the distinctive arid regions of northwest China, water yield is relatively low because the precipitation is limited and evaporation rates are high. Water yield in the basin varies spatially between the plains, located mainly in the central and northeastern parts, and the mountains of the northwestern margins. As shown in Figure 4, mountainous areas receive more precipitation and have lower evaporation rates due to lower temperatures (Monteith 1981), so water yield is correspondingly higher. The Bayanbulak grassland plains are at a higher elevation than other plains in the basin, and have correspondingly higher precipitation and lower evaporation. Coupled with the fact that the main land use here is livestock grazing (Zhang *et al.* 2002), the Bayanbulak grassland plains produces higher water yields than the plains at a lower elevation.

In addition to differences in precipitation, land use also influences water yield. The change in mean water yield is affected by the areas of different land use types in mountainous areas and lowland areas during 1985–2015. The mean water yield on grassland is the highest due to the fact that this land cover type consumes a proportionally smaller amount of water through lower values for evapotranspiration (Hibbert 1983). Water yield on cultivated land is lower because crops consume more in growth and evapotranspiration. The large mean water yield on forest land is related to the distribution where precipitation is high. The large mean water yield on built-up areas is affected by the increased impervious surface (Mitchell *et al.* 2001), to some extent modulated by increased water consumption and evaporation. The high value of water yield from areas classified here as water (as well the reduction in water yield from these areas over time) is related to their distribution being mainly in mountainous areas. The change in mean water yield on unused land is related to relatively high infiltration rates on most sub-categories of land in this classification (Zhou *et al.* 2015).

Attribution of water yield and policy implication of water resources

Modelling using InVEST reveals that, consistent with existing research (Hoyer & Chang 2014), precipitation is the main driver of water yield and that the mountainous areas yield the most water, although land use does have a secondary effect. In order to maintain water resources in the basin, the authorities responsible for water resources management should consider reducing vegetation damage, introducing rational grazing, and restoring and protecting water, converting unused land into other land uses.

In order to promote the protection, restoration and more sustainable utilization of water resources in the Bosten Lake basin, the Government of Xinjiang Uygur Autonomous Region of China has implemented a number of environmental initiatives. For example, the 'Three Red Lines Control Indicators for the Implementation of the Most Strict Water Resources Management System in Autonomous Prefectures' was introduced in 2015. More recently the 'Implementation of the Most Strict Assessment Methods for Water Resources Management System (Trial) in Bayingol Mongolian Autonomous Prefecture' was established.

CONCLUSIONS

High-resolution precipitation and temperature data obtained through statistical downscaling are applied in this study through the InVEST model to simulate the water yield in the Bosten Lake basin. The results show that the InVEST model can be successfully applied in data scarce regions such as those of northwest China. It is noted that water yield in the basin has increased between 1985 and 2015, particularly in the mountainous areas. As anticipated, water yield correlates positively with precipitation. Land use is also an important, if secondary driver; water yield values are highest in grassland, followed by those areas characterized as water (including snow), forest, built-up areas, cultivated land, and unused land respectively. This study demonstrates that reliable water yield assessments are possible in data scarce regions and can help to facilitate more effective water resources management, and soil and water conservation. In future, adjusting the model to take into account surface water and groundwater exchange, as well as water consumption, should enable further improvements in the accuracy of the simulation.

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