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Ecological environmental flow estimation for rivers with complicated hydraulic conditions

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ABSTRACT

Estimating ecological environmental flow in tidal rivers is one of the major challenges for sustainable water resource management in estuaries and river basins. This paper presents an ecological environmental flow framework that was developed to accommodate highly dynamic medium tidal estuaries found along the Yellow Sea coast of China. The framework not only proposes a method of water quality-based ecological flow for tidal gate-controlled rivers but also proposes a method of water demand for scouring and silting to protect ports in coastal viscous sediment environments. The framework integrates the instream water requirements of water quality, sediment and basic ecological flow, and considers the temporal and spatial variation differences for the environmental flow requirements of tidal rivers. This study emphasizes the significance and necessity of continuous monitoring of ecological data in determining the environmental flow of tidal rivers. The output of this study could provide vital references for decision-making and management of the water resource allocation and ecological protection in tidal rivers.

Key words: basic ecological flow, ecological environmental flow, hydrodynamic model, medium tidal estuary, sediment transport, water quality

HIGHLIGHTS

- This study develops an ecological environmental flow framework for highly dynamic medium tidal estuaries.
- This study suggests a method of water quality-based ecological flow for tidal gate-controlled rivers.
- This study proposes a method of water demand for scouring and silting.

1. INTRODUCTION

Estuaries are semi-enclosed coastal transition zones, where freshwater inflow from rivers mixes with saline water from the sea due to tidal action. The environmental flow for estuaries is normally defined as the level of freshwater inflow required by the estuarine ecosystem to achieve satisfactory ecological objectives. However, quantifying this value is generally difficult, as the traditional methodology for studying the fluvial systems cannot be directly employed in estuaries (Xie *et al.* 2022; Gusti *et al.* 2023). Where rivers encounter estuaries, a transition zone called tidal river reach develops where riverine and tidal processes both affect flow and sediment transport processes. With the rapid growth of anthropogenic activities, frequent eutrophication, river bed sedimentation and ecosystem degradation occur (Walsh *et al.* 2013; Yang *et al.* 2014, 2015; Seijger *et al.* 2019), flows are not sufficient to sustain the deltas. As a result, environmental flow estimation in tidal rivers has become one of the major challenges for sustainable water resource management in estuaries and river basins. Previous studies have highlighted the significance and urgency of this challenge (Richter *et al.* 1997; Sun *et al.* 2009; Poff *et al.* 2010; Arthington *et al.* 2018).

The hydrodynamic process of the tidal river is a complex phenomenon that relies upon the upstream freshwater inflow and downstream tide. However, investigations into tidal rivers have been relatively poor due to difficulties in addressing complex responses of estuarine ecosystems to freshwater inflows and collecting required ecological data (Arthington *et al.* 2006; Alcázar *et al.* 2008). Research on environmental flows in tidal rivers began in the 1990s (Adams & Bate 1994; Matsumoto *et al.* 1994; Peirson *et al.* 2002; Liu *et al.* 2005). However, previous studies only focused on limited functions of estuarine ecosystems, leading to oversimplified descriptions of the characteristics of environmental flows. More recently, Sun *et al.* (2015) proposed an approach to environmental flow assessment that considers spatial pattern variations in potential habitats affected by river discharges and tidal currents in the Yellow River Estuary. Akter & Tanim (2018) established an environmental flow threshold in an ungauged semidiurnal tidal river in Bangladesh. Van Niekerk *et al.* (2019) presented an environmental flow methodology that was developed to accommodate shallow, highly dynamic micro-tidal estuaries found along the wave-dominated coast of South Africa. However, very few studies have been conducted to estimate the environmental flow in tidal rivers along the Yellow Sea coast of China.

Jiangsu Province, located in southeast China, with a coastline of over 1,000 km along the Yellow Sea, possesses the largest amount of coastal area in China. Over the past few decades, numerous projects such as beach reclamation, river dredging and the construction of sluices, dams, bridges and culverts have been implemented in the coastal regions of Jiangsu. However, these projects have resulted in water scarcity (Maren *et al.* 2023), severe riverbed siltation (Tao *et al.* 2012), saltwater intrusion and a pervasive downward trend in aquatic biodiversity and ecosystem condition (Xu *et al.* 2016; Cui *et al.* 2018; Cao *et al.* 2020). These modifications have significantly altered the hydrologic and hydrodynamic regimes of the tidal river reach and have threatened the health of the river ecosystem. Despite this, very few research studies on the environmental flow in this area have been conducted. Therefore, the development of approaches for calculating environmental flows in these estuaries is highly desired.

The aim of the study was to propose a flexible framework for determining the environmental flow of tidal river reach in southeast China, considering both water quantity and water quality as well as the requirements of sediment movement. The Xinyang River of Yancheng City was selected as the study site (Figure 1), and a hydrodynamic model was integrated with a water quality model and a sediment transport model to estimate the water quality-based environmental flow (EFw) and sediment scouring-based environmental flow (EFs), respectively. The basic ecological flow (EFb) was also estimated using the Tennant method (Tennant 1976). Finally, the environmental flow of the tidal river (EFt) reach was obtained by selecting the maximum value among the EFw, EFs and EFb. The results of this study could provide valuable references for decision-making and management of water resource allocation and ecological protection in tidal rivers.

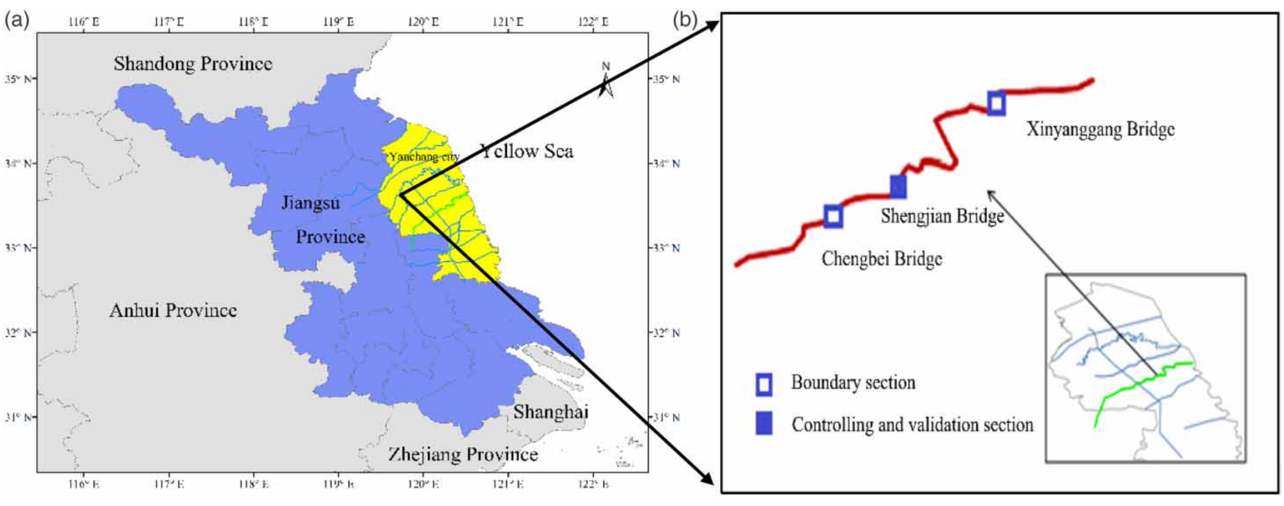

Figure 1 | Location of the study site. (a) Major tidal rivers in Yancheng City. (b) Boundary sections and controlling section of the Xinyanggang River for hydrodynamic model.

2. STUDY REGION

Yancheng City, located in the north of Yangtze Delta economic zone, has the Yellow Sea in its east and is situated downstream of the Huaihe River basin. Its coastline is 582 km long, with a beach area of 4,553 km^2. The tide level range falls within 2–3 m, making it a medium-tidal estuary. The plain landforms have long been influenced by the interlacing of the Huai River, the Yangtze River, the Yellow River and the Yellow Sea. The sediments carried by the Yellow River in the north and the Yangtze River in the south from alluvial deposits are under the influence of wind, waves and tides.

Yancheng City is located in the transition zone from subtropical to warm temperate climate, resulting in uneven distribution of precipitation throughout the year. Precipitation is concentrated in the flood season from May to September, which accounts for 71.5% of the total annual precipitation. The rivers entering the sea mainly include the Sheyang River, Xinyang River, Huangsha River, Doulong River, Chuandong River and Guan River (Figure 1(a)). The Xinyang River has a total length of 69.8 km and a watershed area of 2,478 km^2. Statistics of different dissolved oxygen (DO), chemical oxygen demand (COD), permanganate index, ammonia nitrogen (NH-N) and total phosphorus (TP) concentrations indicated that the water quality of the Xinyang River fell within the V type during 2010–2013 because of the high TP concentration (Table 1). Temporal variation of monthly TP concentration further disclosed that the higher TP values are found in May–September of the wet season and October–November of the dry season (Figure 2). It is worth noting that the TP concentration in the wet season was much higher than that in the dry season. Table 2 shows the silt condition of the five major Fig tidal rivers in Yancheng City. Severe sedimentation occurred downstream of the sluices, particularly in the Xinyang River, where the cross-section area has decreased to only 16.5% of the initial area and the average river bed siltation height increased by 5.3 m.

All the major river channels into the Yellow Sea in Yancheng City have been equipped with gates for tide and brine prevention, desalination and irrigation, and flood control and drainage. However, the original balance of sediment movement was disrupted, and the tidal current is unable to carry away all the sediment brought by the tidal current during low tide. This results in the sediment settling and gradually accumulating under the gate. To make matters worse, the amount of sediment under the gates is increasing every year, leading to a continuous decline in the river's drainage capacity.

The background analysis conducted revealed that all the tidal rivers above the sluices were characterized by low water quality, whereas the river reach located downstream of the sluices was plagued by severe sedimentation.

3. METHODOLOGY

3.1. Hydrodynamic model

The Saint Venant equations, which comprise the equations of continuity and momentum, were employed to describe the flow movement in the tidal river reach.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

Table 1 | Water quality indicator analysis of the main tidal rivers in Yancheng City

Rivers	Cross-section	DO	Permanganate index	NH-N	COD	TP	Water quality type
Xinyang River	*Yancheng (new)*	II	III	II	I	V	V
	Chengbei Bridge	II	III	III	IV	V	V
	Shengjian Bridge	II	III	III	III	V	V
	Waterworks of Xinyang River	II	III	III		V	V
	Xinyang River Sluice	I	III	III	III	V	V
Huangsha River	Shengli Bridge	II	III	III	IV	V	V
	Waterworks of Huangsha River	II	III	III		V	V
	Huangsha River Sluice	I	III	III	IV	V	V
Sheyang River	Yongxing	I	III	I	I	IV	IV
	Funing Waterworks	II	III	II	I	IV	IV
	Funing	II	III	III	I	IV	IV
	Heli	I	III	III	III	V	V
	Wuxun	I	III	II	I	V	V
	Sheyang Waterworks	II	III	II	I	V	V
	Sheyang Sluice	I	III	III	IV	V	V

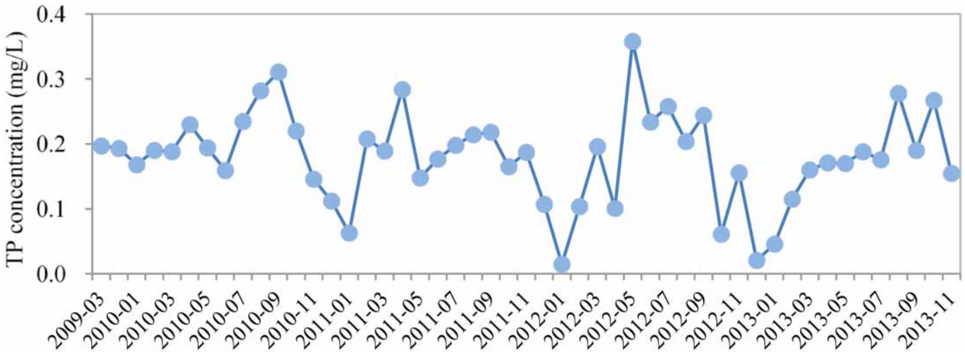

Figure 2 | Temporal variation of the daily TP concentration of the Xinyanggang River.

Table 2 | Sediment deposition of the main tidal rivers in Yancheng City

Items			**Tidal rivers**				
			Xinyang River	**Sheyang River**	**Huangsha River**	**Doulong River**	**Chuandong River**
Downstream of the sluice (km)		(1)	10.6	15.2	13.7	6.7	12
Average cross-section area (m^2)	Sluice built	(2)	1,841	2,290	654	521	105
	Now	(3)	304	875	354	258	15
	Decrease	(4)	1,537	1,415	300	263	90
	(3)/(2)	(5)	0.165	38.2	541	49.5	14.3
Channel volume (10^4 m^3)	Sluice built	(6)	1,951.6	3,480.9	896	349.1	126
	Now	(7)	320.3	1,334.9	486.5	172.3	18
	Siltation	(8)	1,631.4	2,146	409.5	176.8	108
River bed siltation height (m)		(9)	5.3	1	0.6	2.2	1

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\alpha Q^2}{A}\right)+gA\frac{\partial h}{\partial x}+\frac{gQ|Q|}{C^2AR}=0, \tag{2}$$

where x is the space coordinate (m), t is the time (s), Q is the discharge (m^3/s); h is the stage above datum (m), A is the flow area (m^2), R is the hydraulic or resistance radius (m), q is the lateral inflow (m^3/s/m), C is the Chezy resistance coefficient, g is the gravitational acceleration (m^2/s) and α is the momentum distribution coefficient.

3.2. Water quality model

The one-dimensional advection-dispersion equation was selected to simulate the water quality.

$$\frac{\partial AC}{\partial t}+\frac{\partial QC}{\partial x}-\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right)=-AKC+C_2q \tag{3}$$

where x is the space coordinate (m), t is the time coordinate (s), C is the concentration (mg/L), D is the dispersion coefficient (m^2/s), A is the cross-sectional area (m^2), K is the linear decay coefficient (1/d), C_2 is the source/sink concentration (mg/L) and q is the lateral inflow (m^3/s/m).

3.3. Sediment transport model

The single cohesive layer models were selected since the study river reach was dominated by the cohesive sediment with the particles ranging in size from 0.0076 to 0.0147 mm.

3.3.1. Single cohesive layer model – deposition

When the mean flow velocity is low enough, suspended particles and sediment flocs may settle onto the bed and remain there without being immediately resuspended, resulting in deposition. This happens when the bed shear stress is less than the critical shear stress required for deposition to occur. The rate of deposition can be expressed by

$$D = \frac{\omega c}{h^*}\left(1 - \frac{\tau}{\tau_{cd}}\right) \quad (4)$$

where D is the source term in the advection-dispersion equation, C is the concentration of the suspended sediment (kg/m^3), ω is the mean settling velocity of suspended particles (m/s), h^* is the average depth through which the particles settle (m), τ is the critical shear stress for deposition (N/m^2) and τ_{cd} is the bed shear stress (N/m^2).

3.3.2. Dynamic stream network storage capacity

The resistance of cohesive sediments against erosion is determined by two factors: the submerged weight of individual particles and the interparticle electrochemical bonds that must be overcome by shear forces before erosion occurs.

$$E = \frac{M^*}{h}\left(\frac{\tau}{\tau_{ce}} - 1\right)^n \quad (5)$$

where M^* is the erodibility of the bed (g/m^2/s) (=erosion coefficient), h is the flow depth (m) and n is the erosion exponent.

3.4. Tennant method

Tennant method (Tennant 1976) was used to calculate the basic ecological environmental flow.

$$W_t = \sum_{i=1}^{12} M_i N_i \quad (6)$$

where W_t is the ecological environmental flow of the river habitat, N_i is the recommended percentage of the ith month discharge and M_j is the mean annual discharge of the jth month.

4. MODEL ESTABLISHMENT

The calculation and storage time step of the hydrodynamic model, water quality model and sediment model were set to 1 and 60 min, respectively. The spatial step for each model was set to 200–500 m. The Shengjian Bridge was chosen as the control section for both the hydrodynamic and the water quality models (Figure 1(b)).

4.1. Hydrodynamic model

The flow discharge process was adopted as the upstream boundary of the model, while the tide level process was used as the downstream boundary. Due to limited observations, only the observed daily flow discharge and water level data for December 2006 were selected for model calibration. The results showed that the roughness coefficient fell within the range of 0.02–0.03. Three tide processes (spring tide, moderate tide and neap tide) were selected for model validation, and the determined coefficient was all higher than 0.80 (Table 3). This indicates that the established model performed well and can be used to simulate the tide movement in the Xinyang River.

Table 3 | Determined coefficient of the hydrodynamic model

	Validation		
Calibration	**Spring tide**	**Moderate tide**	**Neap tide**
0.63	0.8	0.83	0.88

4.2. Water quality model

The TP concentration was chosen as the control indicator of the water quality model, with the goal of reaching Class IV of the surface water environmental quality. The TP concentration of 0.250 mg/L (inferior Class V water quality) was chosen as the initial condition of the water quality model to calculate the ecological environmental flow. The gauge sections of the Chengbei bridge and the Xinyang sluice were selected as the upstream and downstream boundaries for the model, respectively.

The main parameters used during the water quality simulation were the longitudinal diffusion coefficient and the pollutant attenuation coefficient. Based on published research near the Xinyang River, these two coefficients were decided as 5–35 m^2/s, 0.08–0.2 (1/d), respectively. The validation results showed that the monthly calculated TP concentration followed a similar pattern as the observed values, with the calculated value falling between one second and twice the observed values (Figure 3). This indicates that the selected parameters are reasonable, and the constructed model is capable of simulating TP variations in the Xinyang River.

4.3. Sediment transport model

The downstream section of Xinyang sluice was selected to simulate the sludge height of the riverbed along the river. The immediate downstream of the Xinyanggang sluice was set as the upstream boundary by assuming its sediment concentration was zero, and the sediment gauging section nearest to the estuary was regarded as the downstream boundary of the model.

Due to limited observed values, only the sludge height of the riverbed at 60, 970 and 3,030 m distance along the river were used for the model calibration (Figure 4). This figure showed that the observed sludge height values were evenly distributed around the curve of calculated ones, indicating that the built model is capable of simulating the variations of the sludge height downstream of the Xinyang sluice.

5. RESULTS AND DISCUSSION

5.1. Water quality based environmental flow

Because water quality differs significantly between wet and dry seasons, the EFw was calculated separately for each season. Correspondingly, July, which has the highest TP concentration during the wet season, and November, which has the highest TP concentration during the dry season, were selected as the representative months.

The environmental flow was calculated as follows: a group of flow discharge was recharged to the upstream of the river, and the EFw was defined as the flow discharge that resulted in a TP target concentration of 0.1 mg/L in the control section, which meets the Class IV of the surface water environmental quality standard the water quality of reaches with the, the recharged flow discharge can be considered as. Based on Figures 5 and 6, we observed that the TP concentration reached

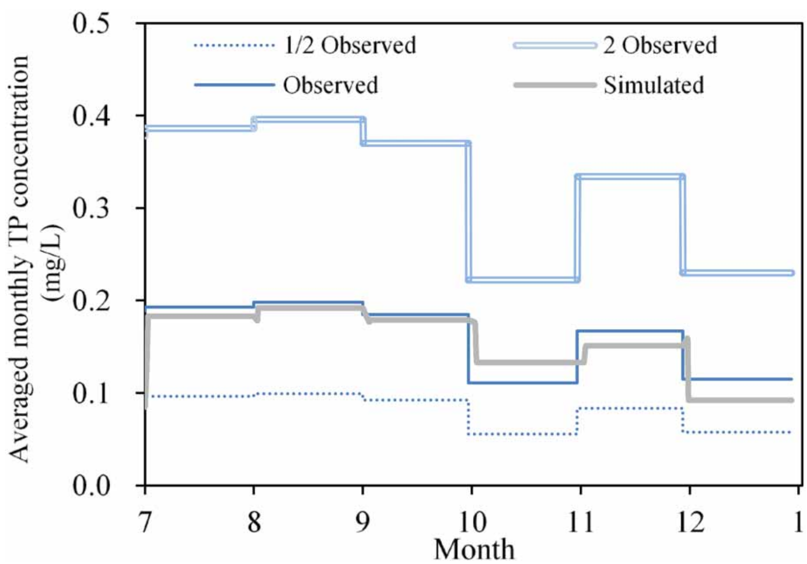

Figure 3 | Validation of the TP concentration in the Xinyanggang River.

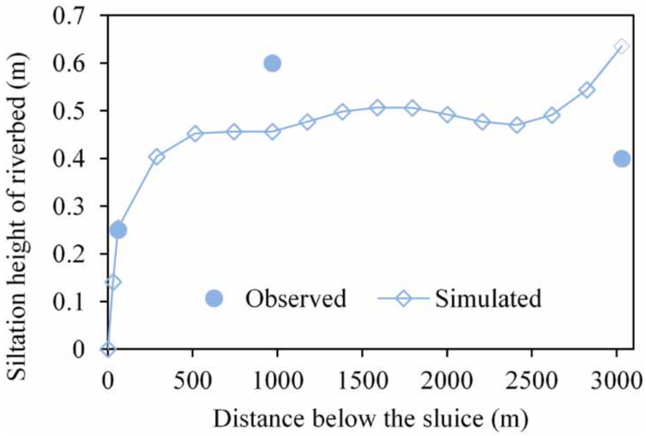

Figure 4 | Calibration of the sludge height downstream of the Xinyanggang sluice.

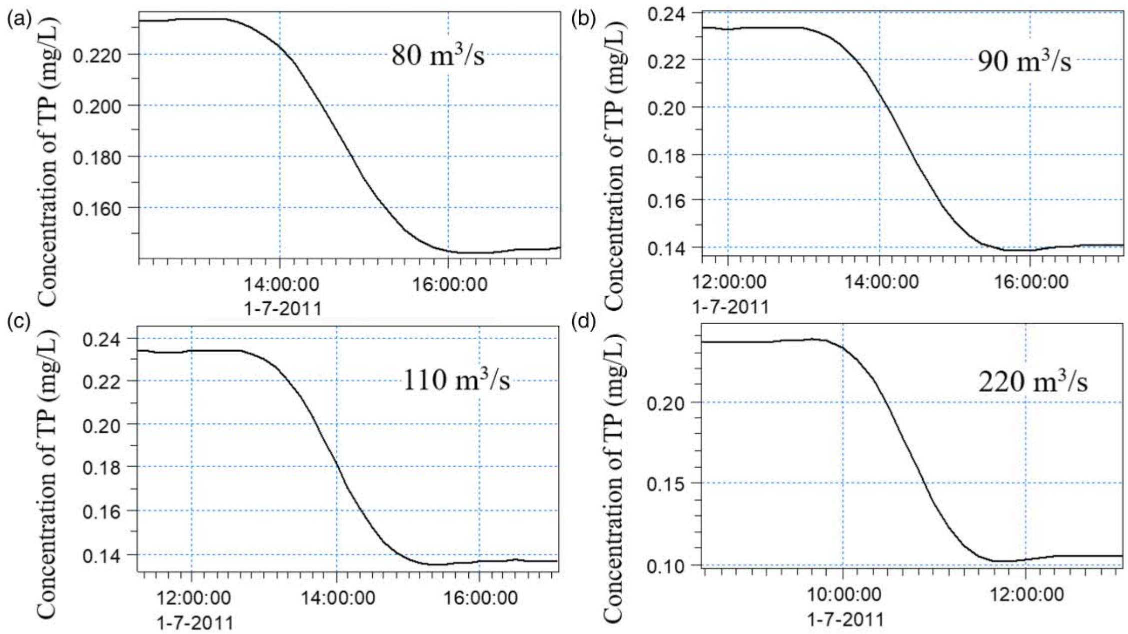

Figure 5 | Temporal variations of the TP concentration at Xinyanggang River control section with different flow recharges during July: (a) 80 (b), 90, (c) 110 and (d) 220 m^3/s.

approximately 0.1 mg/L when the recharged flow increased to 220 and 60 m^3/s during July and November, respectively. Therefore, the EFw for the wet and dry seasons of the Xinyang is 220 and 60 m^3/s, respectively.

5.2. Sediment scouring based environmental flow

The EFs were calculated by following steps: first, the target sludge height of the river bed was set at 0.15 m based on the river hydraulic condition; second, the water release from the Xinyang sluice was regulated; third, the released water discharge was considered as an environmental flow for sediment scouring once the sludge height of river bed was stable around 0.15 m. It can be seen that the riverbed sludge height was kept at 0.15 m when the water was released at 40 m^3/s (Figure 7); thus, the water discharge of 40 m^3/s was regarded as the EFs for protecting the downstream of the Xinyang River. It was also mentioned that these EFs can be applied during the dry season since the Xinyang sluice will be opened to release flood during wet seasons.

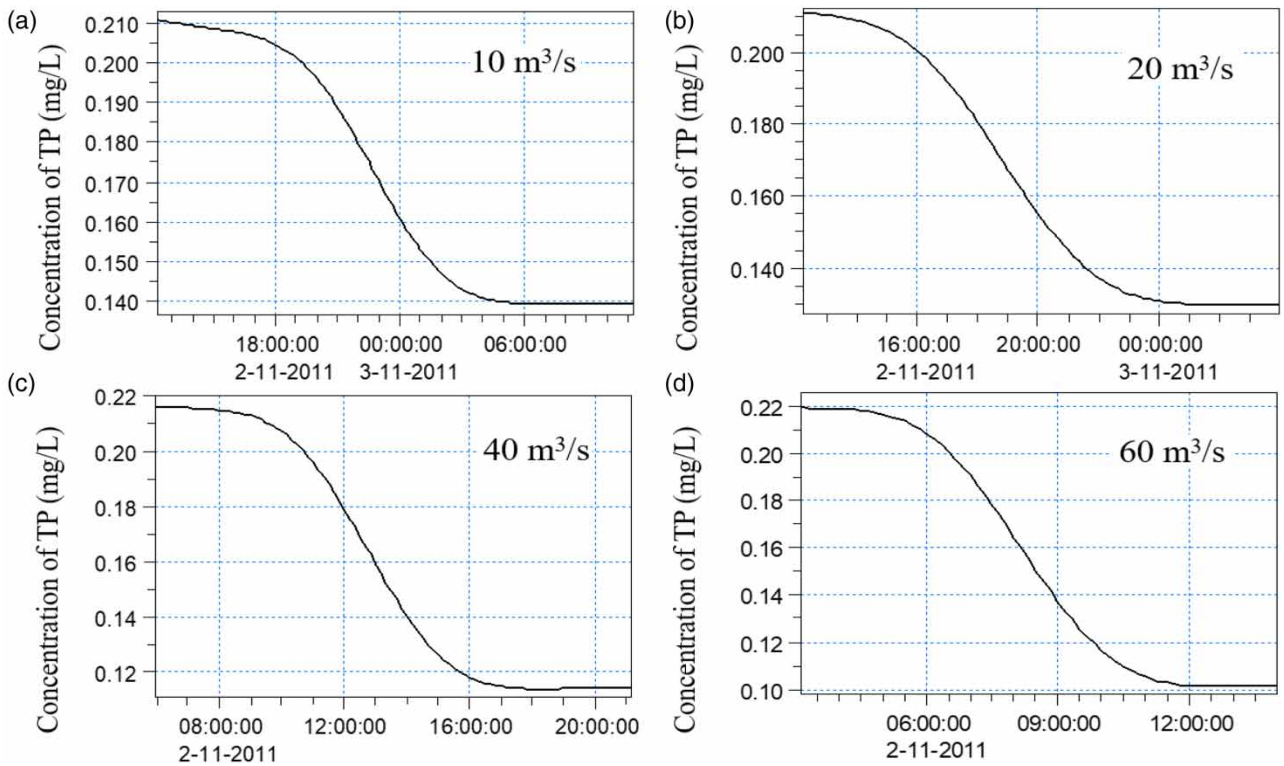

Figure 6 | Temporal variations of the TP concentration at Xinyanggang River control section with different flow recharges during November: (a) 10, (b) 20, (c) 40 and (d) 60 m^3/s.

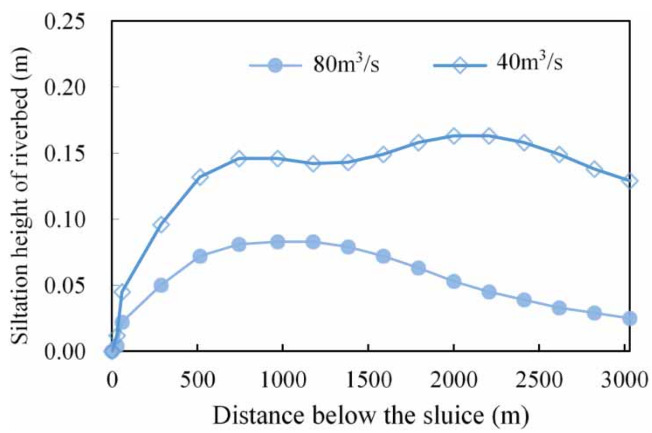

Figure 7 | River sludge height along the downstream of the Xinyanggang sluice with different released water discharges.

5.3. Environmental flow in tidal river reach

The EFb for the Xinyang River was calculated and presented in Table 4. It can be seen that the optimum range of flow during the wet season is 53.4–89 m^3/s, while during the dry season, it is 20.1–33.5 m^3/s.

The environmental flow above the Xinyang sluice can be obtained from the higher value between the EFw and the EFb. Therefore, for the wet season, the environmental flow above the Xinyang sluice is 220 m^3/s, and for the dry season, it is 60 m^3/s. For the environmental flow below the Xinyang sluice, it is mainly up to the EFs and thus it equals 40 m^3/s instead.

Table 4 | Seasonal basic ecological flow

Narrative description of flows	Recommended base flow regimen (m^3/s) Wet season (May–September)	Dry season (October–April)
Flushing or maximum	178	67
Optimum range	53.4–89	20.1–33.5
Outstanding	35.6	20.1
Excellent	26.7	16.8
Good	17.8	13.4
Fair or degrading	8.9	10.1
Poor or minimum	8.9	3.4
Severe degradation	0–8.9	0–3.35

5.4. Discussion

Special geographical location determines the estuary region always being affected by intensified anthropogenic activities, which leads to frequent water pollution and persistent sedimentation. Therefore, ecological water requirements for water quality and sediment movement must be considered during the estimation of the environmental flow for tidal rivers. To address these challenges, the EFw is calculated to satisfy the water demand for dilution and self-purification of the water body. This can help maintain the water quality in the estuary region and ensure the health of aquatic ecosystems. Similarly, the EFs are calculated to meet the water demand for sediment transport. This helps maintain a certain channel volume and drainage capacity in the tidal reach, which is critical for navigation and flood control. By ensuring sediment movement, the EFs can also contribute to preventing the sedimentation of the riverbed and maintaining the stability of the ecosystem. Therefore, considering both EFw and EFs is crucial in estimating the environmental flow for tidal rivers, as it helps maintain the ecological health and functionality of the river system.

In the study, a framework for determining the environmental flow of medium tidal rivers was proposed. The framework integrates the instream water requirements of water quality, sediment and basic ecological flow, which satisfies the water demand for the sediment scouring to protect river channels and for the survival and reproduction of aquatic life in tidal river reaches. The framework considers temporal and spatial differences in the environmental flow requirements of tidal rivers, such as the wet season and dry season, above and below the sluice. It is easily understood and operational. In addition, the datasets required are not difficult to obtain. The relatively sound understandability and practicality make it have the potential to be widely applied in tidal river reaches dominated by cohesive sediment. To the best of our knowledge, this is the first attempt to estimate the environmental flow in the mid-tide rivers and also in the tidal rivers flowing into the Yellow Sea, China. What needs to be emphasized is that the selected sediment module should be matched with the sediment particle size. In addition, the objective of the water quality simulation should also be selected based on the actual water quality condition of the tidal rivers. For instance, the water quality conditions of the Xinyang River were assessed, and it turned out that only the TP indicator did not meet the required standards. Therefore, only the TP target concentration was set as the objective of the model simulation. Due to the lack of ecological monitoring data, such as fish spawning quantity and fish catch number, although it considered the ecological aspect by the basic ecological flow, the study did not consider the specific ecological factors. The four major carp are the common fish taxa in the Jiangsu coastal region. This demonstrates the significance and necessity of continuing to monitor ecological data when determining the environmental flow of tidal rivers. Instead, we divided the periods into wet and dry seasons to better consider the water amount demand differences during the reproductive period and non–reproductive period for living creatures in river systems. Salinity was also not considered since it lacks monitoring. Therefore, the next step is to build a site monitoring station to monitor consecutive salinity concentrations to improve the ecological environmental flow of the tidal river reaching the Yellow Sea estuary.

6. CONCLUSIONS

It is important to maintain ecological environmental flows in rivers to ensure the health and stability of the river systems, particularly in the face of increasing anthropogenic activities. The Xinyang tidal river has been assessed and an ecological environmental flow has been estimated for both the wet and dry seasons, as well as above and below the Xinyang sluice.

The ecological environmental flow required above the Xinyang sluice during the wet season is 220 m^3/s, which means that at least this amount of water must flow through the river to maintain the health and stability of the ecosystem. Similarly, during the dry season, a minimum of 60 m^3/s is required. Below the Xinyang sluice, the required ecological environmental flow is 40 m^3/s.

The output can be used as a reference to ensure the rational utilization and development of coastal water resources in the area, taking into account the needs of the ecosystem. It can also help promote the health and stability of the river systems in the face of changing environmental conditions and increasing anthropogenic activities.

FUNDING

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adams, J. B. & Bate, G. C. 1994 *The Fresh Water Requirements of Estuarine Plants Incorporating the Development of an Estuarine Decision Support System*. Vol. 1. South African Water Research Commission. WRC Report 292/1/94 ISBN186845-130-5.

Akter, A. & Tanim, A. H. 2018 A modeling approach to establish environmental flow threshold in ungauged semidiurnal tidal river. *Journal of Hydrology* **558**, 442–459. https://doi.org/10.1016/j.jhydrol.2018.01.061.

Alcázar, J., Palau, A. & Vega-Garcı, C. 2008 A neural net model for environmental flow estimation at the Ebro River Basin, Spain. *Journal of Hydrology* **349** (1–2), 44–55. https://doi.org/10.1016/j.jhydrol.2007.10.024.

Arthington, A. H., Bunn, S. E., Poff, N. L. & Naiman, R. J. 2006 The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16** (4), 1311–1318. https://doi.org/10.1890/1051-0761(2006)016[1311:tcopef]2.0.co;2.

Arthington, A. H., Kennen, J. G., Stein, E. D. & Webb, J. A. 2018 Recent advances in environmental flows science and water management – Innovation in the Anthropocene. *Freshwater Biology* **63** (8), 1022–1034. https://doi.org/10.1111/fwb.13108.

Cao, Z., Wang, L., Yang, L., Yu, J., Lv, J., Meng, M. & Li, G. 2020 Heavy metal pollution and the risk from tidal flat reclamation in coastal areas of Jiangsu, China. *Marine Pollution Bulletin* **158**, 111427. https://doi.org/10.1016/j.marpolbul.2020.111427.

Cui, L., Li, G., Ouyang, N., Mu, F., Yan, F., Zhang, Y. & Huang, X. 2018 Analyzing coastal wetland degradation and its key restoration technologies in the coastal area of Jiangsu, China. *Wetlands* **38** (3), 525–537. https://doi.org/10.1007/s13157-018-0997-6.

Gusti, G., Kawanisi, K., Sawaf, M., Khadami, F. & Xiao, C. 2023 Investigating tidal river dynamics in a longitudinally varying channel geometry. *Continental Shelf Research* **253**, 104901.

Liu, W. C., Liu, S. Y., Hsu, M. H. & Kuo, A. Y. 2005 Water quality modeling to determine minimum instream flow for fish survival in tidal rivers. *Journal of Environmental Management* **76** (4), 293–308. https://doi.org/10.1016/j.jenvman.2005.02.005.

Maren, v. D. S., Beemster, J. G. W., Wang, Z. B., Khan, Z. H., Schrijvershof, R. A. & Hoitink, A. J. F. 2023 Tidal amplification and river capture in response to land reclamation in the Ganges-Brahmaputra delta. *CATENA* **220** (Part A), 106651. https://doi.org/10.1016/j.catena.2022.106651.

Matsumoto, J., Powell, G. & Brock, D. 1994 Freshwater-inflow need of estuary computed by Texas Estuarine MP model. *Journal of Water Resources Planning and Management* **120** (5), 693–714. https://doi.org/10.1061/(asce)0733-9496(1994)120:5(693).

Peirson, W. L., Bishop, K. & Van Senden, D. 2002 *Environmental Water Requirements to Maintain Estuarine Processes, WRL Technical Report Number 3, ISBN 0 6425 48277*. School of Civil and Environmental Engineering, University of New South Wales, Environment Australia.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E. & Warner, A. 2010 The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards. *Freshwater Biology* **55** (1), 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.

Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. P. 1997 How much water does a river need. *Freshwater Biology* **37** (1), 231–249. https://doi.org/10.1046/j.1365-2427.1997.00153.x.

Seijger, C., Datta, D. K., Douven, W., van Halsema, G. & Khan, M. F. 2019 Rethinking sediments, tidal rivers and delta livelihoods: Tidal river management as a strategic innovation in Bangladesh. *Water Policy* **21** (1), 108–126. https://doi.org/10.2166/wp.2018.212.

Sun, T., Yang, Z. F., Shen, Z. Y. & Zhao, R. 2009 Environmental flows for the Yangtze Estuary based on salinity objectives. *Communications in Nonlinear Science and Numerical Simulation* **14** (3), 959–971. https://doi.org/10.1016/j.cnsns.2007.10.006.

Sun, T., Zhang, H., Yang, Z. & Yang, W. 2015 Environmental flow assessments for transformed estuaries. *Journal of Hydrology* **520**, 75–84. https://doi.org/10.1016/j.jhydrol.2014.11.015.

Tao, J. F., Yang, T., Xu, F. & Yao, J. 2012 Effect of large scale tidal flat reclamation on hydrodynamic circulation in Jiangsu coastal areas. *Asian and Pacific Coasts* **2011**, 662–669. https://doi.org/10.1142/9789814366489_0077.

Tennant, D. L. 1976 Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries* **1** (4), 6–10. https://doi.org/10.1577/1548-8446(1976)001<0006:ifrffw > 2.0.co;2.

Van Niekerk, L., Taljaard, S., Adams, J. B., Lamberth, S. J., Huizinga, P., Turpie, J. K. & Wooldridge, T. H. 2019 An environmental flow determination method for integrating multiple-scale ecohydrological and complex ecosystem processes in estuaries. *Science of the Total Environment* **656**, 482–494. https://doi.org/10.1016/j.scitotenv.2018.11.276.

Walsh, C. T., Reinfelds, I. V., Ives, M. C., Gray, C. A., West, R. J. & van der Meulen, D. E. 2013 Environmental influences on the spatial ecology and spawning behaviour of an estuarine-resident fish, *Macquaria colonorum*. *Estuarine, Coastal and Shelf Science* **118** (118), 60–71. https://doi.org/10.1016/j.ecss.2012.12.009.

Xie, D., Wang, Z., Huang, J. & Zeng, J. 2022 River, tide and morphology interaction in a macro-tidal estuary with active morphological evolutions. *CATENA* **212**, 106131. https://doi.org/10.1016/j.catena.2022.106131.

Xu, C., Pu, L., Zhu, M., Li, J., Chen, X., Wang, X. & Xie, X. 2016 Ecological security and ecosystem services in response to land use change in the coastal area of Jiangsu, China. *Sustainability* **8** (8), 816. https://doi.org/10.3390/su8080816.

Yang, Z. F., Sun, T. & Zhao, R. 2014 Environmental flow assessments in estuaries related to preference of phytoplankton. *Hydrology and Earth System Sciences* **18** (5), 1785–1791. https://doi.org/10.5194/hess-18-1785-2014.

Yang, Z. F., Sun, T. & Qin, X. S. 2015 Calculating methods for quantifying environmental flows in estuaries: A case study of Haihe River Basin, China. *Journal of Environmental Informatics* **6** (2), 72–79. https://doi.org/10.3808/jei.200500057.

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