Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268	Vol. 14	No. 3	pp. 587-594	2015

Original Research Paper

Response of Ecological Base Flow to Water and Sediment Dispatching in Irrigation Areas Along Water-Deficient and Sediment-Laden River

Hongjie Wang*, Jianen Gao*(**)(***)†, Jianmei Ji*, Xiuquan Xu and Chunhong Zhao*****

*College of Water Resources and Architectural Engineering, Northwest A & F University, Yangling, Shaanxi Province, China

**Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi Province, China

***College of Natural Resources and Environment, Northwest A & F University, Yangling, Shaanxi Province, China

†Corresponding Author: Jianen Gao

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 13-10-2014
Accepted: 23-11-2014

Key Words:
Ecological base flow
Sediment dispatching
Sediment-laden river
Weihe river

ABSTRACT

Ecological base flow is a basic requirement of water flow for a healthy river ecosystem. But in Weihe River the ecological flow is not guaranteed because of the water shortage, high sediment concentration and considerable agricultural water use along the river. In this study, Baojixia under-tableland irrigation area was selected as a representative area to which a mathematical model of one-dimensional steady water non-uniform sediment regulation was applied, to analyse the impact of channel desilting on guaranteeing the ecological base flow of Weihe River. The results indicated that scouring and silting of the channel was significantly correlated with the channel water capacity and sediment content in water flows. In addition, channel desilting contributed to $55.9\times10^4 m^3$ and $79.2\times10^4 m^3$ water saving in the irrigation area in January and December which belonged to the dry season. Their contribution rates to basic flow were 3.5% and 4.9%, respectively.

INTRODUCTION

River ecological base flow is regarded as a basic requirement for aquatic organisms, and a certain amount of flow should be maintained to sustain a healthy river system (Richter et al. 1997, Smakhtin 2004). It is described as the minimum flow mainly measured by recorded flow data, wetted perimeter method and habitat method (Jowett 1997). The most widely used 'Montana' method (Tennant 1976) suggested an optimum range of the mean flow to provide aquatic organisms a good environment according to the different habitats. Based on the relation between river flow and river geometry, hydrologic and watershed characteristics are used to estimate the river base flow (Oha 1995). These methods can help us to know about the bottom line of the river environment. However, to meet the human water needs, the water needs of river ecosystem have been neglected (Richter et al. 2003). Water scarcity (Postel 2000), large amount of agricultural water use (Cai et al. 2003) and pollutant emission (Sharpley et al. 1994) lead to a problem that river ecological base flow is not ensured. It is a general problem in the arid and semi-arid areas and is particularly serious in the Weihe River basin, the largest tributary of the Yellow River. Decrease in the amount of water resources, serious water pollution in the middle and lower reaches of Weihe River and the riverbed elevation at downstream, poses a great threat to the river basin development (Gao 2009).

The main confliction of the river water resources development, spreads at the worldwide scale. Given that there are many factors influencing the river base flow, human activity plays a leading role. Reasonable water resource scheduling and regulation could alleviate this contradiction. Zhang & Cai (2001) advised that a comprehensive study should be put forward to research on the regional ecological water demand and define the effects of water resource regulations on the ecological base flow. Petts (1996) proposed some constraints of regulating river water resources to protect the river ecosystem. Lin & Li (2010) and Song et al. (2007) analysed the effect of Baojixia water diversion at Linjiacun Section to the mainstream ecological base flow and proposed some measures from the perspective of policy and management to sustain the river ecosystem. Although many researches and measures on guaranteeing the river ecological base flow are put forward, but that how to supply enough water for the food production under the condition of maximum river base flow security, is still a major contradiction in the irrigational area along water-deficient and sediment-laden river (Tornqvist & Jarsjo 2012). Furthermore, the low water efficiency of the irrigation channel caused by sedi-

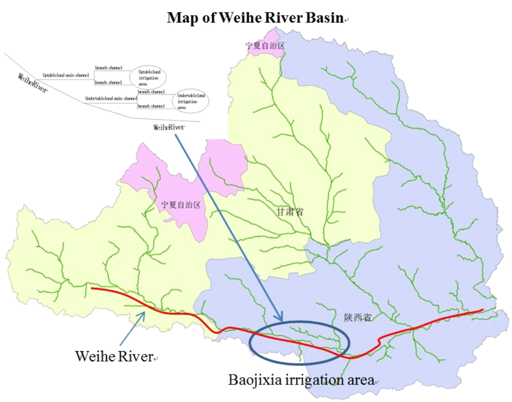

Fig. 1: The location and abridged general view of Baojixia under tableland irrigation area.

ment silting aggravates the contradiction which is the main problem in Baojixia under-tableland irrigation area.

Baojixia under-tableland irrigation area (Fig. 1) is irrigated by gravity system, diverting water from Weihe River. The amount of average annual diversion water is 438.8 million m^3 (Wang & Liu 2011) and the average annual sediment content is 26.4 kg/m^3, that means 7.02 million tons of sediment delivered by irrigation channel. Channel sediment silting is a common phenomenon caused by long-term use of muddy water, poor channel condition and the limit of management level. Until 2007, the total amount of deposition in the channel was 136.39×10^4 m^3, and the deposited length had reached 669.54 km occupying 57.6% of the total length (1161.479 km) (Li 2007). The channel capacity is decreased and the irrigation time is prolonged as a result of the largest amount of deposition in the channel. Thus, we aim at analysing the effect of water and sediment dispatching of irrigation channel on the river ecological base flow protection, using a mathematical model of one-dimensional steady non-uniform water and sediment dispatching in Baojixia undertable-land irrigation area.

MATERIALS AND METHODS

The one-dimensional steady water non-uniform sediment regulation mathematical model: The amount of water diversion is determined by the channel water efficiency under the constant water consumption of the irrigation area. But channel silting is a common phenomenon in Northern China, where the problem of water scarcity and sediment-laden constitutes a major impediment to the harmonious development of human beings and nature. Considering that the channel water efficiency is connected with the properties of channel and water flow regime, proper irrigation water management was essential to the best use of deficient water resources (Lee et al. 2005) and to the sediment delivery. The relationship between channel scouring or silting and channel water efficiency is a premise for quantitatively determining the effect of channel water saving on protection of the river ecological base flow. Thus, the one-dimensional steady water non-uniform sediment regulation mathematical model developed by Gao & Wan (1997) was used to determine the effect of channel water and sediment dispatching on channel water saving and then on guaranteeing the river ecological base flow. The characteristics of the channel water flow and sediment were coupling and simulated in the model. As the form of irrigation channel is relatively simple, the flow was assumed to be steady in the mathematical model. It is composed of the following equations:

(1) Continuity equation of steady flow:

$$\frac{\partial Y}{\partial x} + \frac{1}{2g}\frac{\partial}{\partial x}\left(\frac{Q^2}{A^2}\right) + \frac{n^2 Q^{2}}{B^2 h^{\frac{10}{3}}} = 0 \qquad ...(1)$$

(2) Momentum equation of flow:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial Y}{\partial x} + g\frac{U^2}{C^2 R} = 0 \qquad ...(2)$$

(3) Equations of bed surface deformation:

$$\frac{\partial G}{\partial x} + B\frac{\partial hs}{\partial t} + \rho' B\frac{\partial Y_0}{\partial t} = 0 \qquad ...(3)$$

(4) Sediment-carrying capability formula:

$$S_* = S_*(U, h, \omega, ...) \qquad ...(4)$$

(5) Equation of continuity of sediment:

$$\frac{\partial (BhUS)}{\partial x} + B\frac{\partial (hs)}{\partial t} = -a\beta\omega(S - S_*) - S_l q_l \qquad ...(5)$$

Where, B is the width of channel, h is the depth of water, U is the mean velocity, Y is the water level, q_l is the lateral inward flow of per unit length, S and S_* are the average sediment concentration and sediment carrying capacity of section, G is the sediment transport rate, ω is the average velocity of suspended load, ρ' is the sediment dry density, S_l is the near-shore sediment concentration of channel, g is the gravity acceleration, C is the coefficient of Chezy formula, R is the hydraulic radius, α, β are the coefficients, X is the distance and t is time.

Data for calibration and validation: In order to evaluate the feasibility of the one-dimensional steady non-uniform water and sediment regulation mathematical model, the measured data, from the original Institute of Water Conservancy Science, on June 26 to July 2 of year 1958 were used as the calibration and validation data, because there was no large scale and continuous observed data of the channel water and sediment in recent years (Table 1). The rel-

Table 1: Observed data of water and sediment in Baojixia irrigation channel in 1958.

Items	Observing location	Date (1958)						
		June 26	June 27	June 28	June 29	June 30	July 1	July 2
Water flow (m^3/s)	Channel inlet	19.67	24.04	23.44	26.75	25.3	26.73	25.79
	11th observatory	19.0	23.2	22.2	24.6	24.7	25.7	24.7
Sediment concentration (kg/m^3)	Channel inlet	48.74	37.7	23.14	22.17	15.08	54.6	15.28
	11th observatory	38.075	37.3	21.7	20.83	15.275	51.625	18.265

Table 2: Channel hydraulic elements.

Depth (m)	Area (m)	Wetted perimeter (m)	Hydraulic radius, R (m)	Slope (J)	Roughness (n)	$R^{2/3}$	$J^{1/2}$	1/n	Velocity (m/s)
0	0	0	0	0.0004	0.025	0	0.02	40	0
0.5	4.88	10.8	0.45	0.0004	0.025	0.59	0.02	40	0.49
1	10.5	12.6	0.83	0.0004	0.025	0.89	0.02	40	0.77
1.5	16.88	14.4	1.17	0.0004	0.025	1.11	0.02	40	0.99
2	24	16.2	1.48	0.0004	0.025	1.3	0.02	40	1.18
2.2	27	16.92	1.6	0.0004	0.025	1.37	0.02	40	1.26
2.8	30.42	12.36	2.46	0.0004	0.025	1.82	0.02	40	1.45

evant data were collected between the channel inlet and the 11th observatory, 10800 m of the total length. The channel section form was relatively single which was a trapezoidal section with channel bottom width 9.0 m, slope ratio 1.5, and channel-bed gradient 0.0004. The channel hydraulic elements are given in Table 2. The sediment grain size is shown in Fig. 2. The range of sediment was 0.003 mm to 1 mm.

Calibration and validation: The model was calibrated determining the three factors that characterized the channel water and sediment transport. Statistical measures were considered to evaluate the model performances and root-mean-square error (RMSE), and relative error (RM) (Dettori et al. 2011) were selected as the statistical evaluation indexes of the main influences of the model. RMSE and RM were defined by the equations below:

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2}{n}} \qquad ...(6)$$

$$\text{RM}=\frac{\left|x-\bar{x}\right|}{\bar{x}} \qquad ...(7)$$

Where x_i was the calculated data, $\bar{x}$ was the observed data, and n was the total number of data.

RESULTS AND DISCUSSION

The aim of Model calibration is to select proper model input parameters to make simulation results best match the measured data (Wang et al. 2013).

Parameter determination for the model: In order to make the model simulation results more accurate, the sediment carrying capacity, the channel roughness and the recovery saturation coefficient should be calibrated, which changed with the variation of channel siltation caused by the high sediment concentration of channel water. The data for calibration are given in Table 3.

Determination of the sediment carrying capacity formula: Sediment carrying capacity formula is used to describe the sediment transport in the channel, and many formulas have been put forward to describe the sediment carrying capacity. Three typical sediment carrying capacity formulas were considered to calculate the channel sediment transport, including, sediment-carrying capacity formula of the lower reaches of the Yellow River irrigation channel, the loess irrigation channel and the one proposed by Wuhan university institute of water resources and hydropower as given below:

(a) The sediment-carrying capacity formula of the lower reaches of the Yellow River irrigation channel (Gao & Wan 1997).

$$S_* = 0.034\left(\frac{V^2}{gr}\right)^{0.36}\left(\frac{V}{W}\right)^{0.86} \qquad ...(8)$$

(b) The sediment-carrying capacity formula of loess irrigation channel (Sha 1965).

$$S_* = 18\frac{V^4}{r^{1.5}W} \qquad ...(9)$$

Table 3: Data of water and sediment in the main channel of Baojixia under-tableland irrigation area.

Number	Discharge (m^3/s)	Velocity (m/s)	Hydraulic radius (m)	Median size (mm)	Temperature(^oC)
1	19.67	1.163	1.37	0.020	27
2	24.04	1.202	1.48	0.020	29
3	23.44	1.119	1.56	0.019	30
4	26.75	1.234	1.49	0.012	28
5	25.3	1.216	1.51	0.012	26
6	26.73	1.233	1.52	0.015	28
7	25.79	1.22	1.51	0.025	26
8	19	1.148	1.19	0.018	27
9	23.2	1.195	1.30	0.016	29
10	22.2	1.187	1.27	0.019	30
11	24.6	1.209	1.34	0.012	28
12	24.7	1.211	1.35	0.012	26
13	25.7	1.217	1.37	0.015	28
14	24.7	1.211	1.35	0.025	26

(c) The irrigation channel sediment-carrying capacity formula proposed by Wuhan University Institute of Water Resources and Hydropower (Zhang et al. 2007).

$$s_* = 0.22\left(\frac{v^3}{gRw}\right)^{0.76} \quad ...(10)$$

Where S_* is the sediment-carrying capacity, v is the cross-section mean velocity, R is the hydraulic radius, and W is the average velocity of suspended loads.

Comparison between the measured and the calculated results by three formulas is shown in Fig. 3 (a - the Yellow River irrigation channel, b - loess irrigation channel, c - Wuhan university institute of water resources and hydropower). It revealed that the formula *a* and *c* could more accurately reflect channel sediment transport. The results calculated by formula *b* were larger than the real value. The RMSE value of formula *a* and *c* were 11.09 and 8.39. Thus, the sediment carrying capacity formula proposed by Wuhan University Institute of Water Resources and Hydropower was adopted to simulate the water and sediment transport.

Determination of the channel roughness: Channel roughness reflect the boundary conditions of interaction between water flow and channel bed. Generally, the roughness value of the channel is between 0.01-0.1 (Lv et al. 2002), but it may be changed with the variation in the channel form and operating condition. The design value of channel roughness in Baojixia under-tableland irrigation area is 0.025, which has been changed with channel sediment silting, and it needs to be redefined before model simulation.

The value of channel roughness is generally derived based on the Manning formula using the measured data of channel water flow velocity (Wang et al. 2006). The Manning formula is given as:

$$C = \frac{1}{n}R^{\frac{1}{6}} \quad ...(11)$$

Where C was the Chezy coefficient, n was the channel roughness, and R was hydraulic radius.

Chezy coefficient (C) could be calculated from the relationship between flow velocity and C, which is described as below:

$$v=C\sqrt{RJ} \quad ...(12)$$

Where v was the flow velocity, and J was the hydraulic gradient.

The calculated average roughness value based on the formula (9) and (10) was 0.021, less than the design value (0.024). The channel bed became smooth as a result of the interaction of water flow and sediment.

Determination of saturation recovery coefficient: The determination of saturation recovery coefficient (Q) is criti-

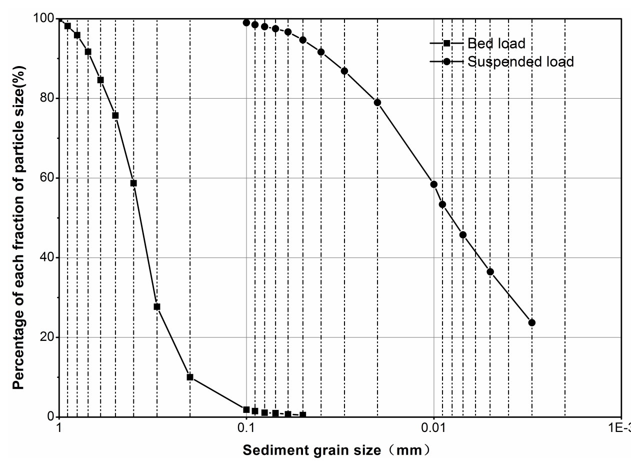

Fig. 2: Sediment gradation of suspended load and bed load.

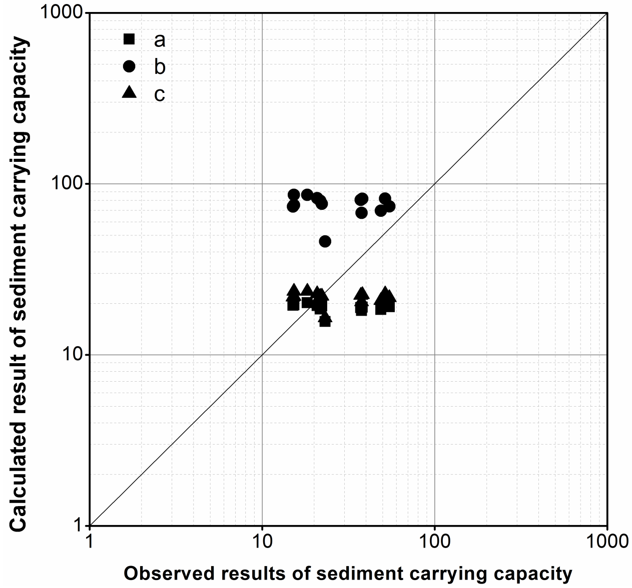

Fig. 3: Comparison of the calculated results of different channel sediment carrying capacity formulas (a - the Yellow River irrigation channel; b - loess irrigation channel; c - Wuhan University Institute of Water Resources and Hydropower) with the measured data.

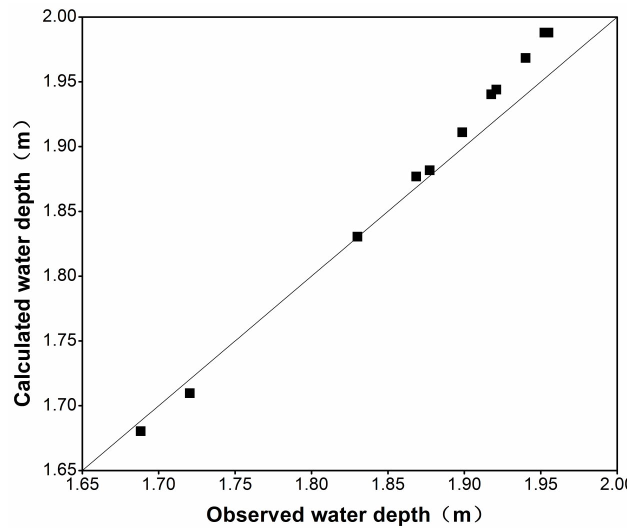

Fig. 4: Measured water depth and calculated depth without silting and scouring.

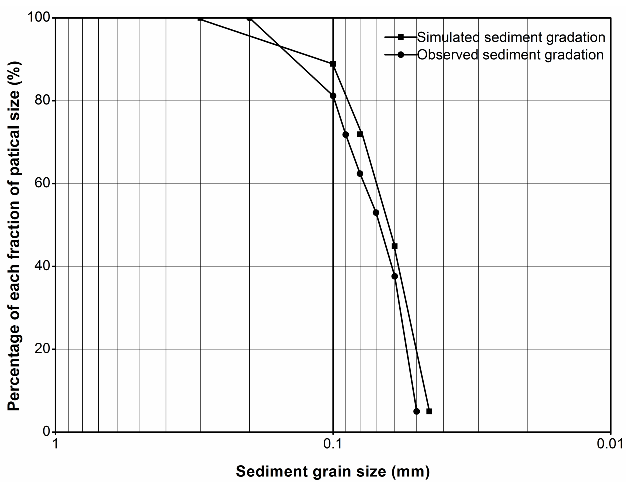

Fig. 5: Comparison of simulated sediment gradation and observed sediment gradation.

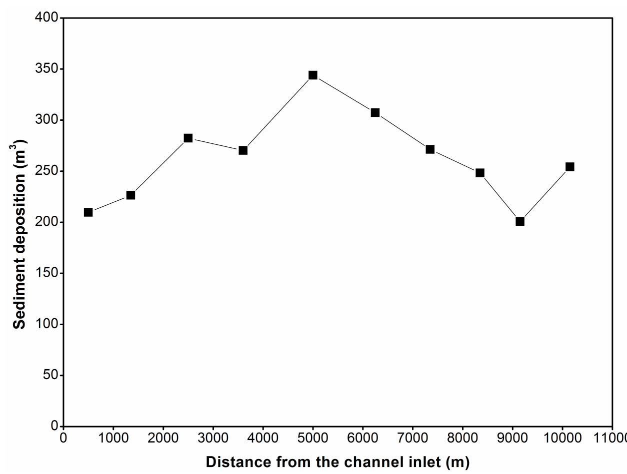

Fig. 6: Sediment deposition and distribution along the channel.

cal in the calculation of the heterogeneous-sand mathematical model. The saturation recovery coefficient (Q) should be theoretically more than 1 which is described as the ratio of the bed sediment concentration to the vertical average sediment concentration in the flow, but it may be less than or close to 1 according to the measured data. It is a comprehensive coefficient and correlates with the condition of channel scouring and silting state (Han & He 1997). In this study, the value of Q was 0.1 considering the silting condition at that period.

RESULTS AND DISCUSSION

The model performance was validated by the calculated results of channel water level, total volume of sediment deposition and the sediment gradation.

Water level is an important identification of the irrigation channel system (Weyer 2001) and its variation could be reflected by water depth. Compared with the observed water depths, the calculated water depths were less when the water flow was less than 20 m^3/s (Fig. 4). The calculated water depth could well match the observed data, with the RMSE value as 0.1. The calculated results of water level revealed that the roughness value was preferable.

Table 4: Channel scouring or silting conditions under different water-sediment combinations.

S[a] (kg/m^3)	Volume of sediment erosion or deposition (m^3)							
	q[b]=10	q=15	q=20	q=25	q=30	q=35	q=40	q=45
5	623.4	680.5	624	169.9	-1270.1	-2044	-16192.6	-41331.7
10	1280.2	1276.2	909.6	432	217.4	-584.5	-8016.2	-25897.9
20	2596.6	2503.2	2035.4	957.2	496.2	-76.9	-5763.7	-8505.1
30	3916.9	3774.4	3429.8	1483.5	775.3	431.2	-4827.9	-5045.5
40	5240.8	5049.8	3880.4	2010.6	1054.6	940.8	-2466.5	-2501.9
50	6568.7	6092	4857.3	4637.7	3859.5	2622.8	-242.3	-833.3
70	6975.9	6241.2	5142.9	4859.8	4518.5	3501.3	-56.5	-417.6
100	11278.9	9019.4	7431.2	7023.1	6529.9	5057.1	-20.4	-208.5
150	19067.1	17914.3	11284.1	10665.2	9915	7669.3	-8.9	-81.3
200	25657.2	24149.4	15186.3	14352.7	13340.4	10308.6	-3.9	-41.3

[a] ‘q’ represents water flow, m^3/s; [b] ‘S’ is sediment concentration.

The channel bed surface is changeable as an exchange of bed load with part of suspended load, which manifest as channel bed erosion and deposition (Dietrich et al. 1989). Fig. 2 showed that there was an overlap over the sediment gradation curve of bed load and suspended load. The sediment diameter was between 0.05 mm to 0.2 mm and the median diameter (D_{50}) of sediment was about 0.058 mm, meaning that the part of sediment diameter greater than 0.05 mm and less than 0.2 mm was the main portion making the channel bed change. The simulated result of sediment gradation (Fig. 5) shows that the median diameter was 0.054 mm, and the trend of the simulated curve was roughly coincident with the observed data.

According to the data observed by the original Institute of Water Conservancy Science on June 26 to July 2 of the year 1958 (Table 1), the channel was in silting state and the total volume of sediment deposition was 29637 m^3. The position of inflexion of bed load curve which had an intersection with the suspended load was at 10%. It meant that the volume of exchangeable sediment was about 2964 m^3. Fig. 6 shows the simulated conditions of channel sediment deposition and distribution along the channel, and the total amount of simulated sediment deposition was less than the observed data, about 2614 m^3. The relative error (RM) value was 0.118 which is considered to be acceptable in sediment simulation. Thus, this model can be used for the channel water and sediment dispatching calculation.

Scenario analysis: Different scenarios of water and sediment combination were set on basis of channel capacity and sand limit with the same duration (7 days) as validation. The range of channel water flow was 10 to 45 m^3/s. Sediment concentrations were 5, 10, 20, 30, 40, 50, 70, 100, 150, 200 kg/m^3. The channel sediment simulation result is depicted in Table 4.

Channel scouring or silting was closely related to the condition of channel water flow and sediment concentration (Table 4). High sediment concentration and low water flow led to channel silting, and on the contrary got opposite result. When water flow is less than 35 m^3/s, and the sediment concentration less than 20 kg/m^3, it could be viewed as no silting in the channel and even scouring when water flow was greater than 35 m^3/s. There could be no sediment silting if the channel run at the design condition (q=45 m^3/s). Thus, reasonable combination of water and sediment could reduce channel silting. The channel water flow is generally not greater than 25 at present. The channel is in the micro silting state under the sediment limit (< 8%, weight ratio) according to the simulated results, which agree well with the actual situation.

Impact of channel sediment siltation on channel water efficiency: The decrease of channel capacity caused by channel sediment deposition led to the decrease in channel water efficiency, the extended irrigation time and the increase in channel leakage loss. The relationship between water leakage loss and water flow derived from the measured data is described as below (Guo 1986):

$$q_s = 13.302Q^{0.6539} \quad ...(13)$$

Where, q_s is the loss of water flow per kilometre, L/s/km; Q is water flow, m^3/s. When the channel water flow reaches 45 m^3/s, q_s is 160 L/s/km. When the depth of channel deposition reaches 1m, the channel water capacity is 23.5 m^3/s and the q_s is 107 L/s/km. Assuming that there is no inflow or outflow along the main channel 180 km long, the channel water efficiency is 0.35 after the sediment deposition, decreasing by 22% compared with that before. In addition, the net irrigation water requirement is 160 million m^3 in normal years, and the water diverted from the river is 356 million m^3 and 457 million m^3 before and after sediment deposi-

Table 5: Average water flow of river, water diversion and sediment concentration (1991-1996).

Month	1	2	3	4	5	6	7	8	9	10	11	12
River flow (m^3/s)	11.19	16.15	21.82	37.82	41.86	75.18	79.41	82.63	67.09	62.16	36.09	16.49
Water diversion (m^3/s)	9.92	10.40	13.29	12.25	11.24	12.97	16.34	17.25	13.66	11.27	14.02	14.07
Sediment concentration (kg/m^3)	0.29	0.39	1.10	1.02	21.04	48.60	83.58	129.1	24.22	6.42	0.70	0.23

tion. It means that additional 101 million m^3 water is diverted from the river. Thus, reasonable diversion discharge and sediment concentration is of great importance for improving the channel water utilization coefficient and for guaranteeing the river ecological base flow.

Impact of Channel water saving by water and sediment scheduling on Weihe river ecological base flow: Ecological base flow as an important index for evaluating the river health has been widely studied in recent years and the calculation methods have also matured. Related studies have shown that in order to maintain the normal river ecological demand, the recent Weijiabao fort river flow should guarantee above 6 m^3/s (Wu et al. 2011). Water flow of Baojixia under-tableland irrigation area has a great impact on guaranteeing the ecological base flow. Table 5 shows the 6-year (1991-1996) average river water flow, sediment concentration and water diversion.

The river base flow could not be guaranteed in January and in December after irrigation water diversion. However, it could not lead to deposition during the dry season because sediment concentration was lower. Flood season is the main period of producing sediment, accounting for 90% of the total annual sediment. Scheduling the water and sediment in flood period to maintain the channel in good condition is a way to reduce channel deposition and save water for guaranteeing the river ecological base flow in dry season.

It has 5-7 days in flood season when the sediment concentration is less than 5 kg/m^3, and can be taken for hydraulic dredging. According to the scouring and silting conditions of different water-sediment combinations (Fig. 7), under the condition of large diversion (> 40 m^3/s) and the sediment limit (< 8%) silting is not going to happen, and scouring will happen if small concentration (< 5 kg/m^3) in flood season. At present, the depth of deposition has reached 1 m. The channel section can realize dredging 16200 m^3, dredging depth of 0.18 m, channel water use coefficient increased by 4.8%. By dredging it can save water respectively in December and January by 55.9×10^4 m^3 and 79.2×10^4 m^3, contributing 3.5% and 4.9% to the river base flow.

CONCLUSION

The decrease in channel water coefficient as a result of channel siltation was an important factor that aggravated the difficulty to guarantee river ecological base flow in water-deficient and sediment-laden river. The one-dimensional steady non-uniform mathematical model was put forward in this study to analyse the impact of channel water and sediment dispatching on the channel water coefficient, and then to determine the contribution of channel water saving to the base flow. The results indicate that through water and sediment scheduling in flood season, the Baojixia under tableland irrigation channel water utilization coefficient can be increased by 20%. That means 55.9×10^4 m^3 and 79.2×10^4 m^3 can be saved respectively in January and in December which contributes 3.5% and 4.9% to the river ecological base flow in non-flood season.

ACKNOWLEDGMENTS

This paper was supported by Natural Science Foundation of China (41371276, 51309194), by National Technology Support Project (2011BAD31B05), by the Subject of National Science and Technology Major Project (2009ZX07212-002-003-02) and by Knowledge Innovation Project of Institute of Soil and Water Conservation, CAS & MWR (Soil and Water Conservation Project) (A315021304) and by Coordinating Science and Technology Innovation Project of Shaanxi province(2013KTDZ03-03-01-01).

REFERENCES

Cai, X., McKinney, D.C. and Rosegrant, M.W. 2003. Sustainability analysis for irrigation water management in the Aral Sea region. Agr. Syst., 76: 1043-1066.

Dettori, M., Cesaraccio, C., Motroni, A., Spano, D. and Duce, P. 2011. Using CERES-wheat to simulate durum wheat production and phenology in Southern Sardinia, Italy. Field Crop Res., 120: 179-188.

Dietrich, W.E., Kirchner, J.W., Ikeda, H. and Iseya, F. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature, 340: 215-217.

Gao, J. 2009. The impact of agricultural water use on ecological baseflow of wei River in Guanzhong Region. J. Wuhan Univ., 42: 11-15 (in Chinese with English abstract).

Gao, J. and Wan, Z. 1997. A numerical model of sediment transport in Handun irrigation district. Int. J. Sediment Res., 12: 283.

Guo, Y. 1986. Irrigation and Drainage. China Water and Power Press, Wuhan (in Chinese).

Han, Q. and He, M. 1997. A study on coefficient of saturation recovery. J. Sediment Res., 32-40 (in Chinese with English abstract).

Jowett, I. 1997. Instream flow methods: A comparison of approaches. Regul. River Res. Manag., 13: 115-127.

Lee, T., Haque, M.A. and Najim, M. 2005. Modeling water resources allocation in a run-of-the-river rice irrigation scheme. Water Resour. Manag., 19: 571-584.

Li, H. 2007. Discussion on siltation causation of canal system in Baojixia irrigation district and its counter measure. Water Resour. Hydropower Eng., 38: 84-86 (in Chinese with English abstract).

Lin, Q. and Li, H. 2010. Influence and guarantee on ecological basic flow of Weihe River from Baojixia water diversion. J. Arid Land Resour. Environ., 24: 114-119. (in Chinese with English abstract)

Lv, H., Pei, G. and Yang, L. 2002. Hydraulics. China Agricultural Press, Peking (in Chinese).

Oha, D. 1995. Estimating minimum instream flow requirements for Minnesota streams from hydrologic data and watershed characteristics. N. Amer. J. Fish. Manag., 15: 569-578.

Petts, G.E. 1996. Water allocation to protect river ecosystems. Regul. River Res. Manag., 12: 353-365.

Postel, S.L. 2000. Entering an era of water scarcity: The challenges ahead. Ecol. Appl., 10: 941-948.

Richter, B., Baumgartner, J., Wigington, R. and Braun, D. 1997. How much water does a river need? Freshwater Biol., 37: 231-249.

Richter, B.D., Mathews, R., Harrison, D.L. and Wigington, R. 2003. Ecologically sustainable water management: Managing river flows for ecological integrity. Ecol. Appl., 13: 206-224.

Sha, Y. 1965. An Introduction to Sediment Kinematics. China Industry Press, Peking (in Chinese).

Sharpley, A.N., Chapra, S., Wedepohl, R., Sims, J., Daniel, T.C. and Reddy, K. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual., 23: 437-451.

Smakhtin, V. 2004. Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. Water Sa., 27: 213-218.

Song, J., Xu, Z., Liu, C. and Li, H. 2007. Ecological and environmental instream flow requirements for the Wei River-the largest tributary of the Yellow River. Hydrol. Process, 21: 1066-1073.

Tornqvist, R. and Jarsjo, J. 2012. Water savings through improved irrigation techniques: Basin-scale quantification in semi-arid environments. Water Resour. Manag., 26: 949-962.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fish, 1: 6-10.

Wang, G., Huang, Y., Wei, J. and Wu, B. 2006. Identification of roughness-coefficient value for channel of the south-to-north water transfer (middle line). Project S. N. Water Transfer Water Sci. Tech., 4: 8-14 (in Chinese with English abstract).

Wang, H., Gao, J. E., Zhang, S. L., Zhang, M. J. and Li, X. H. 2013. Modeling the impact of soil and water conservation on surface and ground water based on the SCS and visual modflow. PloS one 8: e79103.

Wang, H. and Liu, Y. 2011. Analysis of irrigation water demand in Baojixia irrigation area Shaanxi. Water Resour., 174-175 (in Chinese with English abstract).

Weyer, E. 2001. System identification of an open water channel. Control Eng. Pract., 9: 1289-1299.

Wu, W., Xu, Z. and Zuo, D. 2011. Research of estimation of river ecological base flow in Guanzhong Weihe River. J. Arid Land Resour. Environ., 25: 68-74 (in Chinese with English abstract).

Zhang, R., Xie, J. and Chen, W. 2007. River Dynamics. Wuhan University Press, Hubei (in Chinese).

Zhang, X. and Cai, H. 2001. A summary on research of the regional water requirement of ecology and the collocated model of water resources. J. of Northwest Sci.-Tech. Univ. of Agri. and For. (N. at Sci. Ed.) 29: 84-88 (in Chinese with English abstract).