Response of Phosphorus near Reservoirs in South Branch of the Yangtze Estuary to the Upstream Runoff and Sediment Load Variations

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Abstract: The water quality of reservoirs in the south branch of the Yangtze estuary is strongly influenced by the phosphorus loadings. The variations of runoff and sediment loads from upstream cause the temporal variations of phosphorus loadings here, which poses potential risks to the reservoirs. The changes of runoff and sediment loads from upstream in the future are uncertain because of human activities and global climate change. An integrated water quality model was established to study the possible changes of phosphorus loadings in the south branch of the Yangtze estuary in the future in response to variations of runoff and sediment loads from upstream. The model contains hydrodynamic, sediment dynamics, and some biochemical processes. The model is well-calibrated and verified based on the related data in 2018. Different sets of runoff and sediment loads from upstream were then applied in this model to learn the changes of concentration of total phosphorus (TP), phosphate (PO_4^{3-}), and particle phosphorus (PP). Results show that the TP concentration has no significant change with different conditions of input of runoff and sediment loads. However, the PO_4^{3-} and PP concentrations are significantly influenced by both the changes of runoff and sediment loads. The annual mean value of PO_4^{3-} concentration would increase by 10-25% if the input of runoff increases by 20% or the sediment loads decrease by 20%. It would decrease by 8-20% if the input of runoff decreases by 20% or the sediment loads increase by 20%. The annual mean value of PP concentration would increase by 12-35% if the input of runoff decreases by 20% or the sediment loads increase by 20%. It would decrease by around 15-30% if the input of runoff increases by 20% or the sediment loads decrease by 20%. The changes of the PO_4^{3-} and PP are caused by the convection and diffusion of the flow, and the adsorption and desorption of sediments. Notwithstanding, these changes would reconstitute the component of TP of reservoirs in the south branch of the Yangtze estuary. Although the PP still takes the main proportion, the proportion of PO_4^{3-} would increase significantly and the growth of plankton would be promoted which may cause a high risk of eutrophication.

1 INTRODUCTION

Phosphorus (P) is one of the most important nutrient elements determining ecosystem production (Sanudo-Wilhelmy et al., 2001; Babu & Nath, 2005). However, excessed P loadings in water would bring about eutrophication following with serious water quality problems (Hilton et al., 2006). In the past decades, anthropogenic inputs of P have increased dramatically in many mega-estuaries, such as the Yangtze, the Mississippi, and the Nile (Goolsby et al., 1999; Ludwig et al., 2009; Xu et al., 2013). The estuarine areas are always densely populated and economically developed. Thus the losses caused by eutrophication here are always huge.

The Yangtze estuary is one of the most urbanized coastal regions of China. The estuarine environment has significantly deteriorated in recent decades (Wang, 2006). The frequency of occurrence of algal blooms has increased with each decade since 1970. From 2000 to 2010 over 100 harmful algal blooms were occurring (Liu et al., 2013). To solve this problem, the government had made some policies to reduce the P loadings from fertilizer, sewage (domestic and industrial), and manure from livestock

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in the upstream river basin. The implementation of these policies has achieved some progress. However, because of human activities and global climate change, the input of flow and sediment loadings from upstream to the Yangtze estuary changes a lot, which causes the adjustment of P loadings in the estuary (Tang et al., 2020). The weather change would change the rainfall in the Yangtze River basin, which further changes the input of flow to the estuary. The flow condition controls the diffusion process, which may change the spatial distribution of P. After the Three Gorges dam started to work in 2003, the sediment loadings to the estuary show a sharp decrease (Chen et al., 2010; Ren et al., 2021). In 2000-2010, the suspended sediment loadings in the estuary decreased about 20-30% (Li, 2012). The adsorption and desorption with suspended sediment are considered as one of the main processes controlling the P circulation in estuarine areas (Froelich, 1988; Shen et al., 2008; Xu et al., 2015) since the P has a high affinity with fine sediment (Stone & English, 1993; Winterwerp & van Kesteren, 2004). Thus, the sediment input condition would change the loadings and constitution of P in water. For preventing and solving new potential water quality problems in reservoirs in the Yangtze estuary, it is necessary to study the P responses to variations of runoff and sediment loads from upstream.

Numerical modeling is an effective approach to study this problem. In the Yangtze estuary, several researchers have used numerical models to study water quality problems. However, water quality processes in these models are mainly based on a single convection-diffusion equation, which is not adequate for much more complex estuary systems. Although some new studies have included some biochemical processes in their models (Wang et al., 2016; Zhu et al., 2016; Ge et al., 2020), their results can only reflect the current situation rather than study the question imposed in this study.

To study the response of P near reservoirs in the south branch in the Yangtze estuary to the variations of runoff and sediment loads from upstream, an integrated water quality model for the Yangtze estuary is developed. The model includes the sediment dynamic processes, the mineralization, and the adsorption and desorption of sediment to achieve the following objectives: (1) show the temporal and spatial distribution of P in the south branch in 2018; (2) study the changes of P loadings in the south branch with the change of flow and sediment input; (3) study the changes of the constitution of P in the south branch with the change of flow and sediment input. This study would also bring some contributions to the knowledge of the geochemical circulation of P in estuarine areas.

2 MATERIALS AND METHODS

2.1 Study Area

The study area is the Yangtze estuary (from Xuliujing to the mouth of the estuary). Hydrodynamic and water quality data were measured in several observation stations in this area (red dots in Figure 1). The water level data in Xuliujing (XLJ) and Shidongkou (SDK) stations are applied for the calibration and verification of the hydrodynamic model. In XLJ, SDK, Beigang (BG), and Nangang (NG) stations, data of temperature, dissolved oxygen concentration (DO), suspended sediment concentration (SSC), total phosphorus concentration (TP), and orthophosphate concentration (PO_4^{3-}) is applied for the calibration and verification of the water quality model.

Three reservoirs settled in the south branch of the Yangtze estuary are the main concerns in this research. They are the Dongfengxisha (DFXS) reservoir, the Chenhang (CH) reservoir, and the Qingcaosha (QCS) reservoir (red stars in Figure 1)

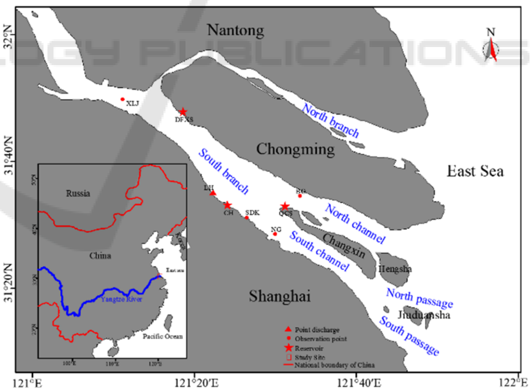


Figure 1: Sketch map of the Yangtze estuary and the distribution of the three reservoirs and the observation stations used in this study.

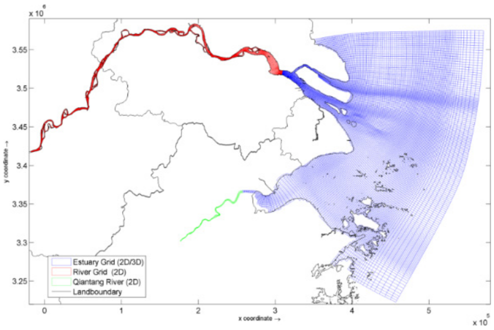


Figure 2: Model domain of the process-based Yangtze estuary model (red grid: Datong-Xuliujing; blue grid: Xuliujing-Sea; green grid: Lucipu-Haining). (Chu, 2019).

2.2 Hydrodynamic Model

The hydrodynamic model for the Yangtze estuary is set up with the upstream boundary set at Datong, the tidal limit, including part of the adjacent East China Sea and the entire Hangzhou Bay based on Delft3D (Chu, 2019). The hydrodynamic processes are modeled in the hydrodynamic model. The model domain is shown in Figure 2, which comprises three regional models with two-dimensional simulation. The bathymetry and coastal line measured in 2018 were used in this study. This hydrodynamic model is well-calibrated and validated (Chu, 2019). More details about the model domain can be learned in Chu's study (2019).

2.3 Water Quality Model

The water quality model is built based on the hydrodynamic model by including the water quality module of Delft3D. The water quality model includes the temperature, the oxygen, the particle inorganic matter, the dissolved inorganic matter, and the organic matter. To be specific, they are the water temperature, the dissolved oxygen, the suspended and bed sediment, the total phosphorus (TP), the particle phosphorus (PP) and, the orthophosphate (PO_4^{3-}) both in water and adsorbed onto sediment. All upstream boundary conditions of all these matters are set in Datong based on the measured data in 2018. The data of the sea boundary are set as constant according to the model calibration. Besides, there is a point source pollution set as discharge in the model (LH shown as in Figure 1), and the data are also set based on the measurement.

Except for the convection-diffusion processes, the following processes are also modeled: the heat exchange, the reaeration of oxygen, the resuspension and sedimentation of sediment, the adsorption and desorption of sediment, and the mineralization of organic phosphorus. Based on the literature and the model calibration, the values of the main parameters for all these processes are determined and listed in Table 1.

Table 1: Values of major parameters of the water quality model.

Process	Parameter	Unit	Value	Reference
Heat exchange	FactRcHeat	-	0.2	Default
	ZHeatExch	°C/d	0.1	
	TCKadsP	-	1	
Oxygen reaeration	KLRear	-	1	Default
Diffusion	XDisper	m^2/s	10	Calibrated
	YDisper		10	
	VertDisper		0.001	
Sediment motion	VSedIM1	m/d	7	Chu, 2019 & Calibrated
	TaucRSIDM	N/m^2	0.3	
	TaucSIM1	N/m^2	0.15	
	VResDM	1/d	7	
Mineralization	Ku_dFdcP20	1/d	0.18	Bowie et al., 1985
	Kl_dFdcP20		0.15	
Adsorption & desorption	RcAdPO4AAP	1/d	0.08	Calibrated
	RcAAPS1	1/d	0.04	Calibrated
	Kads_20	(mol/L) (1-a)	3.8	Default
	KdPO4AAP	m^3/g	0.7	Calibrated

Note: the specific meanings of the abbreviations in the table can be learned in the Manual of the Delft3d (D-Water Quality Processes Library Description (Version 5.01), 2017)

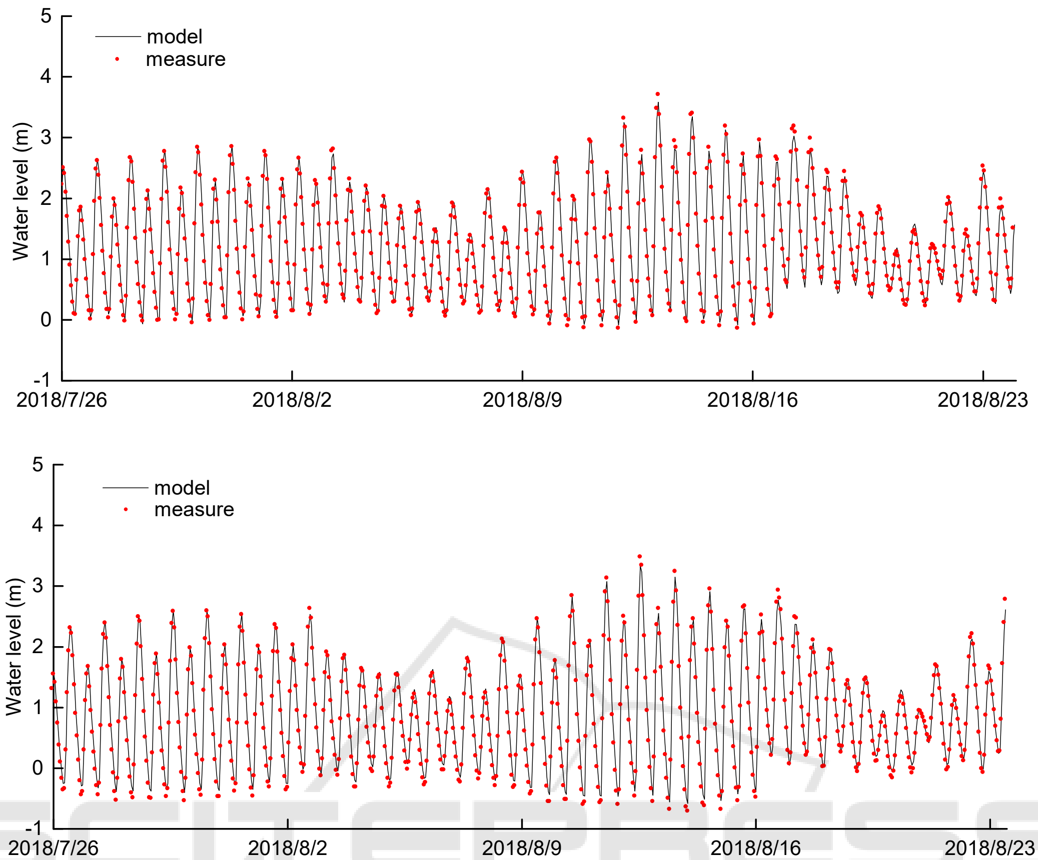


Figure 3: Verification of the water levels at (a) XLJ and (b) SDK stations.

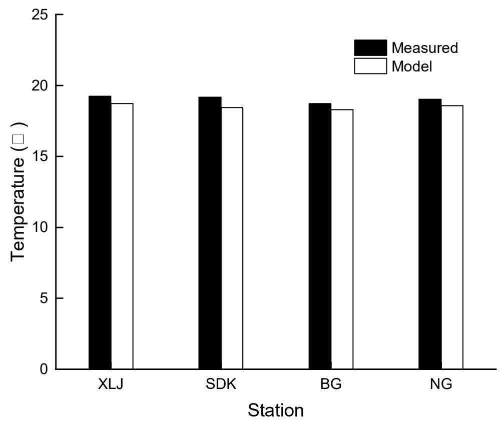
The model is calibrated and verified with the measured data in 2018. The well-calibrated and verified model is considered as the original case (Case 1). Then 4 cases based on the original one are set to change the input of flow and sediment. The flow condition of the upstream boundary increases to 120% and decreases to 80% of the original to learn the change of the flow (Case 2 and 3). The sediment condition of the upstream boundary increases to 120% and decreases to 80% of the original to learn the change of the sediment (Case 4 and 5).

3 RESULTS AND DISCUSSION

3.1 Calibration and Verification

3.1.1 Hydrodynamic Model

An integrated verification of the hydrodynamic model was carried in Chu's work (Chu, 2019). In this research, the following data are collected to show the brief verification of the hydrodynamic model, while more details about it can be learned in Chu (2019). In Figure 3, hourly data of water level in flood season in 2018 in XLJ and SDK stations are well verified. The good verification indicates the hydrodynamic conditions in the water quality model are accurate and reliable.



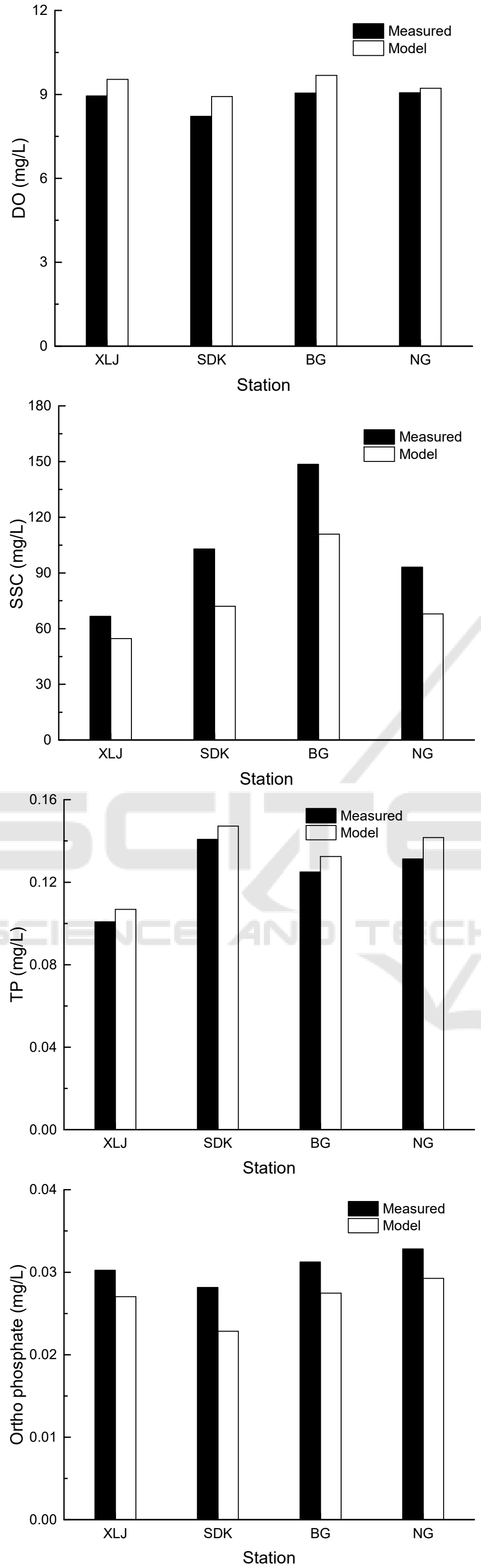


Figure 4: Comparison of the modeled water quality results with the measured data in 2018 in the Yangtze estuary.

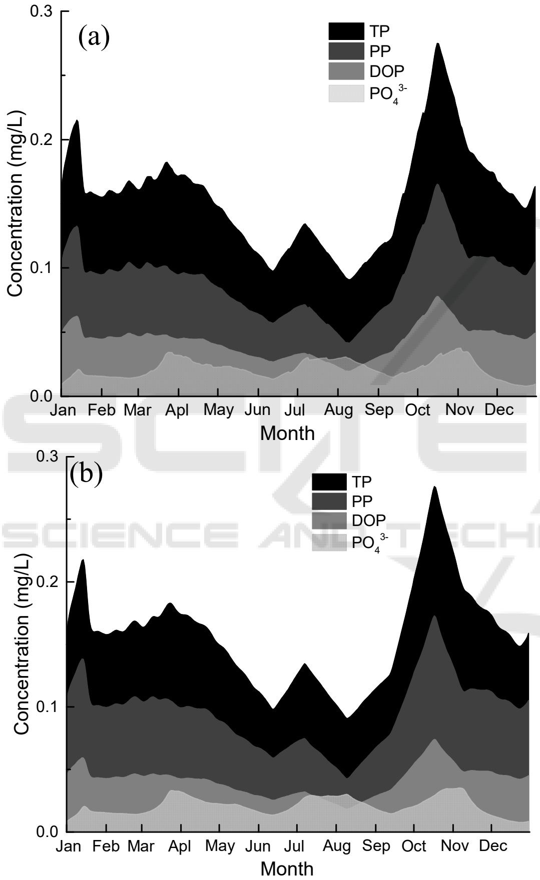
3.1.2 Water Quality Model

The annual average values of water quality parameters along the south branch of the Yangtze estuary were calculated for the comparison with the model results. The modelled temperature, DO, SSC, TP, and PO_4^{3-} are all generally in good accordance with the measured data (Figure 4). The average relative errors for temperature, DO and SSC are 2.8%, 5.9%, and 25.1%, respectively. The average relative errors for TP and PO_4^{3-} are 6.1% and 13.1%, respectively. The errors of temperature, DO and TP are below 10%. The maximum error occurs in SSC, but the errors are below 30% which is acceptable in the simulation of sediment. The relatively significant errors of SSC also cause the errors of PO_4^{3-} to be relatively large (over 10%). This is because sediment is the important carrier of the PO_4^{3-} in water. In general, the model performed well in the simulation of P concentration in the Yangtze Estuary.

3.2 P Distribution in 2018

The results of the time series of TP, PP, dissolved organic phosphorus (DOP), and PO_4^{3-} in three reservoirs in 2018 are shown in Figure 5. It can be seen that the changing trend and concentration of different P fractions among the three reservoirs are very similar, which indicates the spatial distribution of P in the south branch has little difference. The concentration of different P fractions in water is in the order of PP ＞ DOP ＞ PO_4^{3-}. The PP takes over 50% proportion of TP. Thus, the changing trend of PP generally determines the changing trend of TP. The changing trend of TP, PP, and DOP are nearly the same. The minimum values are from June to August, while the maximum values are in October. In January and October, the TP concentration exceeds 0.2 mg/L. In the summertime, the TP concentration reaches the minimum of the whole year, but still over 0.1 mg/L. The maximum concentration of the TP can reach around 0.27 mg/L in October, the concentration of PP and DOP also reach the maximum of 0.17 and 0.07 mg/L respectively at this time. The PO_4^{3-} concentration is relatively stable, fluctuating between 0.01 - 0.03 mg/L.

Three reasons can explain the changing trend of P loadings in the estuary. Firstly, the upstream boundary conditions of different P fractions play the main role. Secondly, the diffusion process controlled by the flow input from upstream affects the P concentration. In flood season, the flow input increase and the mixing process of P in the estuary get promoted, which decreases the P concentration in the south branch. In the dry season, the situation is just the opposite. Thirdly, the adsorption and desorption of sediment control the transform between particle and dissolved P. The sediment input from upstream determines the suspended sediment concentration (SSC) in the estuary. The amount of P adsorbed onto sediment would increase if the SSC increases, and the PP concentration will increase and relatively the dissolved P concentration decrease.



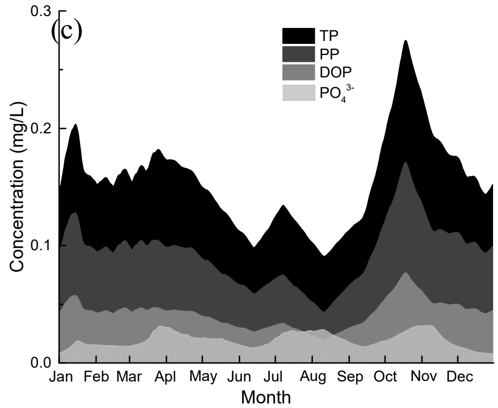
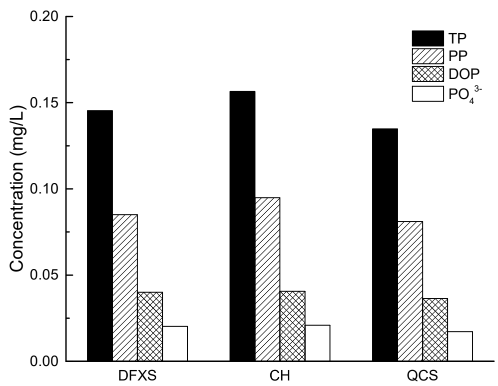


Figure 5: The time-series results of TP, PP, DOP, and PO_4^{3-} in DFXS (a), CH (b), and QCS (c) reservoirs.

In Figure 6, the annual average concentration and proportion of different P fractions in three reservoirs are shown. The situation of the three reservoirs does not show a significant difference. The annual average concentration of TP is around 0.15 mg/L. The annual average concentration of PP, DOP, and PO_4^{3-} are 0.08 - 0.095, 0.035 - 0.04 and 0.015 - 0.02 mg/L, respectively. Because of the discharge of the Liuhe river near the CH reservoir, the P concentrations in the CH reservoir are a bit higher than those of the other two reservoirs. The annual average concentration of P in the south branch in 2018 maintains a relatively low concentration after 2015 compared with those from 2000 to 2010 (Shen et al., 2008; Hou et al., 2009). The constitution of TP in three reservoirs is almost the same. The particle phosphorus accounts for the largest proportion reaching around 60%, while the phosphate took the least proportion, with only 12 - 13%. The proportion of DOP is 25 - 30%.



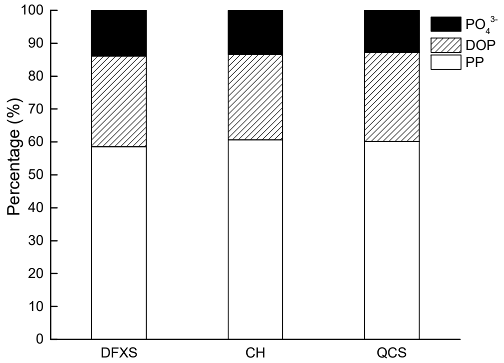
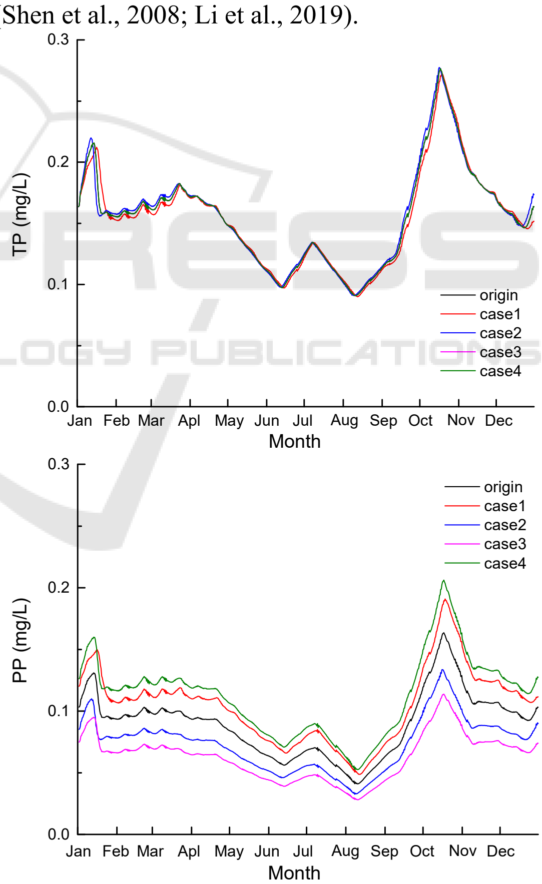


Figure 6: The annual average concentration (a) and proportion (b) of different P fractions in the three reservoirs.

3.3 Effect of Flow and Sediment Input

According to the modeling results in 2018, the P distribution, concentration and constitution in three reservoirs are generally the same. This similarity also shows in the case studies. Thus, the results of the one-year time series of TP, PP, and PO_4^{3-} of the original case (2018) and the 4 study cases of the DFXS reservoir are taken as the representative of the three reservoirs in the following analysis (Figure 7). In each case, only the upstream boundary conditions of flow or sediment are changed while other conditions are consistent with the original case. The changing trends of TP, PP, and PO_4^{3-} of different cases are generally the same as those of the original case, which is controlled by the time series of P concentration conditions of the upstream boundary. The TP concentration of 5 cases shows little difference. However, the concentrations of PP and PO_4^{3-} show changes with the various flow and sediment input conditions.

The changing trends of the PP and PO_4^{3-} are inverse. With the increase of the flow (case2) and the decrease of sediment input (case3), the PP shows a decrease while the PO_4^{3-} shows an increase. With the decrease of the flow (case1) and the increase of sediment input (case4), the PP shows an increase while the PO_4^{3-} shows a decrease. Generally, when the flow input increase and the sediment input decrease, the concentration of PP would decrease and the concentration of PO_4^{3-} would increase. On the contrary, when the flow input decrease and the sediment input increase, the concentration of PP would increase and the concentration of PO_4^{3-} would decrease. These changes are affected by the convection and diffusion, and the adsorption and desorption processes of sediment. The suspended sediment concentration (SSC) would decrease because of the diffusion process with the flow input increase. Both the increase of the diffusion process and the decrease of SSC would further decrease the PP concentration in the south branch. However, the situation of the PO_4^{3-} is relatively complex under these conditions. The increase of the flow input promotes the mixing processes of PO_4^{3-}, which decreases the PO_4^{3-} concentration in the south branch. On the contrary, the increase of the flow input decreases SSC, the amount of carrier of PO_4^{3-}, which increases the PO_4^{3-} concentration in the south branch. It can be concluded that the effect of adsorption and desorption on the PO_4^{3-} concentration is more significant than that of diffusion because of the increase of PO_4^{3-} in case2 and decrease of it in case1. In the real nature, the effect of adsorption and desorption of sediment on the PO_4^{3-} concentration would even become more significant when taking the release of P during the sediment resuspension into consideration, like the situation in the MTZ (Shen et al., 2008; Li et al., 2019).



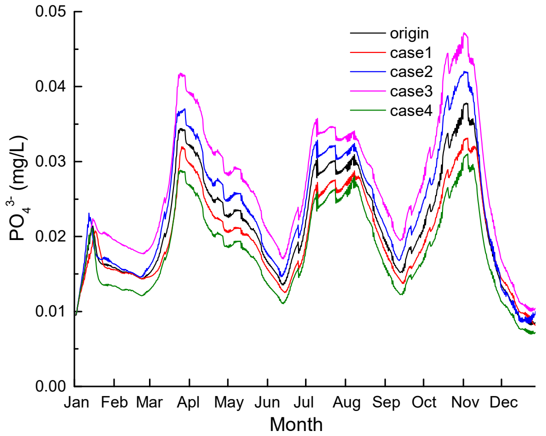


Figure 7: The time-series results of (a) TP, (b) PP, and (c) PO_4^{3-} of different cases in the DFXS reservoir.

The annual average concentration and proportion of different P fractions of different cases in DFXS reservoirs are shown in Figure 8. The PO_4^{3-} concentration increases about 10% and 25%, respectively when the flow input increase by 20% and sediment input decrease by 20%. The PO_4^{3-} concentration decreases about 8% and 20%, respectively when the flow input decrease by 20% and sediment input increase by 20%. The PP concentration increases about 12% and 35%, respectively when the flow input increase by 20% and sediment input decrease by 20%. The PP concentration decreases about 15% and 30%, respectively when the flow input decrease by 20% and sediment input increase by 20%. The amplitude of variations of cases with changes of sediment input (case3 and 4) are larger than those with changes of flow input (case1 and 2). This further verifies that the effect of adsorption and desorption of sediment would play more significant roles in the P distribution than the diffusion process does.

The constant TP concentration and various PP and PO_4^{3-} concentrations between different study cases indicate a shift of the P fractions in water. The proportion of DOP is generally stable between 20-30%. PP always takes the most proportion among all cases, although it decreases to 45-50% when the sediment input decreases by 20%. The absolute difference of the PO_4^{3-} of different cases is not big, but its relative changes are significant. Its proportion is nearly twice as much as the original when the sediment input decrease by 20%. This shift of the constitution of the P would bring some potential water quality problems. The construction of dams in the Yangtze basin, especially the Three Gorges dam completed in 2003, decreased the sediment input to the estuary from nearly 480 Mt/a in the 1950s to less than 150 Mt/a in the 2010s (Chen et al., 2010). The construction of dams will continue during the next few decades (Chen et al., 2010). This will keep decreasing the sediment input and increasing the proportion of PO_4^{3-}. The government has taken action to reduce the nutrients fluxes into the estuary in recent years. Although the TP concentration has decreased, PO_4^{3-} concentration would stay at a high level or even increase because of the increase of its proportion. In the geochemical circulation of P, PO_4^{3-} is the only fraction that can be directly taken by the food web, like algae (Meybeck, 1982). Thus, the high concentration of PO_4^{3-} would still keep the water eutrophicated.

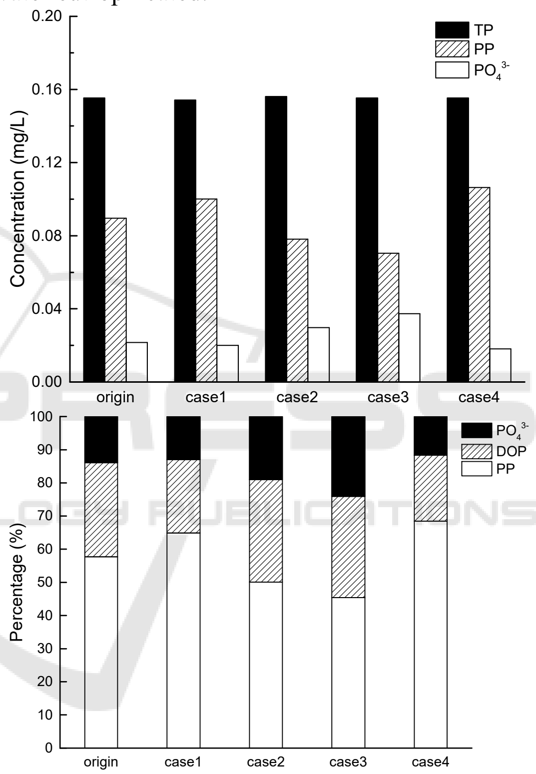


Figure 8: The annual average proportion of PP, DOP, and PO_4^{3-} among TP of different cases in DFXS reservoir.

4 CONCLUSION

Because of human activities and global climate change, the flow and sediment input from upstream to the Yangtze estuary change a lot, which brings about the variation of P loadings and some potential water quality problems. An integrated water quality model was established with Delft3d to study the P distribution in 2018 in the south branch of the Yangtze estuary and its possible changes in the future in response to variations of runoff and sediment loads from upstream. The general conclusions are as follow:

(a) In 2018, the average TP concentration is around 0.15 mg/L, but it can reach over 0.2 mg/L in October. The particle P fractions took the largest proportion (over 60%), while the PO_4^{3-} occupied the least proportion (around 10%). The P concentration in the south branch in the dry season is higher than that in the flood season.

(b) Both PP and PO_4^{3-} concentrations change with the changes of flow and sediment input, which brings about the reconstitution of the component of TP in the south branch. When the flow input increases or the sediment input decreases, the PP concentration would increase and PO_4^{3-} concentration would decrease. When the flow input decreases or the sediment input increases, the PP concentration would decrease and PO_4^{3-} concentration would increase.

(c) The diffusion process and adsorption and desorption of sediment are the main processes controlling the response of P to the upstream runoff and sediment load variations. The adsorption and desorption would play a more significant role than the diffusion process does.

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