Variation of economic value produced by environmental flow in water-scarce basins of Northwest China

Siyu Yue, Huaien Li and Bo Cheng

ABSTRACT

With intensification of human activities, environmental flow is often diverted for human use, particularly in areas with water scarcity. Accurate assessment of economic value produced by environmental flow will help protect environmental flow by means of economics. Based on the concept of opportunity cost, we can estimate economic value produced by environmental flow in water-scarce basins by the maximum loss caused by reduced amounts of water and the availability of water for other purposes. In this study, we propose a method that combined results of water scarcity assessment incorporating environmental flow with an opportunity cost approach to obtain economic value produced by environmental flow on the sub-basin scale. Then, we take the Wei River Basin in Northwest China as an example to test the feasibility of this method and use scenario analysis to discuss the influence of climate factor and land-use factor on economic value produced by environmental flow. This method can better present distribution and variation characteristics of economic value produced by environmental flow more directly and provide a reference for future ecological compensation in water-scarce basins.

Key words | economic value produced by environmental flow, Northwest China, opportunity cost method, water-scarce basin, water scarcity assessment incorporating environmental flow

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HIGHLIGHTS

- Economic value produced by environmental flow was a novel direction for recent environmental flow research.
- A simple approach was proposed in this study to present the considerable economic value produced by environmental flow in monetary terms.
- Economic value produced by environmental flow was displayed in the form of maps that more directly reflected distribution and variation of economic value produced by environmental flow.
- The influence of climate factor and land-use factor on economic value produced by environmental flow was discussed by means of scenario analysis.
- The Wei River Basin, which is the typical water-scarce basin in Northwest China, was taken as a case to test the feasibility of this method.

INTRODUCTION

As a valuable natural resource, water is needed by all organisms for growth and survival and thus is the most important and active factor in an ecosystem (Garrick *et al.* 2017). Water is also an irreplaceable resource for agriculture and industry (Poole *et al.* 2013). As human activity intensifies, flow extraction from the river is increasing in terms of the amount extracted for a variety of needs, including urban uses, irrigation (Zaag *et al.* 2010), industry and hydropower (Gómez *et al.* 2014). In recent years, environmental flow (e-flow)

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has gained more attention. It refers to the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Arthington *et al.* 2018). However, when the contradiction between supply and demand of river water resource is sharp in dry seasons, the limited water resource is often diverted for human use, particularly in areas where water is scarce. From an ecological economics perspective (Sepúlveda 2013), the reason for this is that considerable economic value produced by e-flow is not presented in monetary terms. If there might have economic loss for protecting e-flow, humans are apt to choose more obvious intuitive economic value brought by agricultural and industrial water. Therefore, it is an important basis of e-flow protection for quantitative calculation of economic value produced by e-flow scientifically.

Several researchers have already proposed their original viewpoints about economic value produced by e-flow. Ojeda *et al.* (2008) estimated the economic value of environmental services provided by restored instream flows in water-scarce basins by means of the contingent value method. Sisto (2009) and Pang *et al.* (2013) used the production loss model to compute compensation figures for irrigators because of e-flow requirements. According to the principle of equal marginal utility, Perona *et al.* (2013) used economic value generated by production water use to reflect economic value produced by e-flow indirectly. Akter *et al.* (2014) provided a method to combine hydro-ecological response model outputs and nonmarket economic values of wetland inundation to estimate a unit price of environmental water. Yue *et al.* (2018) quantified the economic value brought by environmental base flow by learning from the evaluation method of ecosystem service. These methods are only preliminary explorations and it still needs further study to establish a relatively complete calculation system of economic value produced by e-flow.

Considering e-flow is a special kind of water resource (Smakhtin *et al.* 2004), we can use economic value methods of water resource as references for research into economic value produced by e-flow. At present, economic value methods of water resources mainly include the shadow price method (Ziolkowska 2015), price elasticity method (Davidson & Hellegers 2011), the Computable General Equilibrium model (Medellín-Azuara *et al.* 2010), fuzzy price method (Zhao & Chen 2008), emergy evaluation method (Díaz-Delgado *et al.* 2014), residual value method (Berbel *et al.* 2011), opportunity cost method (Tilmant *et al.* 2015) and cost–benefit analysis (Arena *et al.* 2014), etc. The concept of opportunity cost expresses the basic relationship between scarcity and choice and also reflects the cost of scarce resources as they are currently being used (Buchanan 2008). For water resources, if they are scarce relative to needs, the use of water for one need prevents its use for other needs (Griffin 2006), and we can measure the opportunity cost of water resources in terms of the value of the best alternative that is forgone or what must be surrendered (Polley 2015).

According to the above ideas, under the situation of water scarcity, in order to protect e-flow, another water-use requirement will inevitably be affected due to the tension between water supply and demand. Then economic value produced by e-flow represents the maximum loss caused by reduced amounts of water and availability of water for other purposes. Therefore, here we attempted to propose a method for estimating economic value produced by e-flow in water-scarce basins by means of the opportunity cost approach. Firstly, we used the method of water scarcity assessment incorporating e-flow to evaluate water scarcity on a sub-basin scale under the water yield modular of the Integrated Valuation of Ecosystem Service and Tradeoffs (InVEST) model. Secondly, we combined water scarcity results and the opportunity cost approach to obtain economic value produced by e-flow on a sub-basin scale. Finally, we used the Wei River Basin (WRB), which is the typical water-scarce basin in Northwest China, as an example to test the feasibility of this method.

MATERIALS AND METHODS

Study area: The WRB

The Wei River (Figure 1), the largest tributary of the Yellow River, originates from the Niaoshu Mountain in Gansu

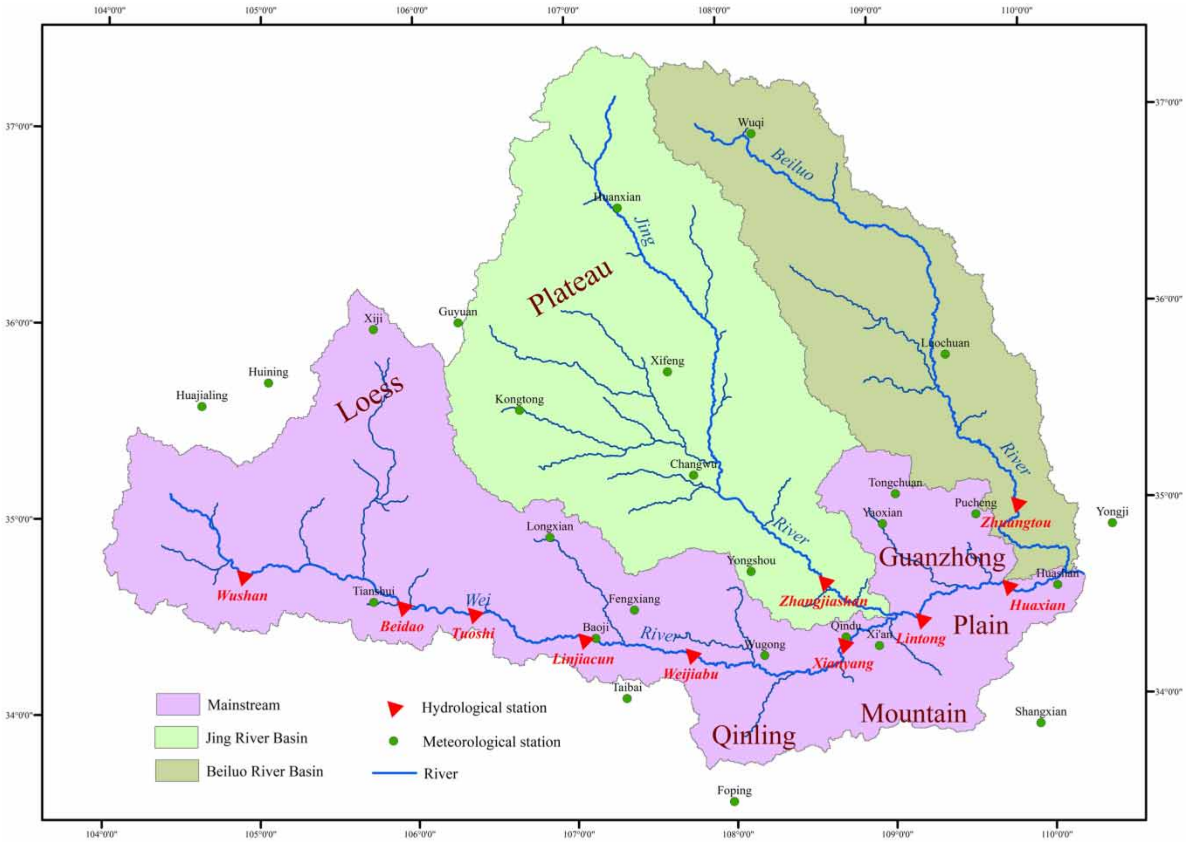

Figure 1 | Location of study area. The WRB can be divided into the Mainstream, the Jing River and the Beiluo River Basins.

Province, flows through the Ningxia and Shaanxi Provinces of China and runs into the Yellow River at Tongguan (Zuo *et al.* 2012). It is 818 km long and has a drainage area of 1.35×10^5 km^2, and annual runoff is 1×10^{11} m^3, which is about 20% of the annual runoff of the Yellow River (Huang *et al.* 2014). The Wei River also has numerous asymmetric tributaries on both sides. On the southern side, all tributaries stem from the Qinling Mountain and are short with rapid flow. These tributaries have abundant runoff and small amounts of sediment. The larger tributaries concentrate on the northern side of the Wei River and mainly originate from the Loess Plateau. These tributaries are long with a slight slope and have high amounts of sediment. The Jing River and Beiluo River are the largest and second-largest tributaries of the Wei River, respectively (Yu *et al.* 2016). The WRB lies in an arid to semi-arid area, with a mean air temperature of 6–14 °C, a mean annual precipitation of 450–700 mm and mean potential evapotranspiration of 800–1,100 mm (He *et al.* 2009). Total annual precipitation varies greatly from year to year, and most precipitation occurs between July and October.

Since ancient times, the WRB has been a settlement for human life and production, and now it has become a densely populated and highly developed area in Northwest China (Cheng *et al.* 2019). Population density in the WRB was 226/km^2, more than the average value of the whole of China (134/km^2) and Northwest China (52/km^2). Meanwhile, the WRB has long been an industrial and agricultural production base (Wu *et al.* 2012). The irrigated area in the WRB was 1.1×10^4 km^2, accounted for 80% of total cultivated area and mainly produced wheat, corn and cotton. The industries in the WRB were engaged in transportation equipment, aerospace, electronics processing and agricultural products. According to the *Statistics Yearbook* compiled by the National Bureau of Statistics of China, the Gross Domestic Product of the WRB in 2018 was USD 244 billion, accounting for about 30% in Northwest China.

Rapid economic development and population increase relied on massive water resources, but the deficient gross amount of water in the Wei River led to the contradiction between water supply and demand (Gu *et al.* 2019). According to the *Water Resources Bulletin* compiled by the Ministry of Water Resources of China, annual domestic water consumption in the WRB was about $4.8 \times 10^9\ m^3$, irrigation water consumption was about $2.4 \times 10^{10}\ m^3$ and industrial water consumption was about $4.8 \times 10^9\ m^3$, but available surface water of the WRB was only $3.2 \times 10^9\ m^3$ in 2018. For a long time, e-flow of the Wei River was difficult to protect because humans did not realize the importance of e-flow, and a series of ecosystem problems occurred, such as discontinuous flow in dry season, poor water quality and damaged ecological structure (Song *et al.* 2007).

Quantitative methods of economic value produced by e-flow

Water scarcity assessment

In general, water scarcity in a given area can be assessed on the basis of both water availability and consumption. The water yield modular of the InVEST model was developed by the Natural Capital Project (Sharp *et al.* 2017). It focuses on water availability and consumption simultaneously and reliably evaluates ecosystem services related to water resources (Redhead *et al.* 2016), applicable to this study.

Principle of the water yield modular. The water yield of the WRB is simulated using the water yield modular of the InVEST model, which is an estimation method that is simply based on a water balance. The main algorithm of the modular is cited from Sharp *et al.* (2017):

$$\mathrm{WY}(x) = (1 - \frac{\mathrm{AET}(x)}{P(x)}) \cdot P(x) \tag{1}$$

where AET(x) is annual actual evapotranspiration for pixel x and $P(x)$ is annual precipitation of pixel x.

(a) For the vegetated land-use and land-change (LULC) condition, the evapotranspiration portion of the water balance, $\frac{\mathrm{AET}(x)}{\mathrm{P}(x)}$, is based on the expression of the Budyko curve:

$$\frac{\mathrm{AET}(x)}{P(x)} = 1 + \frac{\mathrm{PET}(x)}{P(x)} - \left[1 + \left(\frac{\mathrm{PET}(x)}{P(x)}\right)^{\omega}\right]^{1/\omega} \tag{2}$$

where PET(x) is potential evapotranspiration and $\omega(x)$ is a non-physical parameter that characterizes natural climatic-soil properties detailed below.

$$\mathrm{PET}(x) = K_c(\mathrm{l}_x) \cdot \mathrm{ET}_0(x) \tag{3}$$

where $\mathrm{ET}_0(x)$ is the reference evapotranspiration from pixel x and $K_c(lx)$ is the plant (vegetation) evapotranspiration coefficient associated with the LULC lx on pixel x.

$$\omega(x) = Z\frac{\mathrm{AWC}(x)}{P(x)} + 1.25 \tag{4}$$

where AWC(x) is the volumetric (mm) plant available water content (PAWC) and Z is an empirical constant that captures local precipitation pattern and additional hydrogeological characteristics.

(b) For other LULC conditions (open water, urban and wetland), actual evapotranspiration is directly computed from reference evapotranspiration, $\mathrm{ET}_0(x)$, and has an upper limit defined by precipitation.

$$\mathrm{AET}(x) = \mathrm{Min}(K_c(l_c) \cdot \mathrm{ET}_0(x), P(x)) \tag{5}$$

The outputs of water yield in the model are summed on sub-basin scale, defined as WY_i.

Water scarcity assessment incorporating e-flow. We assess water scarcity that incorporates e-flow on sub-basin scale using the equation (Boithias *et al.* 2014):

$$\mathrm{WS}_i = \frac{\mathrm{WY}_i - \mathrm{EF}_i}{\mathrm{CW}_i} \tag{6}$$

where, for sub-basin i, WS_i is water scarcity assessment, WY_i is water yield, EF_i is flow and CW_i is consumptive water use.

According to research results for water scarcity indices that incorporate e-flow (Brown & Matlock 2011), $WS_i < 1$ represents a water scarcity sub-basin (human water use is tapping into e-flow), and $WS_i \geq 1$ represents a water surplus sub-basin (the available water before e-flow is in conflict with human use).

Economic value produced by e-flow

For a water scarcity sub-basin ($WS_i < 1$), giving priority to e-flow demand will influence the purpose of water resources and corresponding benefit is surrendered. We can estimate the economic value produced by e-flow by the opportunity cost of e-flow, which is the maximum benefit brought by different purposes of water use in this sub-basin i. For a water surplus sub-basin ($WS_i \geq 1$), the opportunity cost of e-flow is USD 0/m^3, and economic value produced by e-flow is also considered to be USD 0/m^3 in this method.

$$V_i = \begin{cases} B_i & WS_i < 1 \\ 0 & WS_i \geq 1 \end{cases} \tag{7}$$

where V_i is the economic value produced by e-flow in sub-basin i; and B_i is the maximum economic benefit brought by different purposes of water use in sub-basin i.

Impact analysis

We estimate the impact of climate factor and land-use factor on the economic value produced by e-flow by Equation (8) and (9), respectively.

$$I_C = \frac{|\overline{\Delta_C}|}{|\overline{\Delta_C}| + |\overline{\Delta_L}|} \times 100\% \tag{8}$$

$$I_L = \frac{|\overline{\Delta_L}|}{|\overline{\Delta_C}| + |\overline{\Delta_L}|} \times 100\% \tag{9}$$

where I_C and I_L are the impact percentage of climate factor and land-use factor on the economic value produced by e-flow, respectively. $|\overline{\Delta_C}|$ and $|\overline{\Delta_L}|$ are absolute average change economic value produced by e-flow affected by climate factor and land-use factor, respectively.

Data source

Scenarios set

As shown in Figure 1, there are 26 meteorological stations in the WRB. Precipitation data collected by these stations from 1980 to 2015 were provided by the National Meteorological Information Center of China. We obtained annual precipitation in the WRB from 1980 to 2015 through arithmetic average method and chose 1992 as a wet year ($P = 25\%$), 1989 as a normal year ($P = 50\%$) and 2004 as a dry year ($P = 75\%$) based on precipitation frequency analysis.

According to the selection of typical years, we set six scenarios to study economic value produced by e-flow of the WRB and its variation under the influence of different climate and land uses. The scenarios were shown in Table 1.

Input maps

The input maps for the water yield modular of the InVEST model were precipitation, reference evapotranspiration (ET_0), LULC, depth-to-root restricting layer, PAWC and sub-basin definition. The raster maps were 1,000 m × 1,000 m data.

Precipitation. Based on annual precipitation data of 26 meteorological stations in the WRB in the wet year (1992), normal year (1989) and dry year (2004), we can obtain precipitation isograms of the WRB in the typical years using the Kriging interpolation method (Figure 2).

ET_0. We calculated ET_0 values for the WRB in the wet year (1992), normal year (1989) and dry year (2004) by the Penman–Monteith method using data provided by the National Meteorological Information Center of China. Then we obtained ET_0 isograms of the WRB in the typical years using the Kriging interpolation method (Figure 3).

The mainly climatic elements of the water yield modular of the InVEST model contain precipitation and

Table 1 | Different climate and LULC scenarios

Scenarios	I	II	III	IV	V	VI
Climate	Wet	Normal	Dry	Wet	Normal	Dry
LULC	1980	1980	1980	2015	2015	2015

Figure 2 | Annual precipitation in wet, normal and dry years obtained through the Kriging interpolation method and based on precipitation data from 26 meteorological stations. Precipitation data were provided by the National Meteorological Information Center of China.

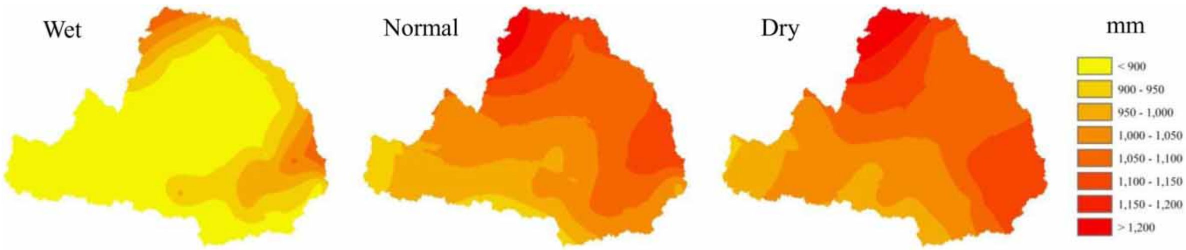

Figure 3 | Annual reference evapotranspiration in wet, normal and dry years. They were obtained through the Kriging interpolation method according to calculation results of the Penman–Monteith method, using data from 26 meteorological stations. All data used in these calculations were provided by the National Meteorological Information Center of China.

evapotranspiration. As shown in Figures 2 and 3, in the WRB, average annual precipitation was 564 mm in wet years, 518 mm in normal years and 468 mm in dry years. Average annual ET_0 was 919 mm in wet years, 1,052 mm in normal years and 1,073 mm in dry years. Moreover, precipitation decreased from south to north, but ET_0 increased from south to north, and there were evident differences between south and north. For example, in dry year, the precipitation in the Loess Plateaus cannot reach 300 mm, but ET_0 was up to 1,200 mm.

LULC. We selected land-use data of the WRB between 1980 and 2015 for this study. They were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences, which used Landsat TM/ETM remote sensing images during this period and performed artificial visual interpretation of the data sources. The land-use data of the WRB reclassified six land-use types using ArcGis 10.4 (Figure 4): (a) cropland, including paddy field and dry land; (b) woodland, including forest land, shrubbery land and sparse woodlot; (c) grassland,

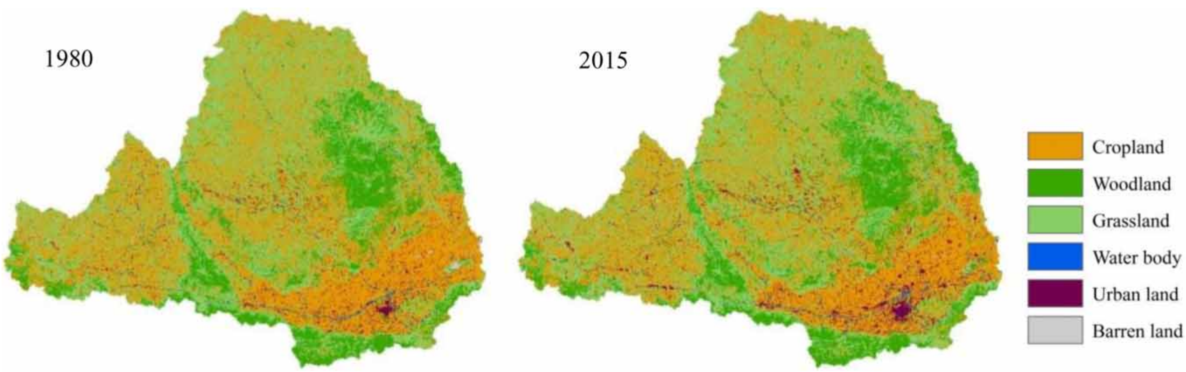

Figure 4 | Land-use and land cover maps of the WRB between 1980 and 2015. Land-use types included cropland, woodland, grassland, water body, urban land and barren land.

including different coverage types; (d) water body, including rivers, lakes and wetlands; (e) urban land, including industrial and residential areas and (f) barren land, including gravel, bare ground and bare rocks (Yu *et al.* 2016).

Between 1980 and 2015, the main land-use types in the WRB were cropland, grassland and woodland, which in total occupied 95% of the entire area of the WRB, and change rates of these land-use types were all less than 5%. Meanwhile, the area of woodland, water body and urban land increased, and the largest increase was seen for urban land, which was 47%. The area of cropland, grassland and barren land decreased, and the largest decrease of 11% was seen for barren land. The largest decreased area was cropland, about 1,909 km^2, which was closely related to the national policy 'Conversion of Cropland to Forest and Grassland' in China.

Depth-to-root restricting layer, PAWC and sub-basin definition. The depth-to-root restricting layer was replaced with the soil depth in this study due to data limitation, and the soil depth map and the PAWC map in the WRB were provided by the Cold and Arid Regions Sciences Data Center at Lanzhou, using the Harmonized World Soil Database version 1.1 established by the Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis as data sources. Meanwhile, we set the threshold of the water catchment area as 400 km^2 and defined 211 sub-basins in the WRB using the Digital Elevation Model under ArcGIS 10.4.

Initial parameters

The input parameters in the water yield modular include K_c, root depth and Z. K_c is used to correct ET_0 to obtain evapotranspiration, between 0 and 1.5 according to the recommendations from FAO. Root depth is adopted as the standard crop coefficient. Z is a constant, between 1 and 30, and it needs to determine by comparing simulated data with the measured data of water yield. Because in existing research, Z value of the WRB was 6 (Wu *et al.* 2018), we set initial Z as 5–7. Initial parameters of the water yield modular were shown in Table 2.

EF_i

Several Chinese researchers have calculated e-flow values of the Wei River using various methods, such as Tennant, wetted perimeter, R2CROSS, etc., and recommended proper e-flow values: 4–6 m^3/s at Linjiacun station, 6–10 m^3/s at Weijiabu station, 8–12 m^3/s at Xianyang station, 12–18 m^3/s at Lintong station and 16–20 m^3/s at Huaxian station (Pang *et al.* 2012). According to these research achievements and relevant regulations of the Yellow River Conservancy Commission, the existing e-flow values of Wei River were: 5 m^3/s at Linjiacun station, 6 m^3/s at Weijiabu station, 8 m^3/s at Xianyang station, 12 m^3/s at Weijiabu station and 20 m^3/s at Huaxian station.

Based on these data, we can obtain the annual amount of e-flow at each hydrological station. We assumed it spread evenly across each pixel x of all the upstream sub-basins (Boithias *et al.* 2014) and calculated $EF(x)$ according to annual amount of e-flow and pixel number. For simply calculation, $EF(x)$ was 6,000 m^3 for each pixel in the WRB, and pixel size was 1,000 m × 1,000 m. EF_i was the sum of $EF(x)$ in sub-basin i.

CW_i

Consumptive water use in the water yield modular refers to the water diverted and depleted from natural freshwater ecosystems for anthropic use and is distinguished from the many instream freshwater ecosystem services provided to humans and those used for biodiversity conservation

Table 2 | Initial parameters of the water yield modular

LULC	Cropland	Woodland	Grassland	Water body	Urban land	Barren land
K_c	0.5–0.7	0.85–1	0.65–0.85	1	0.3–0.5	0
Root depth (mm)	300–2,000	1,000–3,000	1,000–2,000	1–1,000	1–500	10
Z	5–7					

(Sharp et al. 2017). Hence, consumptive water use can be assumed to be the water removed from the watershed water balance for each LULC and mainly includes irrigation water, industrial water and domestic water (Boithias et al. 2014).

Consumptive water-use input in the water yield modular is the average water consumption per year for a pixel in each land-use type. In this study, we used a simple method to estimate consumptive water use for each land-use type in the WRB. (1) We obtained annual consumption of irrigation water, industrial water and domestic water in the WRB from the *Water Resources Bulletin* compiled by the Ministry of Water Resources of China. (2) We let irrigation water correspond to consumptive water use in cropland, and industrial water and domestic water correspond to consumptive water use in urban land. And we supposed consumptive water use in the other land-use types was $0\,m^3$. (3) We assumed CW (x) was spread evenly across land-use types, so we can obtain CW (x) according to annual consumptive water use and pixel number in each land-use type. Then CW (x) in cropland was $4\times10^4\,m^3$ in wet years, $5\times10^4\,m^3$ in normal years and $6\times10^4\,m^3$ in dry years. CW (x) in urban land was $1.5\times10^5\,m^3$ in the typical years. CW (x) in the other land-use types was $0\,m^3$. The pixel size was $1{,}000\,m\times1{,}000\,m$. (4) CW_i is the sum of CW (x) in sub-basin i.

B_i

The benefits brought by water resources differ according to land-use types. In this study, we used a simple method to estimate the maximum economic benefit of water resources in each sub-basin of the WRB. (1) Based on the research achievements of Cheng (2017), the benefits of agricultural water and industrial water in the WRB were USD $0.71/m^3$ and USD $2.52/m^3$, respectively. For the purposes of simplifying calculation, we considered these two values as the benefit brought by water resources in cropland and urban land, respectively. The social benefits brought by water resources in urban land, such as supporting human life, were not considered in this study. (2) Based on the study of Geng (2005), the defined benefits brought by woodland and grassland water resources were USD $0.62/m^3$ and USD $0.57/m^3$, respectively. (3) The benefits brought by water resources in other land-use types were USD $0/m^3$. (4) B_i was represented by the benefits brought by water resources in the majority of land-use types in sub-basin i.

Model calibration and validation

Methods of model calibration and validation

We chose Nash–Sutcliffe Efficiency coefficient (NSE), relative error (RE) and determination coefficient (R^2) as indicators of model calibration and validation.

NSE. The equation for NSE is:

$$\mathrm{NSE}_j = 1 - \frac{\sum(\mathrm{MR}_j - \mathrm{SR}_j)^2}{\sum(\mathrm{MR}_j - \overline{\mathrm{MR}}_j)^2} \tag{10}$$

where NSE_j is the Nash–Sutcliffe efficiency coefficient, MR_j is the measured annual runoff, SR_j is the simulated annual runoff and j is year.

The variation range of NSE is $-\infty$ to 1. The closer NSE is to 1, the better the hydrological model simulation. Typically, a $\mathrm{NSE} > 0.5$ indicates that the model effectively simulates the hydrological process of the river basin.

RE. The equation of RE is:

$$\mathrm{RE}_j = \frac{\mathrm{MR}_j - \mathrm{SR}_j}{\mathrm{MR}_j} \times 100\% \tag{11}$$

where RE_j is the relative error.

A positive RE_j value indicates simulation values were greater than measured values, whereas a negative RE_j value showed that simulation values were less than measured values; if the RE_j value was 0, the simulation was equal to the measurement. Long-term average RE value in the model validation should be lower than $\pm20\%$.

R^2. The equation for the correlation coefficient is:

$$r = \frac{\sum(\mathrm{MR}_j - \overline{\mathrm{MR}}_j)(\mathrm{SR}_j - \overline{\mathrm{SR}}_j)}{\sqrt{\sum(\mathrm{MR}_j - \overline{\mathrm{MR}}_j)^2(\mathrm{SR}_j - \overline{\mathrm{SR}}_j)^2}} \tag{12}$$

where r is the correlation coefficient.

R^2 is the square of the correlation coefficient. The closer R^2 is to 1, the better fit the model.

Results of model calibration and validation

Model calibration. Based on precipitation and ET_0 data in the WRB from 1980 to 2000, we can obtain the simulation annual water yield at Huaxian station from 1980 to 2000. Then we adjusted the parameters and calibrated the water yield modular by comparing simulated data with measured data from 1980 to 2000. The measured data at Huaxian station were from the *Annual Hydrological Report* compiled by the Ministry of Water Resources of China. The indicators in calibration period were: NSE = 0.82, RE = 8.57% and $R^2 = 0.90$ (Figure 5(a)), which illustrated simulation results basically consistent with measurement.

Model validation. We input precipitation and ET_0 data in the WRB from 2001 to 2015 into the calibrated water yield modular, and got the simulation annual water yield at Huaxian station from 2001 to 2015. We validated the water yield modular by comparing simulated data with measured data from 2001 to 2015. The indicators in the validation period were: NSE = 0.63, RE = −4.01% and $R^2 = 0.82$ (Figure 5(b)), meeting the requirements, which indicated that the water yield modular of the InVEST model was appropriate for the WRB.

Final parameters of the water yield modular were shown in Table 3.

RESULTS AND DISCUSSION

Water scarcity in the WRB

We input the above data into the calibrated water yield modular of the InVEST model and processed model outputs under ArcGis 10.4 to obtain water scarcity assessment of the WRB under different scenarios (Figure 6). $WS_i < 1$ represents a water scarcity sub-basin, and the smaller the value for WS_i, the more serious the water scarcity in sub-basin *i*. $WS_i \geq 1$ represents a water surplus sub-basin.

Water scarcity in the WRB was mainly concentrated in two areas but for different reasons: (1) The Loess Plateau is located in the northwest of the WRB and the lower water yield was caused by low rainfall with robust evapotranspiration. (2) The Guanzhong Plain is an alluvial plain that is downstream of the Wei River and is one of the most densely populated and highly developed areas in Northwest China

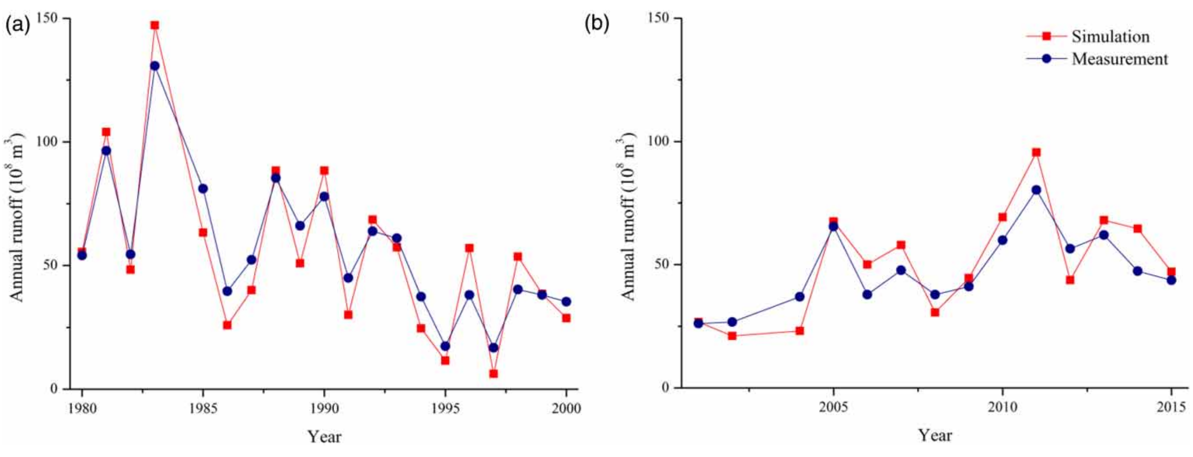

Figure 5 | Comparison of simulated annual runoff and annual runoff measured at Huaxian station in calibration period and validation period. (a) Calibration period (b) Validation period.

Table 3 | Final parameters of the water yield modular

LULC	Cropland	Woodland	Grassland	Water body	Urban land	Barren land
K_c	0.6	1	0.85	1	0.3	0
Root depth (mm)	2,000	3,000	2,000	500	500	10
Z	6.2					

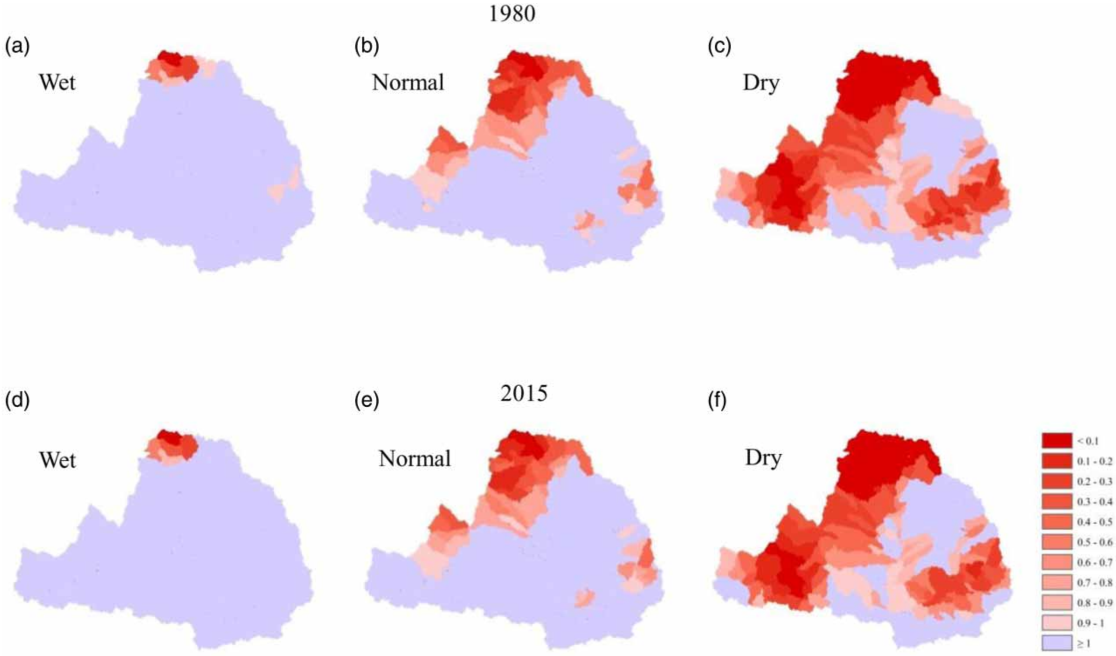

Figure 6 | WS_i maps of the WRB under different scenarios. Assessment results were on the sub-basin scale. (a) Scenario I. (b) Scenario II. (c) Scenario III. (d) Scenario IV. (e) Scenario V. (f) Scenario VI.

due its smooth terrain and fertile soil. This region has large areas of irrigated cropland and urban agglomeration, which together increase the amount of consumptive water use.

We analyzed the influence of climate factor on water scarcity. In wet years (Scenario I and Scenario IV), most sub-basins can meet the requirement of e-flow and human water use simultaneously except for some sub-basins in the north of Jing River Basin. In normal years (Scenario II and Scenario V), the number of water scarcity sub-basins increased, and there also appeared water scarcity sub-basins in the Guanzhong Plain, which indicated that water scarcity deteriorated in the whole WRB. Water scarcity in dry years (Scenario III and Scenario VI) was more serious than wet and normal years, and $WS_i \geq 1$ only appeared in sub-basins dominated by land-use types of woodland and grassland.

We discussed the impact of land-use factor on water scarcity. For one, water scarcity in the sub-basins affected by human activities was more serious than little interference sub-basins. For example, the Guanzhong Plain belonged to a water scarcity area, because it consisted of the sub-basins mainly including cropland and urban land. Conversely, the majority of land-use types in sub-basins of the Qinling Mountain were woodland and grassland, and there was no water scarcity in the typical years. For another, water scarcity in the WRB under LULC in 2015 (Scenario IV, Scenario V and Scenario VI) was better than LULC in 1980 (Scenario I, Scenario II and Scenario III). This may be related to the decreased area of cropland in the WRB, which was about 1,909 km^2 between 1980 and 2015. The decreased cropland led to reduced consumptive water use in the WRB and then ameliorated water scarcity in the WRB.

Actually, according to water balance, water scarcity was the synthetic result of climate factor and land-use factor. (1) Climate factor: precipitation and evaporation were the main forms, wherein reduced precipitation and increased ET_0 during dry years caused a sharp decrease in water yield. This was the reason that water scarcity was more serious in dry years than wet and normal years. (2) Land-use factor: changes in underlying surface affected water cycle and in turn water yield, and the close relationship between consumptive water use and land-use patterns, such that irrigated agricultural land and urban land were more vulnerable to water scarcity. Therefore, water scarcity in areas disturbed by human activities was more severe than in areas that had less human interference.

Economic values produced by e-flow in the WRB

Using the results for water scarcity, based on B_i, we can obtain distribution and variation of economic values produced by e-flow through Equation (7). Water scarcity assessment related to a sub-basin scale. As such, economic values produced by e-flow were unit price on sub-basin scale (Figure 7).

The high economic values area and area of serious water scarcity, which included the Loess Plateau and the Guanzhong Plain, essentially overlapped, and the area of high economic values expanded as water scarcity was aggravated. In wet years, the majority of water surplus sub-basins ($WS_i \geq 1$) gave most sub-basins an economic value produced by e-flow of USD 0/m^3. This was because scarcity was a prerequisite for opportunity cost. If there was no water scarcity in sub-basin, e-flow could be guaranteed, opportunity cost of e-flow was USD 0/m^3 and economic value produced by e-flow was also considered to be USD 0/m^3 in this method. With the aggravation of water scarcity, the number of sub-basins with economic values produced by e-flow higher than USD 0/m^3 clearly increased, which implied climate factor can obviously affect economic values produced by e-flow. The higher economic values produced by e-flow (>USD 0/m^3) were seen for sub-basins that contained a high percentage of urban land and cropland, had severe water scarcity and higher benefit of water resources. Whereas the economic values produced by e-flow in woodland and grassland sub-basins were nearly USD 0/m^3 due to a water surplus.

Through statistically analyzing the sub-basins data in Figure 7, the unit economic values produced by e-flow in the whole WRB under different scenarios were shown in Table 4.

Economic values produced by e-flow under different scenarios were USD 0.02–0.48/m^3. For climate factor, economic values produced by e-flow in dry year were higher than wet and average year. For land-use factor, whole economic values produced by e-flow under LULC in 2015 were slightly lower than 1980.

The impact of climate factor and land-use factor on economic values produced by e-flow can be assessed through Equations (8) and (9). According to Table 4, the absolute average change value of economic values produced by e-flow affected by climate factor $|\overline{\Delta_C}|$ was USD 0.23/m^3, and the absolute average change value of economic values produced by e-flow affected by land-use factor $|\overline{\Delta_L}|$ was USD 0.01/m^3. Therefore, the impact percentage of climate

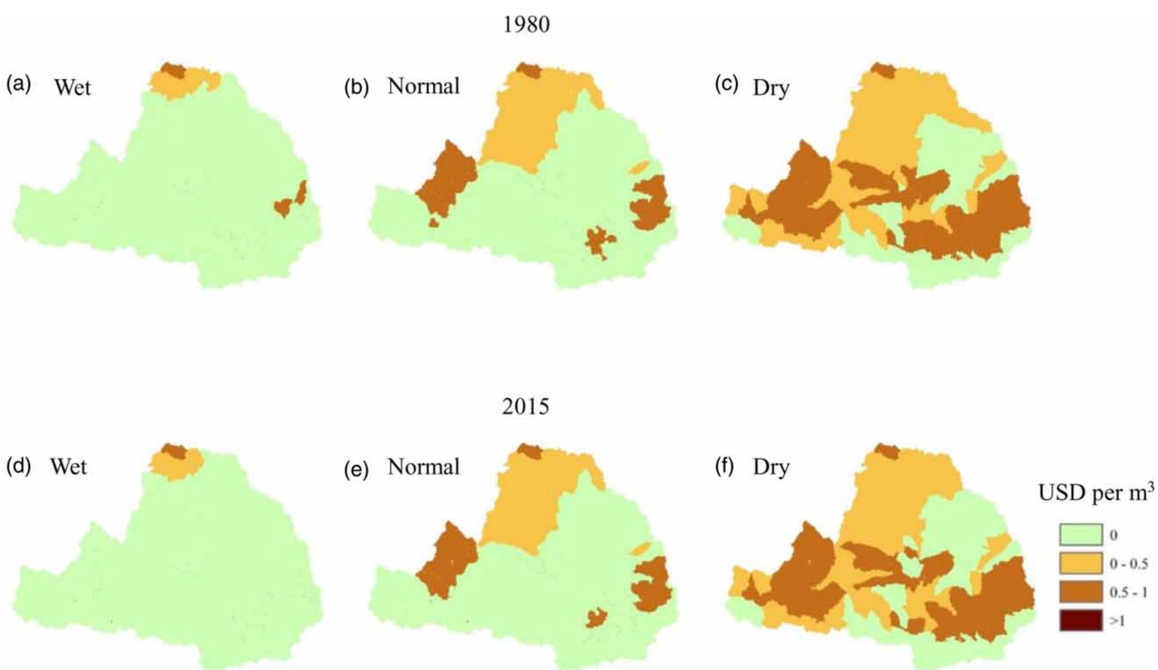

Figure 7 | Economic values produced by e-flow in the WRB under different scenarios. Estimated results were on sub-basin scale. (a) Scenario I, (b) Scenario II, (c) Scenario III, (d) Scenario IV, (e) Scenario V, (f) Scenario VI.

Table 4 | Economic values produced by e-flow in the whole WRB under different scenarios

Scenarios	I (Wet, 1980)	II (Normal, 1980)	III (Dry, 1980)	IV (Wet, 2015)	V (Normal, 2015)	VI (Dry, 2015)
Economic values produced by e-flow	0.03	0.20	0.48	0.02	0.19	0.46

The unit is USD/m^3.

factor I_C was 95.83%, and land-use factor I_L was 4.17%. It was obviously that climate factor had a remarkable influence on economic values produced by e-flow.

Discussions

Method characteristics and rationality analysis

Economic value produced by e-flow is a novel direction for e-flow research in recent years, and quantitative calculation methods are currently in the exploration stage. Compared to the relatively complete calculation system for e-flow, there were only a few methods to estimate economic value produced by e-flow, such as contingent value method, production loss method, hydro-ecological response method and ecosystem service valuation method. These methods had their own characteristics. The contingent value method (Ojeda *et al.* 2008) was a nonmarket valuation technique, and its reliability was more open to be queried due to deviation of the method itself. The production loss method (Sisto 2009) was mainly used to calculate economic compensation needed to protect e-flow and was not a direct method to estimate economic value produced by e-flow. The hydro-ecological response method (Akter *et al.* 2014) integrated hydro-ecological response model outputs and nonmarket economic values to estimate a unit price for e-flow but may not be suitable for all areas, particularly those that lack hydro-ecological response data. The challenge for the ecosystem service valuation method was the selection of appropriate parameters for a given study area (Yue *et al.* 2018).

In this study, we adopted a relatively simple method to study the variation of economic value produced by e-flow in water-scarce basins. We used the method of water scarcity assessment incorporating e-flow to evaluate water scarcity on sub-basin scale and combined the water scarcity results and opportunity cost approach to obtain economic value produced by e-flow on the sub-basin scale. Compared to the methods mentioned above, this process was simple, with less input data, and yielded results that can be displayed unit economic values produced by e-flow in form of maps. The output results of this method reflected distribution and variation of economic values produced by e-flow more directly and revealed critical areas of economic values produced by e-flow, as well as providing the impact of climate factor and land-use factor on economic values produced by e-flow using scenario analysis.

We applied this method to the WRB, which is the typical water-scarce basin in Northwest China. Economic values produced by e-flow in the WRB were USD 0.02–0.48/m^3 through the study, which were lower than residential water price in the WRB (USD 0.82/m^3). It was reasonable in terms of residents' ability to afford economic values produced by e-flow and prepare for future e-flow eco-compensation. The results were also relatively close to the benefit per unit discharge of ecological base flow in the Wei River obtained by Yue *et al.* (2018), which were USD 0.19–0.87/m^3, so it can be assumed that the results of this method were basically rational.

Limitations

However, the opportunity cost is not equal to economic value. We estimated economic values produced by e-flow simply by means of the opportunity cost approach, but the method does have some limitations.

First, if water resources can simultaneously satisfy requirements for human use and e-flow, opportunity cost of e-flow was USD 0 per m^3. In this study, the economic value produced by e-flow was also assumed to be USD 0/m^3 for simplicity. However, e-flow may still have significant potential value for various purposes, such as recharging groundwater, transporting sediment and fertilizing inundated areas. These values are not dependent on alternative uses and not considered in this study. Therefore, economic value produced by e-flow assessed by the opportunity cost approach is relatively low.

Second, we estimated water scarcity and economic value produced by e-flow on sub-basin scale and assumed that if $WS_i < 1$, water scarcity existed, and the opportunity cost of e-flow was the maximum loss caused by a reduction in the water available for other purposes. In fact, water scarcity in one sub-basin was often supplemented by water surplus in another sub-basin by means of water diversion. It therefore follows that water scarcity in an entire basin may not exist, and an overall opportunity cost would not exist. These more complicated situations were not considered in this study and required further study.

CONCLUSIONS

When available water is scarce, giving priority to e-flow inevitably influences human water-use requirements. In such cases, economic value produced by e-flow can be estimated by opportunity cost, which is considered to be the benefit brought by the next-best use of water resources. With the guidance of this view, we combined water scarcity assessment outputs and opportunity cost to estimate economic value produced by e-flow, which we displayed in the form of maps that more directly reflected distribution and variation of economic value produced by e-flow.

Using the WRB in Northwest China as a case study, we tested the feasibility of this method. Our results showed that: (1) The high economic value area and areas having serious water scarcity essentially overlapped and included the Loess Plateaus and the Guanzhong Plain; (2) Economic values produced by e-flow in the WRB were USD 0.02–0.48/m^3; (3) The high economic value produced by e-flow was commonly seen in the sub-basins that had cropland and urban land and (4) Climate factor had an even greater influence on the economic value produced by e-flow than land-use factor.

This study provides a simple and effective approach to present considerable economic value produced by e-flow in monetary terms and simplifies the search for ways to balance human water use and e-flow using economic leverage. However, given the limitation of opportunity cost approach used in this study, additional work was needed to study further.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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