Numerical experiments on stagnation points influenced by the Three Gorges Dam in the Yangtze Estuary
Jianqiao Han and Libing Huang

ABSTRACT

In order to study the changes of stagnation points in the Yangtze Estuary influenced by the Three Gorges Dam operation, 3-D hydrodynamic and sediment transport model ECOMSED was used to simulate the dynamic process of flow varying with the river discharge and tide of the Yangtze Estuary. The results show that the location of stagnation points varied markedly in different areas after the impoundment of the Three Gorges Dam, with the large extent of downward movement during flood periods due to the hydrodynamic enhancement of the Yangtze River in the North Branch, while the movement range was smaller in the South Branch. Along with the runoff changes, the variation extent from big to small is North Channel, South Passage and North Passage, while the rank order changed as South Passage, North Channel and North Passage as valued by the tidal changes. After the impoundment of the Three Gorges Dam, the movement range of stagnation points reduced because of the reduction in river discharge. Thus, it can be considered that the turbidity maximum zone has a decreasing trend which might lead to changes in geomorphic features of the Yangtze Estuary.

Key words | flow dynamics, numerical experiments, runoff, stagnation points, Three Gorges Dam, Yangtze Estuary

INTRODUCTION

Stagnation points represent an approximately balanced region of runoff and tidal dynamics in an estuary area, which link the water, sediment and geomorphology. The variation of stagnation points in the location significantly affects saltwater intrusion and the distribution of the turbidity maximum zone (TMZ), and further influence the ecosystem and geomorphological evolution (Svitski et al. 2005; Walling 2006; de Jonge et al. 2014). Stagnation points will change due to the reduced runoff dynamics affected by the reservoir which was built on the upper reaches of the river. Therefore, it is of great significance to research the variation of the stagnation point locations influenced by the large-scale water conservancy project for the theory and practice of estuarine evolution (Yang et al. 2006; Yang et al. 2011a).

Analyses of water and sediment transport mechanisms can determine the location of the stagnation points, where the current velocity is zero in the river estuary (Shi & Li 1995; Yang et al. 2011b). In the Yangtze Estuary, the principal factors affecting stagnation points are runoff and tidal action (Hoover & Ackerman 2004), and the location of stagnation points should be within the region of the TMZ and entrance bar. The entrance bar in the North Branch is located within the mouth, while it is located at the entrance region in the North Channel, North Passage, and South Passage. Runoff change influenced by the impoundment of the Three Gorges Dam has led to the location variation of stagnation points in the Yangtze Estuary (Lou et al. 2015), and stagnation point positions in various geomorphic units may show different characteristics due to different local topography. Most researchers focus on microscopic studies of local areas (Chen et al. 2006; Li et al. 2012), however, published research focuses on the macroscopic variability regularity of stagnation points where geomorphic units are insufficient.
In this paper, in order to study the changes of stagnation points in the Yangtze Estuary influenced by the Three Gorges Dam operation, 3-D hydrodynamic and sediment transport model ECOMSED was used to simulate the effects and factors of the stagnation points under a variety of runoff and tidal conditions in each geomorphic unit of the Yangtze Estuary. At the same time, the trends and causes of stagnation point changes are analyzed based on the river flow changes which are influenced by the Three Gorges Dam. This work reveals the changes and causes of stagnation points after the impoundment of the Three Gorges Dam, which was significant to both the distribution of the TMZ and the trend predictions of geomorphological evolution in the Yangtze Estuary.

STUDY AREAS

The Yangtze Estuary is a typical region of land and ocean interaction. It can be divided into three segments according to the dominance of the runoff and tide (Tong et al. 2013). The effects of runoff play a leading role from Datong to Jiangyin in the near-estuary region. Tidal affects act as the principal factor in the offshore area which stretches from the harbor entrance to the 30–50 m depth line, while the effects of runoff and tide play an equally important role from Jiangyin to the harbor entrance. According to the analysis of measured data, stagnation points were mainly distributed within the entrance bar area. Therefore, we choose a region that extents from Xuliujing to 123 30 E for 92 km (Figure 1).

There are three bifurcations and four outlets into the sea in the Yangtze Estuary. It is initially divided into the North Branch and South Branch at Chongming Island. Subsequently, the South Branch splits into the North Channel and South Channel when it encounters Changxing Island, then the South Channel departs into the North Passage and South Passage at Jiuduansha Shoal (Wang et al. 2008).

Hydrodynamic conditions of the research area include runoff, tide, storm waves, Coriolis force, brine density flows, longshore currents and so on (Zhu et al. 2012). Research has shown that the estuarine circulation that is...
mainly influenced by runoff and tide is closely related to the generation of stagnation points. While the influence of storm waves is small except for those caused occasionally by typhoons or winter storms, longshore currents and the Taiwan warm current are relatively weak (Yu et al. 2013). Thus, in this study, the variations of the stagnation point locations mainly focus on the changes of runoff and tide.

**METHODS**

The establishment of the ECOMSED model

The ECOMSED model includes hydrodynamics, waves, sediment transport and other modules. This model is widely used throughout the world because it can exactly simulate the 3-D characteristics of water and sediment movement within estuaries (Du et al. 2007; An et al. 2009; Mandang et al. 2009). In this paper, the hydrodynamics module is used to assess the changes in stagnation points influenced by the Three Gorges Dam; the control equations of the model are as follows.

Flow continuity equation:

\[ \nabla \cdot \mathbf{V} + \frac{\partial W}{\partial z} = 0 \] (1)

Flow momentum equation:

\[ \frac{\partial U}{\partial t} + \mathbf{V} \cdot \nabla U + W \frac{\partial U}{\partial z} - fV = - \frac{1}{\rho_o} \frac{\partial P}{\partial x} + \frac{\partial}{\partial z} \left( K_M \frac{\partial U}{\partial z} \right) + F_X \] (2)

\[ \frac{\partial V}{\partial t} + \mathbf{V} \cdot \nabla V + W \frac{\partial V}{\partial z} + fU = - \frac{1}{\rho_o} \frac{\partial P}{\partial y} + \frac{\partial}{\partial z} \left( K_M \frac{\partial V}{\partial z} \right) + F_Y \] (3)

\[ \rho g = - \frac{\partial P}{\partial z} \] (4)

where \( \mathbf{V} \) is the horizontal velocity vector in \( (U, V) \), \( \nabla \) is the operator in the horizontal gradient and \( U, V \) and \( W \) are the velocity in the \( x, y \) and \( z \) directions, respectively. \( \rho_o \) is the reference density, \( P \) is pressure, \( K_M \) is the vertical turbulent mixing coefficient and \( f \) is the Coriolis parameter. \( F_X \) and \( F_Y \) are the diffusion terms in the \( x, y \) directions, respectively.

Sediment transport equation:

\[ \frac{\partial C_k}{\partial t} + \frac{\partial UC_k}{\partial x} + \frac{\partial VC_k}{\partial y} + \frac{\partial(W - W_{sk})C_k}{\partial z} = \frac{\partial}{\partial x} \left( A_H \frac{\partial C_k}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_H \frac{\partial C_k}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_H \frac{\partial C_k}{\partial z} \right) \] (5)

where \( C_k \) is sediment concentration, \( A_H \) is the horizontal diffusion coefficient, \( K_H \) is the vertical diffusion coefficient and \( W_{sk} \) is the settling velocity of flocculation sediment.

In this study, the hydrodynamic module is applied to simulate the characteristics of water and sediment movement, and is equivalent to a 200 × 200 plan grid area that extends from Xuliujing to 123° E and is divided into ten layers vertically. The upstream boundary conditions are defined according to the one-dimensional unsteady flow model calculation over a long range. The one-dimensional model boundary is determined by the measured discharge of Datong upstream and off the Yangzi River Estuary, while the downstream boundary is given by harmonic analysis. The calculation equation is as follows:

\[ h_p(t) = A_0 + \sum_{q=1}^{Q} f_q H_q \cos \left( \sigma_q t + (\nu_0 + u)_q - \epsilon_q \right) \] (6)

where \( h_p(t) \) is the tide prediction, \( A_0 \) is sea level altitude, \( f_q \) is the intersection factor of a tidal component, \( \sigma_q \) is angular velocity, \( (\nu_0 + u)_q \) is the initial phase angle of astronomy, \( t \) is time, \( q \) is the number of the tidal component, \( H_q \) is the amplitude of the tide and \( \epsilon_q \) is the special epoch of the tide. \( H_q \) and \( \epsilon_q \) are known as harmonic constants.

All this research is related to eight principal tidal components (S2, M2, N2, K1, P1, O1, K2, and Q1) and three shallow-water tidal components (M4, MS4, and M6) (Cao et al. 2012). The primary interest is the influence on stagnation point distribution of the variation of runoff and tide. Therefore, the salinity is only considered as a calculation condition but not an influence factor, and the salinity values imposed on the upstream and downstream boundaries are chosen as 0.21‰ and 27.1‰, respectively (Li et al. 2012).

**Verification of ECOMSED**

Observational data obtained on August 24, 2004, were used to verify the flow velocities and tidal levels derived from the ECOMSED simulation. Accurate velocities collected, based...
on the exact tidal levels, are accordant with the actual situations. The results of flow velocity and direction are presented in a representative part in Figure 2. The full lines and points represent calculated and measured values, respectively. The flow velocity and direction of Shihua station are described in Figure 2(a), and of Baimao station in Figure 2(b).

Each day exhibits two rising and falling trends of tides. The directions of the runoff tide are coincident during the falling tide, and the duration of the falling tide is longer than that of the rising tide. The error between the calculated and measured averaged flow velocities is less than 0.2 m s\(^{-1}\).

It is possible that the time of the appearance of maximum flow velocity is different at each location, so we choose B marked in Figure 3 as a control point. Horizontal velocity distribution at the time of maximum and minimum ebb is described in the following section. The flow direction at the time of the appearance of maximum and minimum flood is opposite to that of maximum and minimum ebb. The horizontal distribution of flow velocities changes continually over time. At maximum ebb, the flow velocity is high and the flow direction is downstream. After the time of minimum ebb, the flow moves upstream and the velocity increases constantly until the time of maximum tide. When the flow velocity reaches its maximum, the flow velocity begins to decrease constantly. In conclusion, the simulated results exhibit conformity with the actual flow distribution.

The location of the stagnation point in the South Passage is 15.12 km from Jiuduansha during the spring tide of August 2005, while it is 4 km from the area which is labeled as K during the spring tide of February 2002. According to the measured data from 1994 to 2004, the stagnation points changed in the range of K to T in the North Passage ranges, as described in Figure 4. All of the calculated results are close to the actual measurements.

The locations of the measured stagnation points are in accordance with the TMZ and entrance bar, and the calculated results show that they are distributed within the area of the TMZ. In conclusion, it can be verified that the calculated results are in accordance with the actual situation. Therefore, it is of great practical significance to study the stagnation points using the ECOMSED model.

**Simulation conditions**

In order to analyze the influence of runoff or tides on the stagnation points of the Yangtze Estuary and their variation of different tidal range, five representative discharges are considered as assessment conditions of the flow into the sea. They are 6,800 m\(^3\) s\(^{-1}\) (minimum flow), 16,300 m\(^3\) s\(^{-1}\) (mean low flow after the impoundment of the Three Gorges Dam), 27,000 m\(^3\) s\(^{-1}\) (average flow after the impoundment of the Three Gorges Dam), 45,000 m\(^3\) s\(^{-1}\)
The stagnation point is defined by the assessment of the quotient of the area of the unit discharge flow hydrograph of the falling tide to that of the whole tide at each station. Falling tide is the dominant flow dynamic if the quotient is less than 50%; in contrast, rising tidal flow is the dominant condition if the quotient is larger than 50%, while the flow path areas of the falling and rising tides are equal if the quotient is equal to 50%.

Data statistics

The stagnation point is defined by the assessment of the quotient of the area of the unit discharge flow hydrograph of the falling tide to that of the whole tide at each station. Falling tide is the dominant flow dynamic if the quotient is less than 50%; in contrast, rising tidal flow is the dominant condition if the quotient is larger than 50%, while the flow path areas of the falling and rising tides are equal if the quotient is equal to 50%.

The unit discharge flow hydrograph for a period of time can be shown by the equation as below:

\[
Q = \frac{1}{T} \int_{0}^{T} \nabla(i, j, t) \, dt
\]  

(7)

In the equation, the model is divided equally into ten layers vertically. \(\nabla(i, j, t)\) is the flow velocity at the point of the grid number \((i, j)\) of the bottom layer, and \(T\) represents the computation time.

The ECOMSED model is applied to simulate the flow velocities in the direction of \(i\) and \(j\) of each grid at different times. According to Equation (7), the bottom unit discharge flow is computed for each grid at different periods. A preferential flow conversion interface can be obtained by importing the computed results into the Tecplot mapping software. Finally, the results are imported into AutoCAD to generate the distribution plots of the stagnation points.

RESULTS AND DISCUSSION

Relationship between stagnation points and runoff

The simulation is performed under the same conditions except for the computational process of the discharge flow. The largest and smallest tidal cycles (spring and neap tides, respectively) are simulated via Equation (7), and the unit discharge and the stagnation point distributions are computed and depicted in Figure 5. As shown in the graphs, the stagnation points
move downstream with the increase of discharge flow during
the neap tide, while in different areas, the large range of the
stagnation points exhibits erratic fluctuation in the North
Branch when the discharge flow is constant. In the North
Channel, as the discharge flow increases from 6,800 to
27,000 m³ s⁻¹, the stagnation point clearly moves down-
stream and the range of movement is substantial. With the in-
crease of the discharge flow, the stagnation point moves
downstream gradually. In the North Passage, the stagnation point locations
and their variation are similar to that of the South Passage,
while the change mainly occurs within the channel of the
North Passage, and the range of the stagnation point is rela-
tive small, i.e. less than that of the South Passage.

Relationships between stagnation points and tide

The above research shows that under the same discharge
flow conditions, the locations of the stagnation points
during the spring and neap tides are obviously different.
Compared with the spring tides, the locations of stagnation
points move eastwards during neap tides. For a detailed
analysis of the influence on the stagnation points impacted
by the tide, 16,300 m³ s⁻¹ and 45,000 m³ s⁻¹ are chosen as
representative discharge flows to investigate the variation
of the stagnation points in the process of the spring and
neap tides. The tidal ranges at point A (Figure 1) during
five tidal periods are shown in Figure 6.

The associated locations of the stagnation points in the
five periods are presented in Figure 7. As the tidal range
decreases, the stagnation points move gradually outward.
Under the same tidal condition, variations of the stagnation
points in the North Branch are most obviously followed by
the North Channel and North Passage, the range of which
is much larger than the others.

Comparison of the influences of runoff and tidal action

To compare the influence on the stagnation points between
runoff and tidal action in different areas, the runoff discharges
corresponding to tidal ranges of 3.39 m and 2.83 m, respect-
ively, have been calculated in Table 1. The analysis results
show that effects of tide on the stagnation points are more sen-
tive than those of runoff in each area. The stagnation points
move upstream with the increment of tidal range, while the
runoff discharge of the North Branch, South Passage, North
Channel, and North Passage should increase 58%, 55%, 40%
and 55%, respectively, to maintain the position of the stagnation
points when the tidal range increases by 20%. The above results
are consistent with the sequence of the influence extent of tidal action on the stagnation points in different regions.

### Reasons for the stagnation point variation

Analysis demonstrated that stagnation points move downstream with the increase of discharge flow. During flood periods, the variation range of the stagnation points in the North Branch is larger than that of the South Branch, followed by the South Passage and North Passage. The generation of the stagnation point variation has much relation to the evolution of geomorphology and the water diversion ratio (Yang et al. 2007; Wang et al. 2008; Dai et al. 2015). Currently, with intensified deterioration conditions of water-diversion and shrinkage of the inlets, the angle between the upstream entrance of the North Branch and the South Branch is nearly 90° (Zhang et al. 2012). The variation of the stagnation points and the diversion ratio are not obvious in the North Branch when runoff is equal to the tidal flow. However, as runoff exceeds the tidal flow during the ebb stage, the reduction in tidal power allows the stagnation points to move downstream. In the North Channel, the morphology affects the variation of the stagnation points, when the discharge is small, and the stagnation points move within the channel. The range of variation is enlarged because of the strength of the hydrodynamic action which is induced by the narrow and deep channel, while with the increase of the discharge, the stagnation points move towards to the junction of the North Channel and estuary, and the range of variation diminishes with the broadening of the inlet. When the discharge increases to a certain degree, the stagnation points dramatically change and completely deviate from the North Channel.

The influence of tide on the stagnation points varies in different channels. In the North Branch, the rising tide is powerful and runoff diversion is rather small. Therefore, the stagnation point is mainly influenced by tidal action, while in the three channels of the South Branch, the locations of the stagnation points vary because of the different landforms. In the South Passage, the tidal power is larger than that of the North Passage because of the concentration in the narrow and deep channel upstream.

### Impact on the evolution of the Yangtze Estuary

Based on a comprehensive understanding of the influences on the locations of stagnation points affected by runoff and tide in...
After the impoundment, the discharge flow increased in dry seasons and reduced in flood seasons, and the amplitude of the runoff variation became smaller. The diversion ratio in the North Channel is larger than that in the South Channel in the ebbing tide, and the ratio in the North Passage is larger than that in the South Passage.

In this work, the spring and neap tides with minimum and maximum flow periods are chosen as representative models before and after the impoundment to investigate the change amplitude of the stagnation points in different areas. The minimum and maximum discharge flows (after 1980) before the impoundment were 7,040 m$^3$/s and 84,300 m$^3$/s, after the impoundment they became 8,380 m$^3$/s and 63,000 m$^3$/s, respectively. The locations of the stagnation points are shown in Figure 8. It can be seen that the variation range in each area after the impoundment is lower than before. In the North Branch, the stagnation points of the upper boundaries stay at the inlet reach of the channel before and after the impoundment, while the stagnation point range of the upper boundary reduced by 3,220 m after the impoundment. In the North Channel and North Passage, the upstream boundary reduced by 3,343 m and 675 m, and the downstream boundary reduced by 1,860 m and 1,033 m, respectively. In the South Passage, there is no obvious change in the upstream boundary, whereas the downstream boundary reduced by 1,049 m.

With the decreasing range of the runoff, there is an obvious reduction tendency in the range of the stagnation points, and the variation ranges of the stagnation point locations are different in each area. In the North Branch, the stagnation points change within the channel, while their range moves outward in the other areas. The order of change range of the stagnation points ranked as North Channel, North Passage and South Passage, and the variation of the stagnation points is in accordance with the diversion ratio except for that of the North Branch. Furthermore, the duration of large discharge is rather short, therefore, the actual main distribution area of the stagnation points is smaller than that derived from the simulation results. Results show that the TMZ has had a decreasing trend in recent years, which is in agreement with the observed data (Yang et al. 2014).

**CONCLUSIONS**

In order to explore the effects on stagnation points of the Three Gorges Dam, the ECOMSED model is employed to simulate the stagnation point changes under different runoff and tidal conditions in the Yangtze Estuary. The conclusions are summarized as follows:

1. The stagnation points are located at the inlet during dry periods, and make great downward movement during flood periods in the North Branch, while the variation extent is smaller in the South Branch. Along with the flow increase, the extent of variation from big to small is North Channel, South Passage and North Passage.
2. The effects of tide on stagnation points are more sensitive than that of runoff. The stagnation points move upstream with the increment of tidal range, while runoff discharge of the North Branch, South Passage, North Channel, and North Passage should increase 58%, 55%, 40% and 55%, respectively to maintain the position of the stagnation points when the tidal range increases by 20%.
3. The stagnation points in the North Branch, North Channel, South Passage, and North Passage moved 3,220 m, 1,860 m, 1,033 m and 1,049 m, respectively due to the runoff discharge decrease after the impoundment of
the Three Gorges Dam. These changes are consistent with the observed data.

(4) It can be considered that the TMZ related to the stagnation points exhibited a decreasing trend, which could induce further changes in the geomorphic features of the Yangtze Estuary.

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation of China (grant number 51609096); Natural Science Basic Research Plan in Shaanxi Province of China (grant number 2017Q4011); and the Doctoral Foundation of Northwest A&F University (grant number 2452015337).

REFERENCES


