Water Resour Manage (2011) 25:913–927
DOI 10.1007/s11269-010-9733-6

Cascade Dam-Induced Hydrological Disturbance and Environmental Impact in the Upper Stream of the Yellow River

Wei Ouyang · Fanghua Hao · Kaiyu Song · Xuan Zhang

Received: 4 September 2009 / Accepted: 8 November 2010 /
Published online: 26 November 2010

Abstract The construction of a dam converts the natural streamflow to human control. It is necessary to learn the accumulated effect of cascade dams on hydrological characteristics, sediment and nutrient pollution discharge. The current research describes the analysis and simulation of streamflow, sand concentration and nutrient pollutant discharge alterations caused by the construction of a cascade of eight dams along the Longliu section of the upper stream of the Yellow River. The analysis shows that the maximum monthly streamflow difference between the inlet and outlet of the Longliu section decreased from 430 to 115 m^3/s, after the appearance of the cascade dams between 1977 and 2006. In the same period, the correlation coefficient (R^2) of monthly streamflow between the inlet and outlet of Longliu dropped from 0.959 to 0.375. The peak of streamflow shifted from June to May and October. The difference in sand concentration between two sections decreased from 0.52 to 0.39 kg/m^3, which was the direct consequence of the operation of the reservoirs. The R^2 value of sand concentrations of the inlet and outlet were also reduced from 0.504 to 0.356. A t-test analysis indicates that the original hydrological nature was significantly disturbed by the cascade dams. The influence of the dams on nutrient pollutant transport was simulated by the SWAT model. This simulation suggests that the cascade dams decreased the discharge of total nitrogen and total phosphorus from 15.4×10^3 t and 1,996 t to 0.4×10^3 t and 328 t, respectively. In conclusion, the accumulated impact of cascade dams on streamflow, sand concentration and nutrient pollutant discharge were analyzed, which were helpful for understanding the environmental features of the entire watershed.

W. Ouyang (✉) · F. Hao · K. Song · X. Zhang
School of Environment, State Key Laboratory of Water Environment Simulation,
Beijing Normal University, Beijing, 100875, China
e-mail: wei@itc.nl

Keywords Cascade dams · Yellow River · Hydrologic alteration · Accumulated impacts · Nutrients pollution

1 Introduction

A hydroelectric dam regulates streamflow, adjusts the downstream flood peak, blocks the continuity of hydrology, alters hydraulic force, and reduces the sediment transport to downstream (Isik et al. 2008; El-Shafie et al. 2009). These influences significantly disturb the original river ecosystem. Maszlea et al. (1998) concluded that runoff profile changes due to dam construction could lead to alterations in channel geometry. The main channel in meandering sections could shrink, while the riverbed in transitional reaches could rise and side bars could grow. In curvy sections, the main channel aggravation could increase. These actions ultimately change hydrodynamics, river geomorphology and the geological structure underneath. A study in Spain demonstrated that artificially regulated reservoirs weakened the natural characteristics of river reaches (Lopez-Moreno et al. 2009). Studies have shown that the dams changed water discharge and disturbed alluvial sand and nutrient transport patterns (Muhammetoglu et al. 2005; Zeilhofer and de Moura 2009). Some researchers have shown that dams retain alluvial sand and nutrients, which subsequently change water quality and even regional vegetation (Stave et al. 2005; Jeong et al. 2007).

As hydropower is booming in China, its environmental impact has attracted some attention. The majority of research in China on dam-introduced impact focused on the hydrological regime (Wang et al. 2005). The hydrological alteration due to the dam along the middle reach of Yellow River has been investigated, and it was found that the Xiaolangdi Reservoir had changed the natural flow regime downstream (Yang et al. 2008). Wang et al. (2006) studied the Yellow River efflux under the influence of artificial and climate change and discovered that the annual average discharge to the sea was reduced by 51%. When the Three Gorges Reservoir (TGR) came into service on the Yangtze River, the hydrologic alteration was the hot spot. The sediment discharged from the TGR dam decreased in 2003, which resulted in a lower suspended concentration and sediment loading downstream and also caused nutritional mineral profile changes in the mouth and surroundings of the Yangtze River (Chu and Zhai 2008). With these results, it was agreed that the hydrologic alteration and related environmental impact of dams has become a main concern in hydrological development plan in China.

In other countries, studies on the impact of dams similarly focused on the hydrological aspects. Some researchers have analyzed silt property changes caused by dams (Hart and Poff 2002; Shah and Kumar 2008). On a spatial scale, the studied area has been extended to an entire river valley from the reservoir itself. Kummu and Varis (2007) demonstrated that the dam operation in the Mekong main stream had greatly reduced annual sedimentation from 150–170 $\times$ 10^9 to 81 $\times$ 10^9 kg. The completion of the Kilichaya dam in Turkey has reduced concentrations of K^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} and changed the channel form due to the retention of large amount of sand (Ahmet et al. 2006). Pringle et al. (2000) also analyzed the channel matrix change, which could affect the quantity and quality of fish and benthos.

Regarding hydrologic alterations, the primary approach is to analyze hydrological monitoring data. With the consideration of water quality, the modeling system was applied to large watersheds with dam operation and mixed land covers (Jung et al. 2008). The hydrologic model (HEC-RAS) analyzed the effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut River (Nislow et al. 2002). The watershed hydrological model, Soil and Water Assessment Tool (SWAT), has a special cell on the reservoir, which can simulate the hydrologic alterations and aquatic ecosystem impact of dams (Hsieh and Yang 2007). The influence of impoundments on river nutrient transport was successfully evaluated by the SWAT in the Raisin watershed (Holvoet et al. 2007). The case studies have proven that the SWAT can model the transport of flow, sediment and phosphorus along the river with the dam (Mishra et al. 2007).

The Yellow River Basin is of the utmost importance for China in terms of food production, natural resource management, and socioeconomic development (Cai and Rosegrant 2004). The hydrological and environmental response after the construction of eight cascade dams was a concern along the upper reach of the Yellow River. Although there are some studies about hydrologic alteration by the dam, most of them focused on the impact of a single dam, and few studies covered the impact of nutrient pollution. Nutrient pollution is the key water pollutant in the Yellow River watershed (Li et al. 2007). Some studies have estimated the nutrient elements that are discharged to the Yellow River estuaries (Zhang et al. 1997). From the aspect of environmental science, the retention of nitrogen (N) and phosphorus (P) by cascade dams can be identified by the SWAT (Rustomji et al. 2008).

The main research objectives were to (a) systematically analyze the streamflow and sand concentration dynamics after the construction of eight cascade dams and (b) simulate and quantify the retention of N and P by the cascade dams with the SWAT.

2 Materials and Methods

2.1 Study Area Description

Hydropower has developed rapidly in China, and the Yellower River Basin has experienced intensive exploitation in the last five decades. To identify the accumulated impact of cascade dams, a section of the Yellow River with expected long-term hydropower exploitation is selected (Fig. 1).

The Longliu Section of the Yellow River is located between Longyangxia and Liujiaxia. This area is a key part of the upper stream of the Yellow River and is located in the eastern part of the Tibet-Qinghai Plateau. Its elevation drops by 795 m over the 438 km length (including the reservoir). There are eight dams in this section. Their locations are shown in Fig. 1, and the attributes are listed in Table 1. All the dams were constructed with the purpose of energy production. The three large dams, Longyangxia, Lijiaxxia, and Qingtongxia also have the functions of irrigation, flood control and fishery.

2.2 SWAT Model and Data Sets

The Soil Water Assessment Tool (SWAT) is a semi-distributed hydrological model and a physically based watershed model. This model simulates the surface and

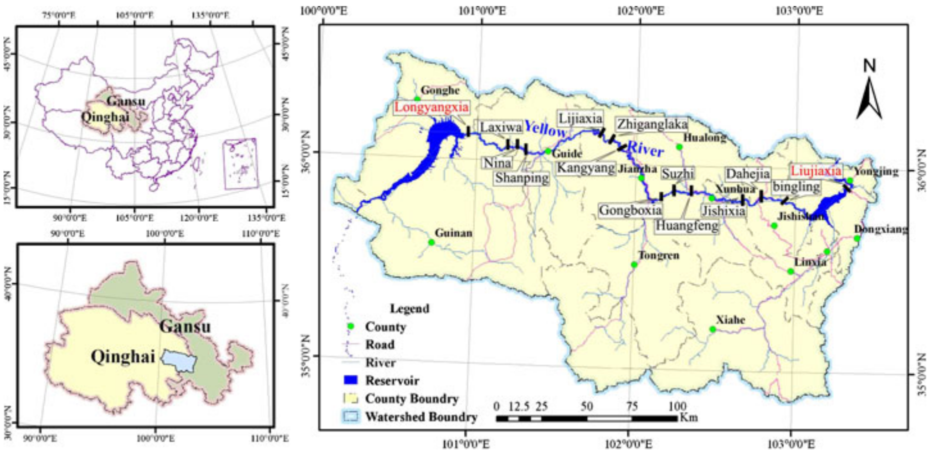


Fig. 1 Distribution of cascade dams in the Longliu Section in the upper stream of the Yellow River

underground water volume and quality and predicts and analyzes the influence of land cover, agriculture, and local management on water volume and quality (Arnold et al. 1998). The SWAT was selected in this study because of its ability to simulate regional water balance and sand transport dynamics at a watershed scale and to provide effective results for additional analyses. The SWAT treats a reservoir as a special water body and simulates water volume, sediment, and N and P dynamics based on reservoir operation parameters (Abbaspour et al. 2007). In this paper, the SWAT was employed to simulate the discharge of N and P after detention by the cascade dams.

1. Land cover and weather data

The land covers in four periods of hydropower exploitation were prepared. According to the availability of satellite images and exploitation processes in last 30 years, the land cover in 1977, 1996, 2000 and 2006 were imported. The land cover data in 1996 and 2000 were part of national databases, which were also classified from Landsat series images (Liu et al. 2003). The land cover data in 1977 and 2006 were

Table 1 Description of cascade dams

Dam	Service date	Water capacity ($\times 10^9$ m^3)	Water level (m)	Dam height (m)	Hydropower capacity (MW)
Longyangxia	10/1986	247	2600	178	1280
Nina	2/2003	0.262	2235.5	43	160
Lijiaxia	12/1996	16.5	2180	155	2000
Zhiganglaka	4/2005	0.154	2050	42.5	190
Kongyang	8/2006	0.288	2033	45	284
Gongboxia	8/2004	2.9	2005	139	1500
Suzhi	9/2006	0.455	1900	51.2	225
Liujiaxia	10/1968	57	1735	147	1225

developed from Landsat MSS and TM images (Ouyang et al. 2010). The land cover in 2006 is shown in Fig. 2.

The daily climatic data were obtained from nine surrounding National Reference Meteorological Stations (Fig. 2). Parameters include precipitation, highest temperature, lowest temperature, sunlight, and wind speed from 1975–2008. These records were calculated and saved as the SWAT weather generator, which provided the temporal-spatial features of watershed weather information.

2. Soil property

Soil property data were obtained from a National Soil Map Database, the Qinghai Soil Record and Ganshu Soil Record. The soil attributes were assembled for the simulation of the water cycle and erosion in hydrological response units (HRUs). The parameters include coarse sand, silt, clay, organic matter, rock fragment content, and moist bulk density.

3. Reservoir operation and related parameters

The cascade dams operate on a temporal schedule, according to the water resource management of whole watershed. From April to June, the discharged water volume increases to larger than 200 m^3/s to meet the demand of agricultural resources in the lower reach. In the rainy period of July to September, the reservoir collects water and the water level increases. In the icy period of December to March of following year, the water in Longyangxia is released and the water level increases in the lower reach.

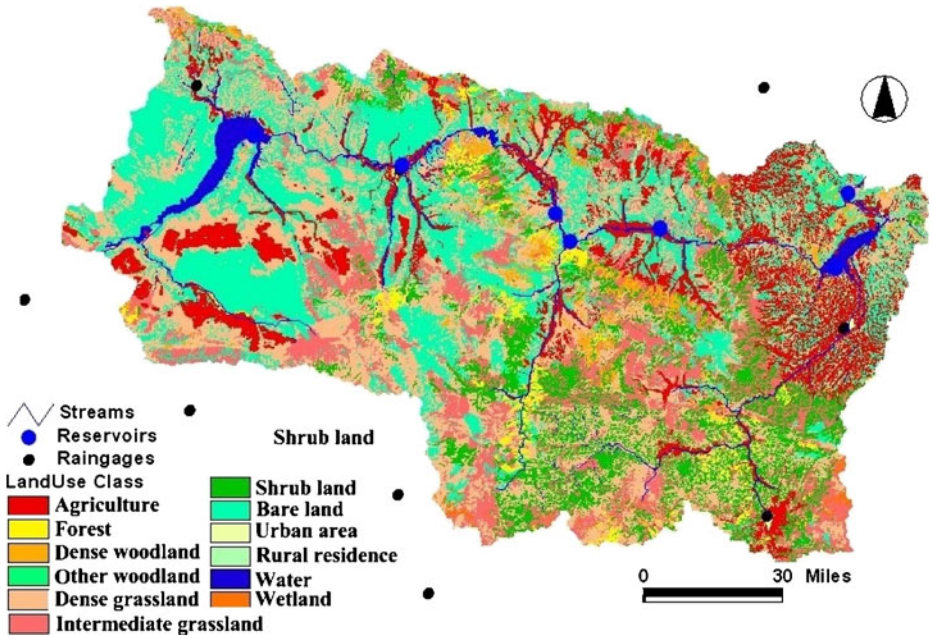


Fig. 2 Land cover of study area in 2006 and distribution of weather stations

Based on the available data and the necessary inputs of the SWAT, the following characteristic indicators of the reservoir operation were set up: the surface area of reservoir when filled to the emergency spillway (RES_ESA *SAem*), surface area of reservoir when filled to the principal spillway (RES_PSA *SApr*), volume of water held in reservoir when filled to the emergency spillway (RES_EVOL *Vem*), volume of water held in the reservoir when filled to the principal spillway (RES_PVOL *Vpr*), monthly averaged outflow rate (RES_OUTFLOW *qout*), average monthly averaged principal spillway release rate (RES_RR *qrel*), beginning month of the flood season, ending month of the flood season, minimum average daily outflow of month (OFLOWMN), and maximum average daily outflow of month (OFLOWMX).

4. Hydrological and pollutants data

Hydrological data include the monthly streamflow and sand concentration in 1975–1978 and 2000–2002, which were recorded at the Tangnaihai (inlet section) and Xiaochuan (outlet section) hydrological monitoring stations. These two stations, located at the inlet and outlet of the studied watershed, monitored the hydrological characteristics of the influent and effluent of the studied watershed. Unlike the hydrological data, there was no regular pollutant monitoring in this area. Zhang et al. (2003) has monitored the nitrogen at the outlet monthly. Yang et al. (2006) has calculated the ratio of phosphorus and nitrogen in this area and estimated the phosphorus concentration. So, the necessary modeling data on streamflow, sand concentration and nutrient pollutants were prepared.

2.3 SWAT Validation

Before the model validation, the previously listed eight reservoir operation parameters were set up. The uncertainty of simulation results was optimized by parameter sensitivity analysis. Based on the monthly monitoring data of streamflow and sand concentration at the Xiaochuan hydrological station, the sensitivity was evaluated with the SWAT automatic analysis module. The water flow was calibrated first, and then the sand concentration and nutrient pollutants were considered. The six dominant parameters affecting water flow, the five most sensitive parameters of soil erosion and the seven nutrient-related parameters were selected and adjusted. The parameters were calibrated after comprehensive consideration of the characteristics of the cascade dams, and their monthly operation pattern were imported into the SWAT model. During the calibration process, the selected sensitivity parameters affecting streamflow, sand concentration and nutrient pollution transport were modified.

The validation period was from January 2000 to December 2002, which was performed with parameters regarding climate, land cover, and soil type. After the validation, the coefficient of correlation of monitored and simulated streamflow was 0.726, and that of sand concentration was 0.968. After that, the N-related parameters were also validated, and the coefficient of determination of simulated and monitored N was 0.779. With the export ratio of N and P, the phosphorus simulation was also validated. A detailed description of validation procedure is given in a previous paper (Ouyang et al. 2009b). The validation results indicate that the simulations of N and P were acceptable.

2.4 Data Analysis Process

By directly monitoring the data of streamflow and sand concentration at inlet and outlet sections of the observed watershed, the correlation and *t*-test analyses were applied to express the effect of the cascade dams with the SPSS software. To compare the streamflow flux after the emergence of the cascade dams, the monthly average streamflow in 1976–1977 was considered as the original hydrological profile. The data in 2000–2002 was treated as the profile after the emergence.

Based on the available monthly monitoring data, the nutrient pollution discharge was simulated on the yearly scale with the SWAT model. The simulation period was from 1977 to 2006, and the yearly N and P pollution discharges at the outlet section were estimated. To highlight the impacts of the cascade dams, the accumulated hydropower capacities (AHC) and summed dam heights (SDH) (Ouyang et al. 2009a) were employed to represent the process of the cascade dams' construction. Their correlations with nutrient pollution discharges were analyzed to identify the ability of the cascade dams to hold nutrient pollution.

3 Results

3.1 Impact of Cascade Dams on Streamflow

The streamflow characteristics at the inlet and outlet of the studied section, before and after the dams' construction, are shown in Table 2. It is clear that the streamflow volume from upper catchments has been reduced in the last 30 years due to weather variation and increased demand. The hydrological difference in the inlet of two sections was analyzed to ascertain the impact of the cascade dams. The yearly volume difference between the inlet and outlet dropped from 82×10^8 to 55×10^8 m^3, a decrease of 33%. This drop suggested that the cascade dams slightly offset general runoff. The inlet monthly peak decreased from 1,425 to 864 m^3/s, and outlet monthly peak decreased from 1,855 to 979 m^3/s. The precipitation in this area contributed to the additional waterflow. The difference between peak volumes declined from 430 to 115 m^3/s, suggesting that the cascade dams reduced peak waterflow value. The *t*-test at a significance level of 0.05 was employed to test the difference of monthly streamflow features over three decades. The significance (Sig.) value of inlet streamflow over three decades was 0.006, but the Sig. value of outlet streamflow was 0.039. The statistical analysis indicates that the inlet hydrological feature did not

Table 2 Statistical analysis of streamflow before and after dams' appearance

	Year	Min (m^3/s)	Max (m^3/s)	Mean (m^3/s)	Standard Deviation	*t*	Sig.
Outlet	1976–1978	423	1855	906	434.85	2.342	0.039
Inlet		183	1425	653	424.51	3.399	0.006
Difference		239	430	253	–	–	–
Outlet	2000–2002	370	979	640	195.62	–	–
Inlet		141	864	420	252.26	–	–
Difference		229	115	220	–	–	–

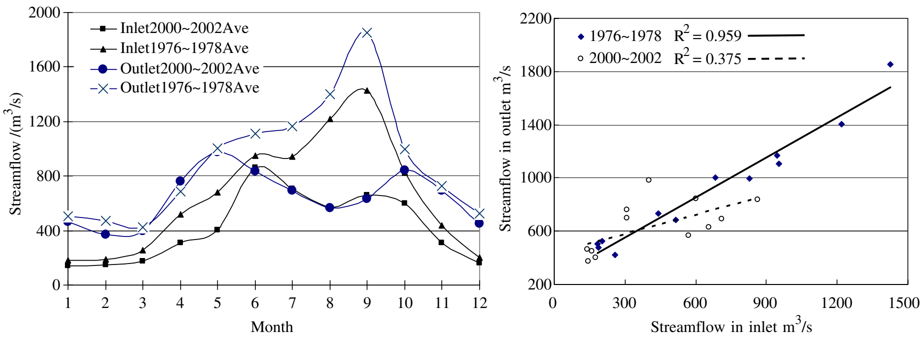


Fig. 3 Comparison and correlation analysis of streamflow of inlet and outlet post-construction

intensively vary, but the outlet streamflow was significantly disturbed by the cascade dams.

Figure 3 shows that the monthly profile of the inlet volume was closely correlated with the outlet profile before the construction of the cascade dams, and the determination coefficient (R^2) was 0.959. The peak volume of the inlet and outlet both appeared in September. In the post-construction period, the correlation pattern decreased, and the R^2 value dropped to 0.375. In 2000, the inlet peak flow occurred in June, while the outlet peak occurred in May and October. The outlet runoff was determined predominantly by the inlet flow before dam construction. In contrast, the correlation analysis shows that the influence on outlet runoff was markedly reduced after dam construction.

3.2 Impact of Cascade Dams on Sand Concentration

The monthly sand concentration profiles were similarly compared with the data in 1976–1978 and 2000–2002. The statistical analysis of sand concentration at the inlet and outlet sections is shown in Table 3. Similar to the decrease in inlet volume, there was also a decrease in mean influent sand concentration, which shrank from 0.41 in 1977 to 0.31 kg/m^3. Over the same period, the mean sand concentration of the outlet was reduced from 0.52 to 0.39 kg/m^3. The difference of the mean sand concentration between two sections dropped from 0.11 to 0.07 kg/m^3, which suggested that the

Table 3 Statistical analysis of sand concentration before and after cascade dams' appearance

	Year	Min kg/m^3	Max kg/m^3	Mean kg/m^3	Standard Deviation	*t*	Sig.
Outlet	1976–1978	0.01	2.67	0.52	0.843	0.752	0.468
Inlet		0.01	1.64	0.41	0.570	0.000	0.000
Difference		0	1.04	0.11	–	–	–
Outlet	2000–2002	0.01	1.82	0.39	0.577	–	–
Inlet		0.01	1.48	0.31	0.438	–	–
Difference		0	0.34	0.07	–	–	–

sand load declined. The maximal influent sand concentration dwindled from 1.64 to 1.48 kg/m^3. At the same time, the peak concentration in the effluent decreased from 2.67 to 1.82 kg/m^3. The difference of the mean sand concentration decreased from 0.11 to 0.07 kg/m^3, which indicated that the cascade dams can hold sand in reservoirs. The *t*-test analysis at a significance level of 0.05 also indicates that the sand concentration at the inlet did not significantly vary. However, the Sig. value of the sand concentration at the outlet shows that the concentration at the outlet was significantly changed by the cascade dams.

Figure 4 shows the monthly variation profile of sand concentration. Before the cascade dam's construction, the monthly sand concentration at the outlet shared the same temporal pattern as the inlet. The highest sand concentration occurred in July. After the construction of the cascade dams, the maximal sand concentration at the outlet was reduced by 32%. Two sand concentration peaks were observed, in June and in August. Comparing with the effluent peak in 2000–2002, the sand concentration peaks accompanied the runoff peak.

The correlation analysis of the inlet and outlet sand concentrations was performed (Fig. 4). After the construction of the dams, the R^2 value decreased from 0.504 to 0.356. The analysis demonstrates that the outlet sand concentration was jointly determined by the influent concentration and the erosion within the Longliu Section in the previous period. After the appearance of the cascade dams, the influent sand was not the main factor. It was demonstrated that the construction and operation of cascade dams effectively reduced outlet sand concentration.

3.3 Impact of Cascade Dams on Nutrients Pollution Discharging

To analyze the N and P retention by the cascade dams, the annual total nitrogen (TN) and total phosphorus (TP) discharge in 1975–1978, 1995–2001, and 2005–2006 was estimated with the SWAT (Fig. 5). The simulations show a clear decline in TN and TP discharges. At the beginning in 1975, the yearly TN discharge was 15.4×10^3 t, which dropped to 0.4×10^3 t in 2006. At same time, the yearly TP discharge was

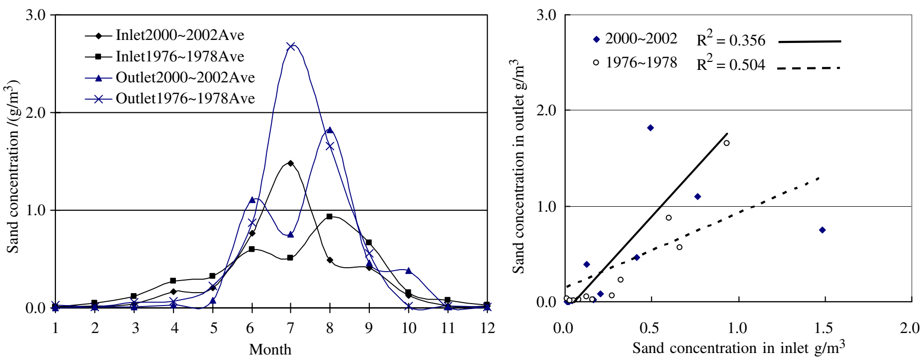


Fig. 4 Comparison and correlation analysis of the inlet and outlet sand concentration post-construction

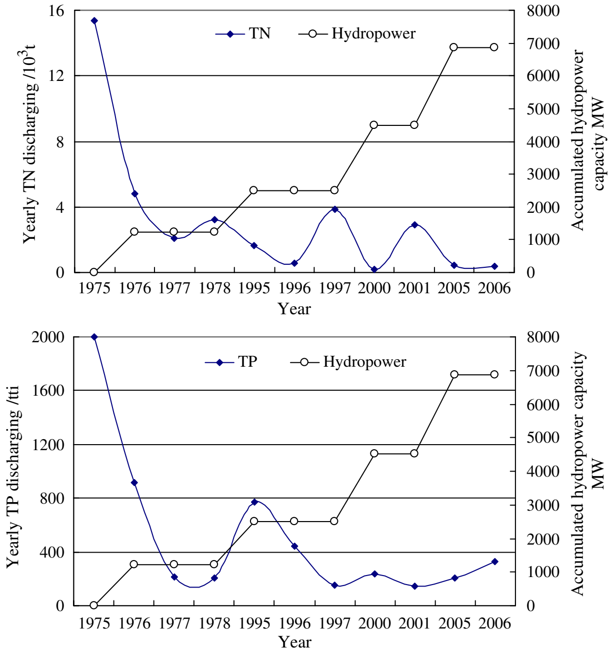


Fig. 5 Variation of the yearly TN and TP discharge

reduced from 1996 t to 328 t. The sharp reduction occurred before the 1990s, and the newer dams had less influence on TN and TP retention. Although there are eight dams along this section, the main retention occurred in the three largest reservoirs (Liujiaxia, Longyangxia and Lijiaxia). After these three reservoirs came into service in the 1990s, the TN discharge was maintained at less than 4×10^3t, sometimes even below 1×10^3 t. During the same period, the yearly TP discharge was below 500 t. In particular, the TP discharge was 144 t in 2001.

The correlation equations of nutrient pollution discharge with accumulated hydropower capacities (AHC) and summed dam heights (SDH) are listed in Table 4. The TN discharge had a closer relationship with the cascade dams' indicators than the TP discharge. The R^2 value of two exponential equations for the TN discharge indicates that the accumulated hydropower capacities (AHC) and summed dam heights (SDH) are acceptable factors to express the accumulated impact of the cascade dams. However, the correlation of TP discharge with AHC was not as good as SDH; so, SDH is the better option to analyze the accumulated impact of cascade dams.

Table 4 Correlation equations of nutrient pollutant discharge with accumulated hydropower capacities (AHC) and summed dam heights (SDH) of the cascade dams

Y	X	Equation	R^2
TN discharge	AHC	$y = 0.4212e^{0.0004x}$	0.621
	SDH	$y = 0.4043e^{0.0036x}$	0.542
TP discharge	AHC	$y = 173.12e^{0.0002x}$	0.397
	SDH	$y = 141.84e^{0.0023x}$	0.537

4 Discussion

4.1 Hydrological Disturbance by Cascade Dams Operation

Previous studies have highlighted the importance of considering precipitation variations in the analysis of hydrological alteration introduced by dams (Lehner et al. 2005). Hence, the daily precipitation over four decades was imported into the model. The regular monitoring data indicates that the precipitation did not vary over the simulation period, and the yearly precipitation was about 250 mm. At same time, the land cover did not change significantly (Ouyang et al. 2010). Hence, the cascade dams, which can absorb the peak flow volume and release it into the steam at a later stage, were identified as the critical factor for the hydrological alteration. These data demonstrate that the natural runoff pattern has become artificially controlled. The human-oriented streamflow fluxes may benefit social and economical development in the downstream sections, but also cause some potential negative impact on the downstream ecosystem.

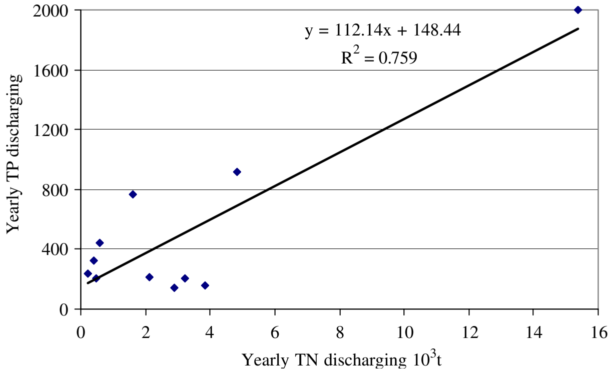
Considering the effect of construction of the cascade dams on streamflow and sand concentration, which is presented here, the role of the dams' operation should be discussed. As shown in Table 1, the Longyangxia, Lijiaxia and Liujiaxia reservoirs had the largest capacities and played a leading role in the hydrological adjustment. As shown in Fig. 3, the streamflow peaked in May and October, which was overlaid with the temporal schedule principle of dam operation. For the whole year, the Longyangxia reservoir is the head key to adjusting water resources and control the runoff peak. The operation of the dams can adjust the river flow based on the needs of downstream water management strategies (Richter and Thomas 2007).

4.2 Sand Concentration Disturbance by Cascade Dams Operation

Streamflow and sand concentration are the common indicators for river ecosystem management, and some methods have been introduced to assess hydrological variability and aquatic ecology (Richter et al. 1997). In the studied area, the three larger dams have the holding function, which was proved by the sand concentration in two different time periods. The other five dams are runoff power stations, which do not have the setting function. With these dams, the original river has been changed into a series of lakes, and the longer hydrological residence time conciliation is good for decreasing the suspended solids (Poff et al. 2007). The hydraulic conductivity has different temporal-spatial variability under the adjustment of dams, which also causes a variation in size and quantity of the sediment (Topping et al. 2007; Genereux et al. 2008). To account for the hydrological difference, the sand transport was also analyzed. The yearly sand discharge from the outlet of the studied area dropped from 925×10^4 t to 492×10^4 t after the appearance of the cascade dams. A disturbance of sand transport due to the operation of the cascade dams was identified.

There are limitations of this research, especially with regards to the available monthly data. Under the operation of the biggest gorge, the roles of the other small reservoirs were not fully understood. If the analysis can be extended to daily temporal resolution, the conclusion will be clearer. Nonetheless, the sand concentration dynamics have been analyzed, and the effect of the dams' operation was highlighted.

Fig. 6 Correlation between annual TN and TP discharges



4.3 Nutrients Pollutants Retention by Cascade Dams

Hydrologic characteristics play a primary role in determining the composition, structure, and function of aquatic, wetlands, and riparian ecosystems (Richter et al. 1996). The presented analysis shows that the cascade dams have changed the hydrological regime feature and affected the downstream ecologic safety of the Yellow River. The cascade dams introduced hydrological alteration and also caused nutrient pollutants to settle down. The Chinese environment bulletin in 2010 stated that N and P were the main pollutants in the Yellow River watershed (MEP 2010). As shown in Table 4, the series of reservoirs decreased the discharge of N and P pollution, which is a positive factor for watershed pollution control.

To further characterize the difference between the TN and TP discharge, the correlation analysis of their monthly discharge was performed. Results show that the R^2 value was 0.759 for the 11-year period. The TN discharge was 112 times the TP discharge. N pollution is predominantly in the dissolved form, while P is mainly in the adsorbed format (Cheng et al. 2007). The R^2 value between the TP and sand discharge was higher than for the TN discharge, which suggests that the P transported by sand adsorption and the N migrated by dissolving in water.

The large R^2 value in Fig. 6 indicates that the cascade dams have a similar effect on the two kinds of nutrient pollution. However, there are still some uncertainties in the simulation of nutrient balance, which is a persistent issue in nutrient pollution modeling (Zhang et al. 2009). According to the theory of the SWAT, the soil evaporation compensation coefficient, available water capacity of the soil layer and soil conservation service curve number are the leading uncertainty parameters. The simulation results would be clearer if there were more data from the field.

5 Conclusions

The accumulated influence of cascade dams on the hydrological principle in the upstream sections of the Yellow River was analyzed with the SWAT and on-site monitoring data. Nutrient pollution retention by the cascade dams was simulated and identified. The process and the overall influence of cascade dams were expressed using accumulated hydropower capacities (AHC) and summed dam heights (SDH).

The pollutant detention analysis indicates that the SWAT model is an option to identify the function of cascade dams. The methodology is generalizable and can be applied to similar studies about the impact of cascade dams.

Considering the operation of the cascade dams, long-term land cover variation and changing climate, the TN discharge decreased from 15.38×10^3 in 1975 to 0.39 $\times 10^3$ t in 2006. The TP discharge decreased from 1996 before to 328 kg after the construction of the cascade dams. The dams disturbed the original watershed eco-environmental pattern, but their detaining function can be used as part of watershed pollution control. Due to the operation of the cascade dams, the sand concentration difference between the outlet and inlet decreased from 0.111 to 0.074 kg/m^3. The disturbed streamflow pattern was the direct consequence of the operation of the dams, especially following the dominant dams. To ensure the eco-environmental stability in the downstream sections of the Yellow River, an ecologically oriented operation should be advocated for this watershed. With adjustment to the dams, the watershed hydrological feature can be adjusted to meet downstream water resource demands.

Acknowledgements Without the courage and comments from Prof. Skidmore at the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, this paper could not have been completed. The authors wish to thank the anonymous reviewers for their helpful advice and the Data Center for Resources and Environmental Sciences Chinese Academy of Sciences (RESDC) for their spatial data assistance. The work in this article has benefited from the financial support of the National Natural Science Foundation of China (Grant No. 41001317, 40930740).

References

Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J Hydrol 333(2–4):413–430

Ahmet K, Kadri Y, Cengiz O (2006) Effects of Kilickaya Dam on concentration and load values of water quality constituents in Kelkit Stream in Turkey. J Hydrol 317(1–2):17–30

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment Part I: model development. J Am Water Resour Assoc 34(1):73–89

Cai XM, Rosegrant MW (2004) Optional water development strategies for the Yellow River Basin: balancing agricultural and ecological water demands. Water Resour Res 40(8):W08S04

Cheng HG, Ouyang W, Hao FH (2007) The non-point source pollution in livestock-breeding areas of the Heihe River basin in Yellow River. Stoch Env Res Risk A 21(3):213–221

Chu ZX, Zhai SK (2008) Yangtze River sediment: in response to three gorges reservoir (TGR) water impoundment in June 2003. J Coast Res 24(1A):30–39

El-Shafie A, Abdin AE, Noureldin A, Taha MR (2009) Enhancing inflow forecasting model at aswan high dam utilizing radial basis neural network and upstream monitoring stations measurements. Water Resour Manage 23(11):2289–2315

Genereux DP, Leahy S, Mitasova H, Kennedy CD, Corbett DR (2008) Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA. J Hydrol 358(93–94):332–353

Hart DD, Poff NL (2002) A special section on dam removal a driver restoration. Bioscience 52(8): 653–655

Holvoet K, Gevaert V, van Griensven A, Seuntjens P, Vanrolleghem PA (2007) Modelling the effectiveness of agricultural measures to reduce the amount of pesticides entering surface waters. Water Resour Manage 21(12):2027–2035

Hsieh CD, Yang WF (2007) Optimal nonpoint source pollution control strategies for a reservoir watershed in Taiwan. J Environ Manag 85:908–917

Isik S, Dogan E, Kalin L, Sasal M, Agiralioglu N (2008) Effects of anthropogenic activities on the Lower Sakarya River. Catena 75(2):172–181

Jeong KS, Kim DK, Joo GJ (2007) Delayed influence of dam storage and discharge on the determination of seasonal proliferations of Microcystis aeruginosa and Stephanodiscus hantzschii in a regulated river system of the lower Nakdong River (South Korea). Water Res 41(6):1269–1279
Jung KW, Yoon CG, Jang JH, Kong DS (2008) Estimation of pollutant loads considering dam operation in Han River Basin by BASINS/Hydrological Simulation Program-FORTRAN. Water Sci Technol 58(12):2329–2338
Kummu M, Varis O (2007) Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. Geomorphology 85(3–4):275–293
Lehner B, Czisch G, Vassolo S (2005) The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 33:839–855
Li QK, Ij HE, Hu YW, Sun J (2007) Unit-analysis-based assessment of agricultural non-point source pollution in Qingtongxia irrigation area. J Ecol Rural Environ 23(4):33–36
Liu JY, Liu ML, Zhuang DF, Zhang ZX, Deng XZ (2003) Study on spatial pattern of land-use change in China during 1995–2000. Science in China (Series D) 46(4):373–387
Lopez-Moreno JI, Vicente-Serrano SM, Begueria S, Garcia-Ruiz JM, Portela MM, Almeida AB (2009) Dam effects on droughts magnitude and duration in a transboundary basin: the Lower River Tagus, Spain and Portugal. Water Resour Res 45(5):W02405
Maszlea DR, Whiteheadb PG, Johnson RC (1998) Hydrological studies of schistosomiasis transport in Sichuan Province, China. Sci Total Environ 216(3):193–203
MEP (Ministry of Environmental Protection of China) (2010) http://jcs.mep.gov.cn/hjzl/zkgb/2009hjzkgb/201006/t20100603_190435.htm
Mishra A, Kar S, Singh VP (2007) Prioritizing structural management by quantifying the effect of land cover and land cover on watershed runoff and sediment yield. Water Resour Manage 21:1899–1913
Muhammetoglu A, Muhammetoglu H, Oktas S, Ozgokcen L, Soyupak S (2005) Impact assessment of different management scenarios on water quality of Porsuk River and dam system - Turkey. Water Resour Manage 19(2):199–210
Nislow KH, Magilligan FJ, Fassnacht H, Bechtel D, Ruesink A (2002) Effects of dam impoundment on the flood regime of natural floodplain communities in the upper Connecticut river. J Am Water Resour Assoc 38(6):1533–1548
Ouyang W, Skidmore AK, Hao FH, Toxopeus AG, Ali A (2009a) Accumulated effects on landscape pattern by hydroelectric cascade exploitation in the Yellow River basin from 1977-2006. Landsc Urban Plan 93(3–4):163–171
Ouyang W, Wang XL, Hao FH, Srinivasan R (2009b) Temporal-spatial dynamics of vegetation variation on non-point source nutrient pollution. Ecol Model 220(20):2702–2713
Ouyang W, Skidmore AK, Hao FH, Wang TJ (2010) Soil erosion dynamics response to landscape pattern. Sci Total Environ 408(6):1358–1366
Poff NL, Olden JD, Merritt DM, Pepin DM (2007) Homogenization of regional river dynamics by dams and global biodiversity implications. Proc Natl Acad Sci U S A 104(14):5732–5737
Pringle CM, Freeman MC, Freeman BJ (2000) Regional effects of hydrologic alterations on river macrobiotic in the New World: tropical temperate comparisons. Bioscience 50:8207–8231
Richter BD, Thomas GA (2007) Restoring environmental flows by modifying dam operations. Ecology and society 12(1):12
Richter BD, Baumgartner JV, Powell J, Braun DP (1996) A method for assessing hydrologic alteration within ecosystems. Conserv Biol 10(4):1163–1174
Richter BD, Baumgartner JV, Wigington R, Braun DP (1997) How much water does a river need? Freshw Biol 37(1):231–249
Rustomji P, Zhang XP, Hairsine PB, Zhang L, Zhao J (2008) River sediment load and concentration responses to changes in hydrology and catchment management in the Loess Plateau region of China. Water Resour Res 44:W00A04
Shah Z, Kumar MD (2008) In the midst of the large dam controversy: objectives, criteria for assessing large water storages in the developing world. Water Resour Manage 22(12):1799–1824
Stave J, Oba G, Stenseth NC (2005) Nordal I Environmental gradients in the Turkwel riverine forest, Kenya: hypotheses on dam-induced vegetation change. For Ecol Manag 212(1–3):184–198
Topping DJ, Rubin DM, Melis TS (2007) Coupled changes in sand grain size and sand transport driven by changes in the upstream supply of sand in the Colorado River: relative importance of changes in bed-sand grain size and bed-sand area. Sediment Geol 202(3):538–556
Wang GQ, Wu BS, Wang ZY (2005) Sedimentation problems and management strategies of Sanmenxia Reservoir, Yellow River, China. Water Resour Res 41(9):W09417

Wang HJ, Yang ZS, Saito Y (2006) Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: connections to impacts from ENSO events and dams. Glob Planet Change 50(3–4):212–225

Yang ST, Cheng HG, Bu QS, Zhang JY, Shi XX (2006) Estimation of soil erosion and its application in assessment of the absorbed nitrogen and phosphorus load in China. Acta Scientiae Circumstantiae 26(3):366–374

Yang T, Zhang Q, Chen YD, Tao X, Xu CY, Chen X (2008) A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. Hydrol Process 22(18):3829–3843

Zeilhofer P, de Moura RM (2009) Hydrological changes in the northern Pantanal caused by the Manso dam: impact analysis and suggestions for mitigation. Ecol Eng 35(1):105–117

Zhang J, Yu ZG, Lui SM, Liu SM, Xu H, Liu MG (1997) Dynamics of nutrient elements in three estuaries of North China: the Luanhe, Shuangtaizihe, and Yalujiang. Estuaries 20(1):110–123

Zhang N, He DW, Chen JS, Cui SB (2003) A preliminary study on nitrogen contamination in the Yellow River system, China. Environ Chem 2(22):105–110

Zhang XS, Srinivasan R, Bosch D (2009) Calibration and uncertainty analysis of the SWAT model using genetic algorithms and Bayesian model averaging. J Hydrol 374(3–4):307–317