A collaborated framework to improve hydrologic ecosystem services management with sparse data in a semi-arid basin

Yifan Wu, Yang Xu, Guodong Yin, Xuan Zhang, Chong Li, Liyu Wu, Xiao Wang, Qiuhong Hu and Fanghua Hao

ABSTRACT

Applying various models to assess hydrologic ecosystem services (HESs) management has the potential to encourage efficient water resources allocation. However, can a single model designed on these principles be practical to carry out hydrologic ecosystem services management for all purposes? We address this question by fully discussing the advantages of the variable infiltration capacity (VIC) model, the soil and water assessment tool (SWAT), and the integrated valuation of ecosystem services and tradeoffs (InVEST) model. The analysis is carried both qualitatively and quantitatively at the Yixunhe River basin, China, with a semi-arid climate. After integrating the advantages of each model, a collaborated framework and model selection method have been proposed and validated for optimizing the HESs management at the data sparse scenario. Our study also reveals that the VIC and SWAT model presents the better runoff reproducing ability of the hydrological cycle. Though the InVEST model has less accuracy in runoff simulation, the interannual change rate is similar to the other two models. Furthermore, the InVEST model (1.08 billion m^3) has larger simulation result than the SWAT model (0.86 billion m^3) for the water yield, while both models have close results for assessment of sediment losses.

Key words | collaborated framework, hydrologic ecosystem services, InVEST, semi-arid area, SWAT, VIC

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HIGHLIGHTS

- A collaborated framework for improving HESs management has been validated.
- VIC model has better runoff reproducing results at semi-arid area.
- Vegetation module may show the difference in the water yield estimation between SWAT and InVEST.

INTRODUCTION

Ecosystem services have been defined as the benefits that humans derive from ecosystem communities that are formed by living and nonliving organisms that maintain the Earth's life support systems (Millennium Ecosystem Assessment (MA) 2005). As the irreplaceability of water for lives and organisms has been recognized, hydrologic ecosystem services (HESs) have received more attention among the various ecosystem services and have become a

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significant driver to address environmental crises, improve human well-being and achieve sustainability goals (Bai et al. 2019). HESs are a series of services that can be categorized into five classifications: improvement of extractive water supply, improvement of water supply, water damage mitigation, provision of water-related cultural services and water-associated supporting services (Brauman et al. 2007).

Models designed for quantifying and mapping the benefits and losses of HESs affected by socioeconomic regulation have been widely requested as a preconditional approach when measures have been implemented (Maes et al. 2012). Hydrologic models, such as the variable infiltration capacity (VIC model), the soil and water assessment tool (SWAT model), and ecosystem services models, including the integrated valuation of ecosystem services and tradeoffs (InVEST model), the resource investment optimization system model (RIOS model) and the artificial intelligence for ecosystem services (ARIES model), are promoted as solutions for watershed decision making (Liang et al. 1994; Arnold et al. 1998; Lüke & Hack 2018). To address the distinct features of different models, research has begun comparing different HESs results that have been quantified and visualized by assorted models. The InVEST, RIOS and SWAT models have been discussed qualitatively with regard to their practical applicability in managing HESs (Lüke & Hack 2018), while the InVEST, SWAT, VIC and ARIES models have been compared by their requirements about the data gaps (Vigerstol & Aukema 2011). To quantitatively test the utility among different models, Dennedy-Frank, who conducted a comparison between the SWAT and InVEST models at the annual scale, found that the amount of baseflow would be one of the reasons for the mismatch between these two models (Gassman et al. 2007; Dennedy-Frank et al. 2016). In general, most of the studies insist on the qualitative analysis of models' theoretical conceptualization, and prove that these models are capable of integrating local environmental protection and economic development in a manner which is efficient for making trade-offs in HESs management (Wainger et al. 2010). However, quantitative analysis between different models are still lacking.

When conducting the HESs management, the model specification, including data requirement, learning effort and simulation unit, would be crucial for practical applications and decision making. Addressing the advantages of different models would help users to utilize the limited available data to capture the maximum benefits of HESs. Commonly, compared with the relatively small watershed suitability for the SWAT model (Qiao et al. 2015), the macro-calculation grids (1–50 km) of the VIC model could help rebuilding the hydrological cycle at territorial or national scale (Zhang et al. 2014), whereas the grids scale of the VIC model may not be flexible enough for interpreting the details in each administration unit, including watersheds, cities or provinces. Benefit from the calculation unit at pixel scales (30 m–10 km), the InVEST model is well prepared to carry out practical measures for local policy makers (Gao et al. 2017), though the algorithm may not be sufficiently scientific for reproducing the hydrologic cycle as the VIC and SWAT model (Vigerstol & Aukema 2011). Therefore, one single model cannot overcome all these inadequacies. Whether it is possible to develop a collaborated framework based on utilizing the features of each models to promote better HESs management has not been fully discussed through former studies.

Not only the characteristics of each model could affect the HESs management, but the demand for varied users would also be another critical factor. For example, scientists focus on the mechanism of hydrologic and ecological processes and how to optimize simulation accuracy to reveal more general natural principles (Gao et al. 2017; Hao et al. 2017). However, managers, including policymakers, stakeholders and engineers, are concerned that the model needs to be simply handled with clear results that would ultimately provide more intuitive choices for decision-making processes (Bagstad et al. 2013). Therefore, a practical model selection approach, which take the gaps in theoretical, data, scale and learning effort into consideration, would be meaningful for different users to choose HES models with their unique purpose.

The objective of this study is to propose and certify the applicability for a collaborated framework, which is composed of two hydrologic models (VIC and SWAT models) and one ecosystem model (InVEST model). A typical semi-arid catchment, the Yixunhe river basin in northern China, was selected as the study area. This study can be simply analyzed in two parts. The first part is to fully discuss the characteristics of each model both qualitatively and quantitatively. The second part is to use three scenarios to detect whether our proposed collaborated framework based on the characteristics of these models could improve the HESs management efficiency when data is lacking. It is noteworthy that water yield and sediment losses have been identified as two investigated HESs in our study.

STUDY AREA AND DATA

Study area

The Yixunhe River basin (YRB) is located in northeast Beijing, China (117°05′E–118°35′E, 39°40′N–42°25′N) with a typical semi-arid climate (Figure 1). YRB is the largest sub-watershed of the Luanhe River basin, a critical ecological conservation watershed of the Beijing metropolitan area. The YRB covers a total area of 6,750 km^2, and its elevation fluctuates from 364 to 1,806 m. The annual average temperature in the YRB ranges from 4.7 to 7.0 °C. The precipitation is extremely seasonal with heavy and frequent rain in summer, and cold and dry conditions in winter. The annual precipitation is approximately 440–570 mm, in which most rainfall occurs from June to September, and the dry seasons extend from November to March. The temperature and precipitation are both lower in the hilly northern part than in the plain southern part. The average runoff coefficient is less than 0.1, and the annual runoff volume is 0.25 billion m^3 (Li *et al.* 2014).

Data source

The vegetation distribution map with a 1,000 m resolution was downloaded from the China subset (http://westdc.westgis.ac.cn) of global land use/land cover maps based on the AVHRR dataset produced by the University of Maryland. Meteorological data, such as precipitation, temperature and wind from 1960 to 1980, was provided by the National Meteorological Administration of China (http://data.cma.cn). The solar energy data was obtained from NASA

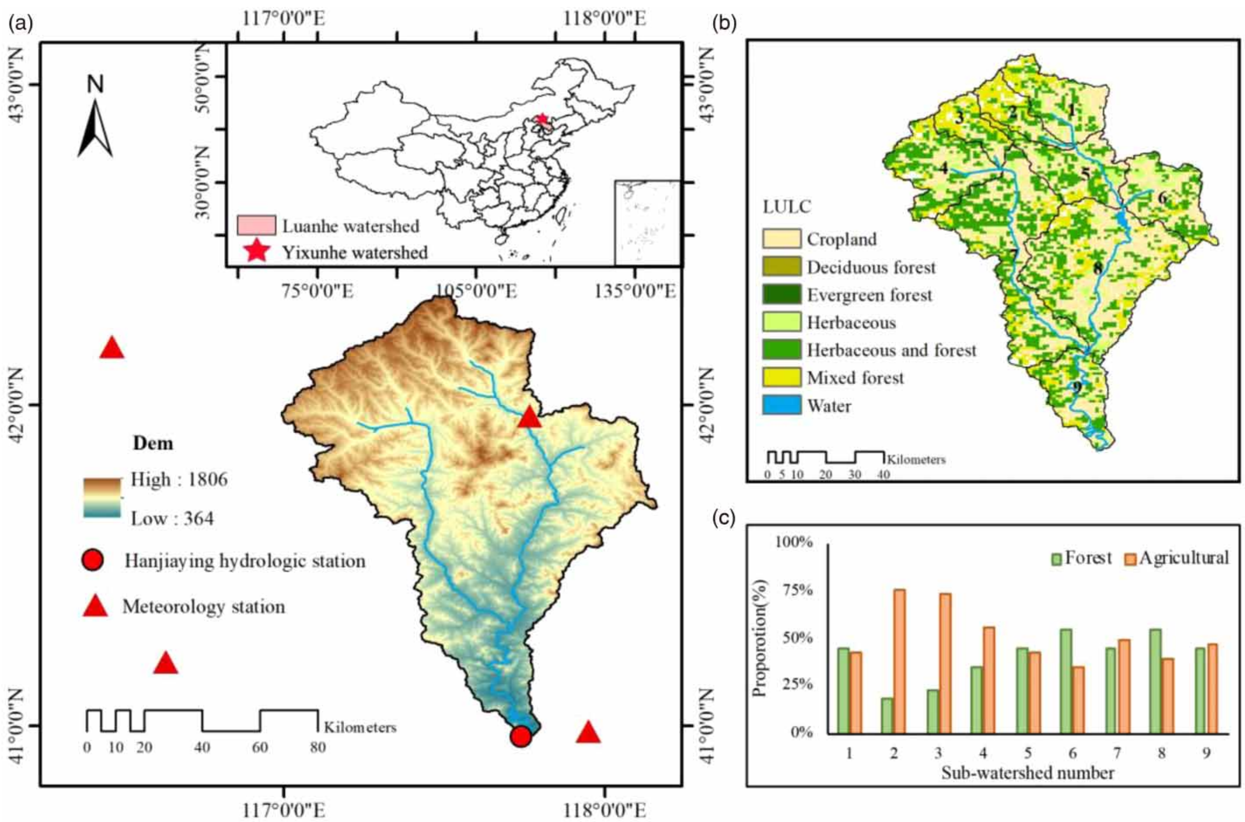

Figure 1 | Location of the Yixunhe River basin (a), vegetation map in 1980 (b) and vegetation proportion (c).

Prediction of Worldwide Energy Resources (https://power.larc.nasa.gov/). DEM data with a spatial resolution of 90 m was downloaded from the Resource and Environment Data Cloud Platform of China (http://www.resdc.cn/). Soil data, including soil types and root depth, was obtained from the China Soil Map Based Harmonized World Soil Database provided by the Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn). The runoff and sediment data sequences were obtained from Hanjiaying hydrologic station.

Data treatment

To minimize the system errors within these models, the same input data and interpolate methods were applied for the data pre-treatment. For all three models, the ET_0 (potential evapotranspiration) was calculated by the Penman–Monteith approach (Beven 1979), using the climatic data sets of meteorological station. Then, all the climatic datasets, including precipitation temperature and ET_0 were interpolated by the IDW (Inverse Distance Weighted) method. Note that all the interpolated meteorological data, DEM and vegetation map have been reclassified as $1{,}000 \times 1{,}000$ m resolution. The sub-watershed vector file, which was required by the SWAT and InVEST model, was conducted by the delineator module of the SWAT model. Different from the VIC and SWAT model, the InVEST model embedded the water yield module instead of the runoff module (Sharp *et al.* 2016). In order to calculate runoff based on the water yield (water retention, runoff and groundwater) (Supplementary Material, Equation (9)), the annual average runoff coefficient has been used to help calibrate the simulated runoff values with the observed data (Li *et al.* 2014). The model calibration and validation are shown in the section 'Model performance' and the well-selected parameters for the VIC, SWAT and InVEST are presented in the Supplementary information.

METHODS

Model description

In this section, the main object is to address whether the proposed collaborated framework could improve the HESs management efficiency in YRB. To achieve this target, the VIC, SWAT and InVEST models are estimated qualitatively and quantitatively to address the characteristics and applicability. The qualitative estimation focuses on the adaptability of the different models, such as the data requirement, learning efforts, the scale for the output results, etc. The quantitative estimation is the major focus on the model simulation process and results interpretation. It should be noted that in our research, whether the estimation provided by these models is accurate enough to make a good decision has not been specified as the major evaluation standard. Our study pays more attention to whether these models can be well applied to handle and improve HESs assessment under data deficient scenarios. The specific introduction relating to these three models is presented in the introduction section of the supplementary information.

Data requirement

Table 1 provides an overview comparison of three models, which has been retrieved from the model introductions. It is necessary to clarify the temporal and spatial scales for the requirements of the input data before starting the assessment of the adaptation for conducting HESs management (Cong *et al.* 2020). The InVEST model has relatively low requirements for input data and does not require a high level of expertise for preprocessing. In contrast, the VIC and SWAT models require more detailed input data, including daily precipitation, daily temperature and snow melting information. The VIC and SWAT models can provide daily runoff estimation in grid and sub-watershed scales, respectively, while the InVEST model can present the annual water yields at the pixel and sub-watershed scales.

Scenarios analysis

We selected 1960–1980 as our study period. It is acknowledged that human activities, including urbanization, irrigation methods and the construction of water reservoirs, were recognized as the major negative effects for HESs simulation (Wang *et al.* 2017). During the selected time period, the low urbanization and environmental protection regulation made it possible for us to minimize the disturbance of human activities (Xu *et al.* 2019), and to address the characteristics of these three

Table 1 | Summary of hydrologic ecosystem services models

	SWAT	VIC	InVEST
HES modules	Water yield, Water retention, Sedimentation, Nutrient, Irrigation	Water yield, Runoff	Water yield, Hydropower production, Reservoir protection, Sedimentation, Nutrient
Input data			
Precipitation	Daily	Daily/Hourly	Annual
DEM	Yes	Yes	Yes
Soil type	Multilayer	Multilayer	Single layer
Snow water	Yes	Yes	No
ET0	No	Daily/Hourly	Annual
Outputs data			
Water yield	Daily	Daily/Hourly	Annual
Runoff	Daily	Daily/Hourly	No
Time scale	Daily	Hourly/Daily	Annual
Operating platform	GIS	LINUX/Windows	Windows
Interface	GIS-based	No	Yes
Scale	Watershed/HRU (hydrologic response unit)	Grid (1–50 km)	pixel (30 m–10 km)/Watershed

models without unexpected errors. Furthermore, as an important eco-barrier for the Beijing-Tianjin-Hebei region (Wu *et al.* 2020), the water yield would largely affect the water availability for residents. Moreover, the large agricultural area would accelerate soil erosion, which may reduce the reservoir's lifetime. Therefore, the water yield and sediment losses, which could increase the risk of the water crisis, have been chosen as two major HESs in our study (Chen *et al.* 2009).

In this study, we use the observation data sequences from 1960 to 1980, as shown in scenario A (Table 2) to fully discuss the characteristics of three models. Then, two scenarios (scenario B and C) were set to testify the proposed collaborated framework to see whether the water yield and sediment losses can be well-rebuilt, if there is a runoff data-sparse period (we hypothesized the runoff data of 1975–1980 was missing). Generally, scenario A works as the control group, where the HESs have been operated by the observation data from 1960 to 1980. Scenario B (without using a framework) and scenario C (using a framework) work as the experimental groups, where we create a data blank period from 1975 to 1980. The objective for establishing these three scenarios is to test whether the HESs in scenario B or scenario C is more similar to scenario A. The specific detailed information for each scenario is shown in Table 2.

RESULTS AND DISCUSSION

Runoff and HESs reproduction

Model performance

Generally, the calibrated models are well-prepared for runoff and HESs simulation (Table 3). The VIC and SWAT model were calibrated and validated using correlation coefficient (R^2) and Nash–Sutcliffe efficiency in three scenarios automatically by the built-in modules (Liang *et al.* 1994; Arnold *et al.* 2012). However, without the calibration and validation module, the InVEST model was calibrated and validated manually by the relative error (Re). The specific parameters and their values for each model are shown in the Supplementary Material, Tables S1 and S2.

Runoff of the three models

The annual mismatch between the simulation results of these three models were mainly due to the different requirements of the data, the divergent targets of the model builder, and the diverse water generation conceptual approaches (Lüke & Hack 2018). In general, the slopes for the runoff

Table 2 | Information for three scenarios

Scenarios	Description
A	① The calibration and validation of the SWAT and VIC models use the runoff observation data from 1960 to 1980 from the hydrologic station. ② The calibration and validation year for the InVEST model were 1975 and 1980, respectively (note: the InVEST model was calibrated by Equation (9) in the Supplementary information to transform water yield to runoff by using the runoff coefficient). ③ Then the HESs for both SWAT and InVEST models were simulated for the period 1975–1980
B	① The calibration and validation of the SWAT model use the runoff observation data from 1960 to 1974 from the hydrologic station. ② The HESs between 1975 and1980 have been simulated by the calibrated SWAT model in step ①. 2460. ③ The InVEST model is calibrated by the HESs of the SWAT model in 1975 and 1980 (note: the InVEST model was calibrated by the simulated HESs of the SWAT model). ④ We use the calibrated InVEST model to calculate HESs from 1975 to 1980
C	① We use the hydrologic station runoff data from 1960 to 1974 to calibrate the VIC model, and reproduce the runoff data from 1975 to 1980. ② The SWAT model is calibrated by the runoff data from 1960 to 1980 (observation data from 1960 to 1974; reproduced data by VIC from 1975 to 1980). ③ The HESs between 1975 and 1980 were simulated by the calibrated SWAT model in step ②. 2461. ④ The InVEST model is calibrated by the HESs of the SWAT model in 1975 and 1980. ⑤ We use the calibrated InVEST model to calculate HESs from 1975 to 1980

of observation versus simulation data for all three models are less than 1, which has revealed that the simulation results are lower than the observed data (Figure 2(a)). One possible reason may be because the elevation was high in the northern part of the study catchment, the melted snow would be the primary factor to generate the runoff in growth seasons (Xu *et al.* 2019). Different from the InVEST model, both the VIC and SWAT models have developed the 'melted-snow' module to estimate the runoff under lower temperature conditions. Therefore, the InVEST model indicated a much lower runoff than VIC and SWAT models (Cong *et al.* 2020) (Figure 2(a)).

Owing to the daily scale input data and well-established hydrologic dynamic algorithms (Supplementary Material, Equations (1)–(4)), the VIC and SWAT models are designed for better reproducibility of the hydrologic cycle, which results in the higher accuracy in runoff simulation. Specifically, the simulation by the VIC and SWAT models is more accurate than the InVEST models. Due to the simplified water balance equation (Supplementary Material, Equation (8)), the InVEST model shows less accuracy in reflecting the annual runoff at the study catchment and demonstrates the highest deviation from the observed data (Figure 2(a), Table 4). Comparing the difference between the VIC and SWAT models, the typical climatic conditions (semi-arid area) may cause a deviation in the simulation results (Arnold *et al.* 1993; Liang *et al.* 1996). Several researches have proved that the VIC model could better produce the runoff in semi-arid area in China (Cheng *et al.* 2009), which may be due to the infiltration excess and saturation excess runoff yield mechanisms of the VIC model having better performance in simulating the hydrologic processes between the surface water, soil layers and ground water, especially in semi-arid areas (Liang *et al.* 1994).

However, when considering interannual variations, all three models display a consistent change rate (Figure 2(b)). In particular, the SWAT and VIC models have nearly the same slope of 0.3955 and 0.3866, and RMSE of 0.59 and 0.56, respectively, while the slope and RMSE for the InVEST model are 0.3444 and 0.71 (Table 4). The fact is that, for most of the HESs decisions, particularly those to avoid, minimize or mitigate harm, the most important information is to identify the changes of the HESs (Wainger *et al.* 2010). Though the simulation result of the InVEST model is not as satisfactory as the other two models for HESs rebuild, the narrow gaps for the interannual change rate between the three models could prove that the InVEST model is capable of identifying the relative changes of HESs (Redhead *et al.* 2018), and could provide a reference for the correct investment to alleviate or utilize the HESs changes.

Water yield and sediment losses

As a classical hydrologic model, the VIC model has not been designed for extended HESs assessment, therefore, the water yield and sediment losses in this section have been quantified by the SWAT and InVEST models. When considering the water yield, though the SWAT and InVEST models have nearly the same interannual change rate of runoff

Corrected Proof

Table 3 | Calibration and validation results of three models (R^2: correlation coefficient; NS: Nash–Sutcliffe efficiency coefficient; Re: relative error)

		Runoff						Sediment					
		Calibration			Validation			Calibration			Validation		
Scenarios	**Model**	**R^2**	**NS**	**Re%**	**R^2**	**NS**	**Re%**	**R^2**	**NS**	**Re%**	**R^2**	**NS**	**Re%**
A	VIC	0.82	0.80	–	0.79	0.75	–	–	–	–	–	–	–
	SWAT	0.76	0.75	–	0.73	0.69	–	0.65	0.63	–	0.77	0.75	–
	InVEST	–	–	3.21	–	–	2.34	–	–	4.58	–	–	3.85
B	SWAT	0.78	0.76	–	0.76	0.74	–	0.62	0.60	–	0.75	0.73	–
	InVEST	–	–	7.17	–	–	8.17	–	–	0.91	–	–	2.51
C	VIC	0.83	0.81		0.80	0.77	–	–	–	–	–	–	–
	SWAT	0.80	0.78	–	0.78	0.76	–	0.63	0.62	–	0.76	0.74	–
	InVEST	–	–	4.11	–	–	4.16	–	–	0.11	–	–	0.87

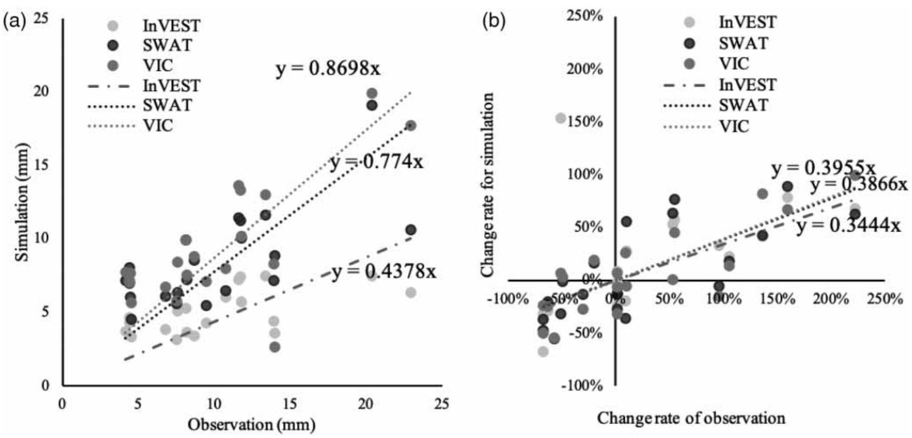

Figure 2 | Runoff simulation accuracy for the three models: (a) the observation data vs simulation results; (b) change rate of observation data vs simulation results.

Table 4 | Root mean squared error (RMSE) in different time scales

	SWAT	**VIC**	**InVEST**		**SWAT**	**VIC**	**InVEST**
Annual	3.89	3.56	6.60	Annual change rate	0.59	0.56	0.71

(Figure 2(b)), the annual water yield (per unit ha) diverges significantly in both the watershed and sub-watersheds scales. Overall, the InVEST model shows a higher amount of five-years average water yield than the SWAT model, with 1.08 and 0.86 billion m^3, respectively (Supplementary Material, Table S3). In general, both models estimate that sub-watersheds Nos. 8 and 9 in the southernmost part of the study area contribute to the largest water yield per unit ha (Figure 3(a)), which has revealed a high consistency between water yield and precipitation (Smith *et al.* 2004). It should be noted that most of the top-ranking sub-watersheds (Nos. 2, 3 and 4) generated by the InVEST model are covered by agriculture in high altitude areas (Figure 1(b)), which is below the change trend line (Figure 3(a)). However, the top-ranking sub-watersheds (Nos. 5 and 6) of the SWAT model are in forest-dominant areas. According to previous studies (Li *et al.* 2019), the forest area has better water conservation ability than the crops (Hengsdijk *et al.* 2005). Without the vegetative growth module, the InVEST model may diminish the high evaporation rate and water demand for photosynthesis and respiration during the crops' growth season (Steduto *et al.*

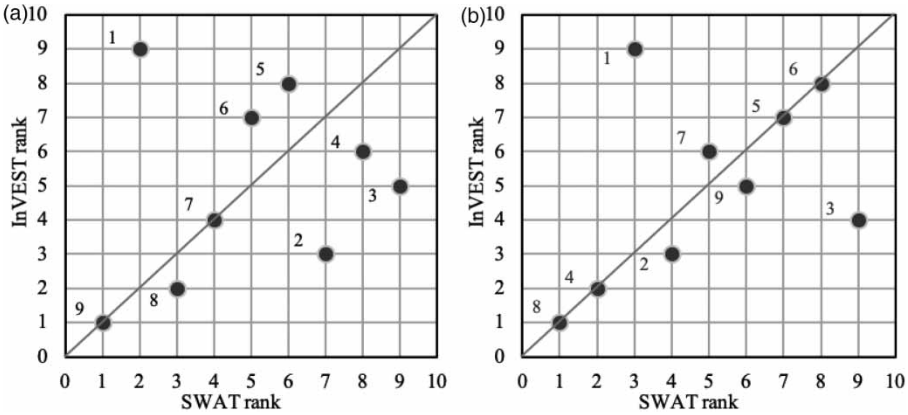

Figure 3 | The HESs (per ha) rankings of sub-watersheds: (a) water yield; (b) Sediment losses (note: the numbers above the plots indicate the sub-watersheds' number).

2007). Moreover, one anomalous sub-watershed (No. 1) was noted for the high ranks of the SWAT model, where half the area is covered by forest and half is agricultural. The total coverage for agriculture and forest may cause the differences between sub-watershed No. 1 and the other sub-watersheds, which would imply that high ecosystem diversity could contain more water.

For the sediment losses, the SWAT and InVEST models have nearly the same total simulation results with 2.3 and 1.9 million tons, respectively (Supplementary Material, Table S4). Different from the water yield, the sediment losses have shown relatively consistent distribution characteristics. Half of the sub-watersheds indicate the same ranks in both the SWAT and InVEST models. A conclusion may be drawn that the sediment losses may be mainly due to the various land use types (Wang *et al.* 2016). As the previous studies suggested, precipitation would be another critical factor for the sediment losses (Zhou *et al.* 2016). In our study, the effect of precipitation is represented by the runoff or water yield. Therefore, we focus on the connection of sequencing between water yield and sediment losses in Figure 3. Significantly, two sub-watersheds (Nos. 1 and 3) presented a high heterogeneity with other sub-watersheds (Figure 3(a) and 3(b)). This feature may prove that the mechanism of water yield (runoff) would be another important factor for sediment losses.

Proposal and validation of the collaborated framework

The collaborated framework for different models would be another research interest for both the earth science and environmental management studies. When applying HESs management to elicit people's preferences, the data availability has always been considered as the main obstacle for HESs simulation. Nevertheless, in most cases, data gaps always exist during continuous monitoring periods. In this study, after fully discussing the advantage qualitatively and quantitatively for VIC, SWAT and InVEST models, we have proposed a collaborated framework (Figure 4) to try to take advantage of each model for carrying out better HESs management in data-deficient scenarios.

The collaborated framework was proposed based on the data availability and the characteristics of the three models in the previous section. When the input data can meet the requirement for all three models, the collaborated framework provides an approach for choosing the appropriate management tool for their unique needs. However, when the observation runoff is deficient, this framework could help users to achieve a better HESs assessment by using the VIC, SWAT and InVEST models.

Adaptability of the collaborated framework

When the data is sufficient for HESs reproduction, the target for our collaborated framework is to help different users fulfill their need for HESs management. In our framework, the data requirement, data time scale, learning efforts, spatial resolution and the operating platform have been considered for users to select the appropriate model to achieve their goals. Overall, the VIC and SWAT models are the better choice for researchers to build the hydrology cycle

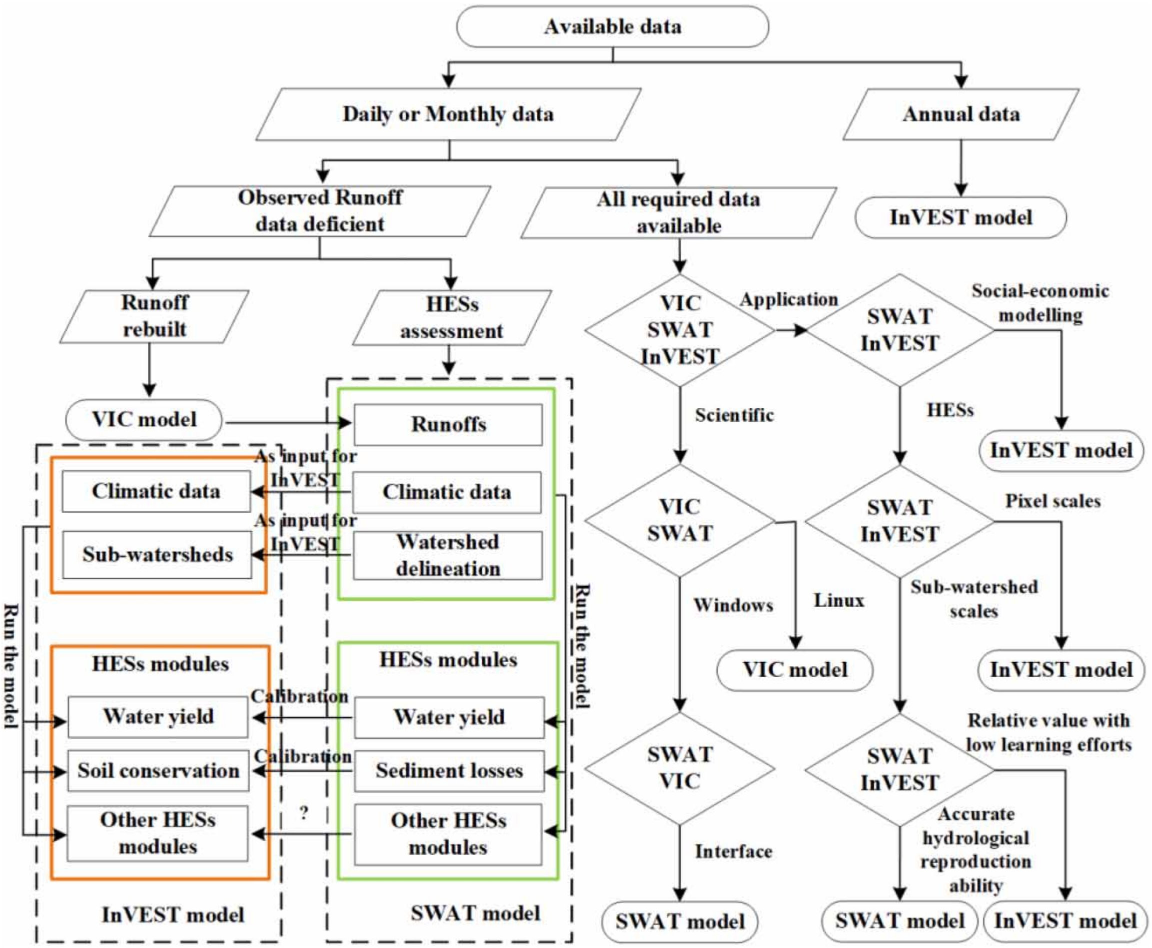

Figure 4 | Collaborated management framework for the watershed decision model.

(Lin *et al.* 2015), and the VIC model requires users to have a basic knowledge in coding (Dang *et al.* 2020), while the InVEST model could be a practical tool for managers to detect the relative changes in HESs for different administration units (Yang *et al.* 2019).

The designed purpose for these three models is different. Both the VIC and SWAT models are designed for scientific use, therefore, the requirement for the parameter verification, observation data acquisition and model establishment are relatively high. Therefore, the VIC and SWAT models need sufficient meteorological and hydrological data to establish integral hydrological proccesses and provide a scientific basis for the development and utilization of water resources. Different from the VIC and SWAT models, the InVEST model is designed for planning or management processes, where the HESs evaluation does not strictly need to be perfectly accurate. This is because the decision-making process occurs in a complicated social and ecological system, where numerous factors are included and play significant roles beyond the accuracy of the hydrologic model estimates (Dennedy-Frank *et al.* 2016).

Spatial resolution could be another factor when choosing a model. As most regulations are operated at the administration unit, including cities, counties and states, the results quantified by the large-grid (VIC) and sub-watershed (SWAT) scales would not be appropriate for supervision, although they can present more accurate outcomes. As the original outputs of the InVEST model are based on pixels, it would be more flexible than the VIC and SWAT models in spatial partitioning for assessing the impacts of various factors on HESs in changing management units (Bai *et al.* 2019). However, when the management unit is based on the sub-watershed scales, the SWAT model with more specific hydrologic process reproducibility could be the better choice for HESs mapping and analyzing than the InVEST model.

Additionally, different operating platforms would also significantly affect the adaptation of the model users for HESs management. The accuracy and the characteristics of large-scale simulations are the reasons why some professional studies prefer the VIC model (Zhao *et al.* 2013). However, the VIC model is based on codes for both LINUX/Windows systems, which has raised the threshold for beginners to handle. Unlike the VIC model, the SWAT and InVEST models have an interface based on the widely used Windows system (Table 1), which can quickly help users become familiar with the models. Nevertheless, the heavier computational package loads of the SWAT make it a resource-intensive model when conducting projects at very large spatial scales, and its complexity package means that building high-quality projects requires expertise that may not be available in many situations (Dennedy-Frank *et al.* 2016).

Validation of the proposed collaborated management framework

According to the previous discussion, when the observed runoff data is deficient, the VIC model could be a better choice to reproduce the hydrological cycle and the output of SWAT could be used to calibrate the InVEST model for HESs assessment, as the sub-watershed delineation is required by both SWAT and InVEST models. The watershed delineation process in the SWAT model could be the input for the InVEST model. Moreover, the climatic dataset in the SWAT model, especially the ET_0, could also be reclassified and directly interpolated for the InVEST model. Based on Figure 4, in the 'observed runoff data deficient' branch, the results for the relative error between the control group (scenario A) and the experimental group (scenarios B and C) are presented in Table 5. Generally, scenario C (using the framework) introduces a better performance than scenario B with nearly a 2% improvement for HESs assessment during the study period.

Specifically, with similar runoff simulation accuracy between the VIC and SWAT models as discussed in the section 'Runoff of the three models', a slight improvement

Table 5 | Relative error for scenario B/C to scenario A of the HESs

	SWAT				InVEST			
	Water yield		Sediment losses		Water yield		Sediment losses	
	B (%)	C (%)	B (%)	C (%)	B (%)	C (%)	B (%)	C (%)
1975	5.43	3.67	4.32	3.12	− 3.12	− 1.35	3.12	3.01
1976	4.89	2.78	5.42	3.85	− 0.73	− 0.22	3.25	2.98
1977	5.13	3.31	5.89	3.91	− 5.89	− 1.67	3.14	3.15
1978	6.76	4.81	7.62	4.22	− 7.65	− 4.45	3.53	3.42
1979	5.78	3.32	4.85	3.11	− 5.34	− 2.15	3.98	3.74
1980	6.24	3.67	6.53	3.43	− 3.66	− 1.79	3.78	3.52

Scenario B: the simulation without using collaborated framework; scenario C: the modified simulation results using collaborated framework.

in scenario C has been determined for the SWAT model. Considering that the sediment losses were mainly based on the different vegetation types, rainfall and slope of the catchment (Zhou *et al.* 2016), the collaborated framework did not show significant improvement for the SWAT and InVEST models. However, with the large amount of sediment losses every year, the slight improvement may help policy makers to carry out better protection regulations for the riverside ecosystem, reservoirs and residential areas downstream of the study catchment.

Our collaborated framework could improve the HESs management when the observation data is deficient. Additionally, whether the collaborated framework could increase the accuracy for other extended HESs' modules (water purification, irrigation, etc.) should be further discussed. Also, our study encourages more researchers to apply our framework to other watersheds with different environmental backgrounds.

Implication

Though our study provided a meaningful approach to improve the HESs management, the limited HESs types in this research may encourage more works to enhance our collaborated framework. The SWAT and InVEST models may be more adaptable than the VIC model for multiple HESs analyses, such as hydropower production, municipal water supply and irrigation regulating. These various modules would help users to further explore how climate, land use/land cover and relative policies change could affect the HESs. The original purpose for the VIC model was to use all effort to maximize the hydrologic reproduction efficiency and accuracy, which would help to reproduce the hydrologic cycle in data-deficient areas, especially semi-arid areas. To address how our collaborated framework would help the HESs management with other modules, the implications are discussed below.

Municipal water supply

Compared with the water yield/surface runoff module of the SWAT and VIC models, the output of the InVEST model provides sufficient spatial resolution (Table 1) for further evaluating HESs, which is more closely related to an urban water supply administration unit. The resolution of pixel level provides effective support for drawing the water resources distribution and interannual variation in needed regions. The municipal water supply module of the InVEST model can also be applied for evaluating the situation of urban water scarcity, which would be practical for analyzing the balance between supply and demand of urban water in a given region. However, the basic need for the data would also be the climate factors and runoff, which could be introduced from our collaborated framework when the data is unavailable.

Hydropower production

The reservoir hydropower module, encapsulated in the InVEST model, can estimate the power generation based on the estimated actual water supply required for electricity production and calculate the value of the energy (Sharp *et al.* 2016). According to the proportion contribution of energy production in each sub-watershed, the value of each sub-watershed in hydropower generation can be calculated. Using this rough budgetary estimation approach, a comparison between the construction cost and energy production revenue for hydropower stations and reservoirs can be quantified, as well as the clear understanding of the distribution of hydropower resources in each sub-watershed. Using our collaborated framework, the water yield in each sub-watershed could be specified, as well as the sediment losses, which has been identified as a major threat affecting the hydropower production rate and life cycle (Thapa *et al.* 2005).

Irrigation

With the increasingly rapid economic globalization and urbanization, it is crucial to estimate the HESs to alleviate water crisis in the future. Different from the VIC and InVEST models, the irrigation module of the SWAT model provides a possibility for researchers and policymakers to forecast the HESs changes under different agricultural scenarios. Owing to human activities, such as agriculture expansion and innovation in irrigation methods, hydrological processes have faced drastic changes (Haddeland *et al.* 2006). The irrigation module takes the fertilization frequency, amount of pesticides usage and crop classification into consideration, and provides daily-scale output results, including runoffs, nutrients and sedimentation changes, to meet the regulation or scientific requirements for the users. Furthermore, when conducting a project that aims to study water resource management based on different irrigation scenarios, the SWAT and InVEST models can work together to make full use of the water scarcity module in the InVEST model and irrigation module in the SWAT model. Linking these two modules, we can identify whether the study catchment has the ability to expand the irrigation dimension and how nutrient export would change.

Limitation

Identification accuracy and resolution for the land use land cover maps would largely affect the models' simulation accuracy. In addition to the climatic factors, topographic conditions and theoretical calculation methods, the vegetation classification accuracy may also affect the results. Specifically, in our study, the recognition ability of forests and shrubs, as well as shrubs and grasslands, are relatively low, which would lead to a mismatch on vegetation classification (Wu *et al.* 2019).

CONCLUSIONS

In this study we have discussed three models (VIC, SWAT and InVEST) for their applicability of HESs management in the YRB, China, and proposed a comprehensive management framework, including model selection and model collaborated approaches. Overall, the results indicate the following conclusions:

1. The VIC and SWAT models can meet the needs for precise water resource control and management at various time scales. The InVEST model is not suitable for overelaborate water quantity control and management, while low data requirement along with the diverse extended modules make the InVEST model an efficient decision-making tool.
2. The VIC model could be the best choice for hydrologic cycle reproduction in identical areas. Moreover, although the InVEST model could not well reflect the actual hydrologic situation, it still can present valuable information for relative changes of the HESs.
3. The collaborated framework aims at coupling these three models and fully uses the advantages of each model. After the validation processes, the proposed model collaborated framework is capable of improving HESs estimation and management in the study catchment.
4. In order to test the adaptability of the collaborated framework, further similar studies under different climate conditions should be conducted. Furthermore, how to collaborate the extended module in the framework would also be a meaningful work in future.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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