Field Measurements and Numerical Simulations of Sediment Transport in a Tidal River

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Fluid Mechanics
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By

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Preface

First of all, I would like to express my gratitude to Professor James Yang at Royal Institute of Technology (KTH), Stockholm, for your exceptional patience, guidance, continuous encouragement and extraordinary support during the past two years. Thank you for your supervision and devoted editing efforts with all my manuscripts.

I am very grateful to Professor T. Staffan Lundström at Luleå University of Technology (LTU) for accepting me as a Ph.D. student and for giving me the freedom to carry out the research. Thank you for your supervision, continual encouragement and support in many ways!

I would like to thank my colleagues in Division of Fluid & Experimental Mechanics, for creating a pleasant and friendly atmosphere, especially to Dr. Gunnar Hellström, Dr. Anders Andersson and Prof. Patrik Andreasson. Your helpful suggestions and comments are valued.

Many thanks go also to Karin Soini, Peter Radkvist, Marianne Engström-Östman and Viola Nilsson at LTU for administrative and practical help.

Professor Wenhong Dai of Hohai University is also acknowledged for assistance during my visits at the University. And my friends, both old and new, no matter where you are now, thank you all for all the fun we had.

Finally, I thank my dear parents and sister for your love and support and for motivating and encouraging me throughout the study. Special thanks go to my beloved girlfriend for filling my life with lots of happiness and immense love.

The work presented in the thesis has been carried out during August 2017 – May 2019 at LTU Division of Fluid & Experimental mechanics and KTH Division of Resources, Energy & Infrastructure.

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In a coastal area, an alluvial lowland river has a free connection with the open sea and its flow is bidirectional. The river basin is often highly urbanized since it hosts valuable ecosystems and natural resources. Along with the growing population, climate change and human activities (e.g., industrialization, agricultural expansion, and fishery industry) pose a significant threat to the health of the river, leading to an unbalance of the flow and the sedimentation and also a considerable degradation of water quality.

With long-term alluvial processes, the river often displays patterns such as meandering, braided, straight, wandering and anastomosing. In addition to the irregular geometry and bathymetry, a tidal river is typically influenced by the freshwater-saltwater interplay, which makes the hydrodynamic processes and sediment transport patterns extremely complicated. For many tidal river systems, cohesive sediment transported with the tides plays an important role. This is not only because of its interaction with flow but also due to its link to bed deformation.

In this thesis, field measurements and numerical simulations of flow and sedimentation in a system, including a confluence and a meandering reach are presented and discussed. The numerical simulations are performed with the Delft3D package, which allows a coupling between complex river geometry, the bathymetry, the flow and the sediment boundaries in one module. Two morpho-dynamic models, a 2D depth-averaged model for the confluence and a 3D model for the meandering reach, are set up to disclose the fluvial processes in respective area.

The objective of this thesis is, by means of extensive field measurements and numerical simulations, investigate flow features and sediment movement patterns in a tidal river. A comparatively long-term river-bed change, including a scour-hole at the confluence and asymmetric cross-sections at the bends, are also examined. Based on the perturbation theory, an improved sediment carrying capacity formula is also derived being suitable for calculations in a tidal environment. This study explores the variability of sediment transport, and reveals the relationship between the flow velocity and suspended load influenced by both the run-off and the tides. Their interactions also generate a different morphological regime as compared to a non-tidal river reach.

This research may support a decision-making process when considering the integrated tidal river management and it also provides a reference for other similar situations. The calibrated and validated model may therefore be a powerful tool for managers or researchers.
Appended Papers

Paper 1


A confluence is a natural component in river and channel networks. This study deals, through field and numerical studies, with alluvial behaviors of a confluence affected by both river run-off and strong tides. Field measurements were conducted along the rivers including the confluence. Field data show that the changes in flow velocity and sediment concentration are not always in phase with each other. The concentration shows a general trend of decrease from the river mouth to the confluence. For a given location, the tides affect both the sediment concentration and transport. A two-dimensional hydrodynamic model of suspended load was set up to illustrate the combined effects of run-off and tidal flows. Modeled cases included the flood and ebb tides in a wet season. Typical features examined included tidal flow fields, bed shear stress, and scour evolution in the confluence. The confluence migration pattern of scour is dependent on the interaction between the river currents and tidal flows. The flood tides are attributable to the suspended load deposition in the confluence, while the ebb tides in combination with run-offs lead to erosion. The flood tides play a dominant role in the morphodynamic changes of the confluence.

Paper 2


Meandering is a common feature in natural alluvial streams. This study deals with alluvial behaviors of a meander reach subjected to both fresh-water flow and strong tides from the coast. Field measurements are carried out to obtain flow and sediment data. Approximately 95% of the sediment in the river is suspended load of silt and clay. The results indicate that, due to the tidal currents, the flow velocity and sediment concentration are always out of phase with each other. The cross-sectional asymmetry and bi-directional flow result in higher sediment concentration along inner banks than along outer banks of the main stream. For a given location, the near-bed concentration is 2–5 times the surface value. Based on Froude number, a sediment carrying capacity formula is derived for the flood and ebb tides. The tidal flow stirs the sediment and modifies its concentration and transport. A 3D hydrodynamic model of flow and suspended sediment transport is established to compute the flow patterns and morphology changes. Cross-sectional currents, bed shear stress and erosion-deposition patterns are discussed. The flow in cross-section exhibits significant stratification and even an opposite flow direction during the tidal rise and fall; the vertical velocity profile deviates from the logarithmic distribution. During the flow reversal between flood and ebb tides, sediment deposits, which is affected by slack-water durations. The bed...
deformation is dependent on the meander asymmetry and the interaction between the fresh water flow and tides. The flood tides are attributable to the deposition, while the ebb tides, together with run-offs, lead to slight erosion. The flood tides play a key role in the morphodynamic changes of the meander reach.

**Paper 3**

Xie, Q.C.; Yang, J. & Lundström, T. S. (2019) Perturbation Theory and Determination of Sediment Carrying Capacity of Suspended Load in a Tidal River. (14th International Symposium on River Sedimentation, to be held September 16‒19, Chengdu, China.)

In a fluvial river, coastal tides often carry suspended load that dominates the sediment transport. The sediment carrying capacity (SCC) is the amount of suspended load transported by the flow, reflecting the erosion and deposition equilibrium in the water body. Based on the perturbation theory the study modifies a method to determine the SCC and apply it to a natural river where tidal currents are predominant. In terms of flow velocity, water depth, particle settling velocity, median grain size and tidal range, an approach is established by means of dimensional analysis and multivariate linear regression. Field data are collected to determine and validate the coefficients of the SCC formula. Compared to previous studies with fewer parameters for the correlation analysis, the procedure is an improvement and can be used to estimate the SCC in similar situations.
This Licentiate dissertation, comprising both field measurements and numerical simulations, is based on the following papers. They are denoted as Paper 1 to 3 in the thesis.


Q.X. was responsible for analyses of field measurement data and numerical simulations, with participation from T.S.L., J.Y., and W.D. The manuscript was written by Q.X. and J.Y. The research of river flow and sedimentation was supervised by J.Y. and T.S.L.


Field data analyses and numerical simulations were performed by Q.X., with supervision from J.Y. and T.S.L. The manuscript was written by Q.X. and J.Y., with comments from T.S.L.


Q.X. conceived the study and analysed the field data, with supervision from J.Y. and T.S.L. The manuscript was written by Q.X. and J.Y., with comments from T.S.L.

During the two years, the author has also participated in other research projects. The related publications are not included in the dissertation but listed below for those who are interested.


Paper 5. Teng, P.H.; Yang, J. & Xie, Q.C. (2019) Improving energy dissipation of a spillway with structural modifications. 38th IAHR World Congress, to be held September 1–6, Panama City, Panama.


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Part I

Introduction and Summary
1. Introduction

Based on the prevailing flow and sediment conditions, a river system can be subdivided into a non-tidal and a tide-driven river (Table 1.1). For the former, reducing the river sediment input impacts the entire system dynamics. For the latter, the sediment is subject to both freshwater run-off and the dominating oceanic currents, showing a bidirectional transport feature driven by flood and ebb tides. The resulting morphodynamic adaption in a tidal environment occurs in weeks or months, which is shorter than the one in a non-tidal river.

Table 1.1 Comparison of the main characteristics between a tidal and non-tidal river.

<table>
<thead>
<tr>
<th></th>
<th>non-tidal river</th>
<th>tide-driven river</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow volume timescale</td>
<td>daily/seasonal</td>
<td>hours</td>
</tr>
<tr>
<td>Main sediment forcing</td>
<td>river run-off (fresh water)</td>
<td>tides (salty water)</td>
</tr>
<tr>
<td>Sediment concentration timescale</td>
<td>days-weeks</td>
<td>hours</td>
</tr>
<tr>
<td>Sediment transport direction</td>
<td>unidirectional</td>
<td>bidirectional</td>
</tr>
<tr>
<td>Morphodynamic adaption time scale</td>
<td>months-years</td>
<td>weeks-months</td>
</tr>
</tbody>
</table>

1.1 Flow dynamics

There are a number of factors that influence the sediment availability and its movement such as river discharge, tides, wind, waves, dredging etc. In this section, the freshwater flow and the tides, are considered to be the two governing factors.

1.1.1 Freshwater flow

Freshwater from a river flows into an estuary and mixes with the salty water of the estuarine ecosystem. The mixing occurs spatially and temporally from climatic influences including tidal actions, seasonal variability and storms etc [1].

This work considers freshwater input exclusively from rivers to simplify the analysis. The freshwater flow is the landward boundary of a tidal river, which provides run-off discharge and is one source of sediment to the estuary. The watershed drainage usually carries sediment from upstream to feed the estuary and the coastal region.

In many tidal rivers, the freshwater flow accounts for a large portion of the water system variability. There is usually an annual cycle driven by a dry and wet season. The freshwater flow affects the salinity gradient, the estuarine circulation, the water quality including turbidity, the productivity and the abundance of species. Interfered by human activities, the freshwater flow is modified by a number of factors, such as the construction of dams, sluice gates, landings and piers, making it significantly different from the natural flow.

1.1.2 Tides

In some tidal rivers, the flow circulation is dominated by strong tides, showing an obvious water level fluctuation and a bidirectional flow. Astronomical tides—the regular rise and fall of the sea level, are forced by the Earth-Moon-Sun gravitational attraction. In most
regions, tides are semi-diurnal, i.e. two nearly equal high and low tides a day, belonging to the category of incomplete standing waves.

A rising tide is termed a flood tide and a falling tide is termed an ebb tide (Figure 1.1). The moment when the water reaches its highest or lowest point is called the slack water. The maximum flood and ebb occur in-between the times of the high and low tides. The tidal range, defined as the difference in height between a high tide and the following low tide, also varies periodically with the phase of the moon in a given month. Tides of maximum range, known as spring tides, occur twice in 29 days, when the lunar and solar tide-generating forces reinforce each other at around full and new moon. Likewise, tides of minimum range, known as neap tides, occur when the lunar and solar-generating forces act against each other—around the first and third quarter of the moon.

Figure 1.1 Description of the tidal terms, adapted from [2].

Tides are also a kind of long waves propagating in the ocean basin. To simplify, if friction, rotation, inertia and obstacles were not considered, a rising-falling cycle would occur every 12 hrs. However, this is not the real case, especially considering the tide propagation inside of a river with complex geometry and bathymetry. The tides propagating in rivers may be disturb, attenuated or amplified [3,4]. These processes modify the duration of the flood and ebb tides creating asymmetries. The inequality of the duration of the flood and ebb creates a residual sediment transport defining whether there is an import or export of sediment. The freshwater flow also influences in this duration[5,6].

1.2 Sediment dynamics

Sediment loads are the sediments carried by the flow or the sediments in motion. According to their moving patterns, sediment loads are typically classified as contact load (rolling or sliding), saltation load, laminated load, and suspended load (Figure 1.2). In these, contact load, saltation load and laminated load all belong to the category of bed load[7]. The total sediment load is defined as: Total Sediment Load = Bed Load + Suspended Load.
To differentiate various types of particles, sediment is subdivided into groups based on the particle sizes. Two classifications are given as described in Tables 1.2–1.3 [7]:

### Table 1.2 Chinese classification

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>&gt; 200 mm</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>0.05-2 mm</td>
<td></td>
</tr>
<tr>
<td>Cobble</td>
<td>20-200 mm</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>0.005-0.05 mm</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>2-20 mm</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>&lt; 0.005 mm</td>
<td></td>
</tr>
</tbody>
</table>

### Table 1.3 Attenberg’s classification

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>Upper Limit</th>
<th>Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>&gt; 200 mm</td>
<td></td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>0.2-2 mm</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>&lt; 0.002 mm</td>
<td></td>
</tr>
<tr>
<td>Cobble</td>
<td>20-200 mm</td>
<td></td>
</tr>
<tr>
<td>Fine Sand</td>
<td>0.02-0.2 mm</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>0.002-0.02 mm</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>2-20 mm</td>
<td></td>
</tr>
</tbody>
</table>

As seen the classifications are the same for the larger sediments, > 2 mm, and differs somewhat for the smaller, < 2 mm. Attenberg’s classification is approved by the International Union of Soil Science (IUSS) as the standard in soil analysis, and it has been widely adopted in European countries. Considering the flocculation effect of fine particles, the cohesive and non-cohesive of sediment are further identified.

#### 1.2.1 Suspended load

Flows at high velocity are turbulent and have eddies of various sizes. If the size of an eddy is much greater than a particle, the eddy may carry the particle for a long time. The transport of the suspended particles is mainly the effect of large-scale eddies. The particles, carried by eddies and moving at the same velocity as the flow, are called suspended load.

In steady turbulent flow, the amount of sediment carried by eddies from the lower layer into the upper layer per time is proportional to the concentration gradient. The sediment falling down from the upper layer into the lower layer is the product of concentration ($S_v$) and the settling velocity ($\omega_s$). If the concentration is in equilibrium, the following equation results:

$$\varepsilon_y \frac{dS_v}{dy} + S_v \omega_s = 0 \quad (1.1)$$

in which $\varepsilon_y$ is the sediment diffusion coefficient and $y$ is the position in the vertical direction. Many researchers have assumed [7]

$$\varepsilon_y = k U_* y \frac{h - y}{h} \quad (1.2)$$

in which $k = 0.41$ is the von Karman constant, $U_* = \sqrt{gsR}$ is the shear velocity, $R$ is the hydraulic radius, $h$ is the average depth if the river is wide and the water is shallow, $s$ is
the energy slope and $g$ is the gravity acceleration. Substituting equation (1.2) into (1.1) and integrating, the vertical profile of the suspended sediment concentration is obtained according to:

$$\frac{S_v}{S_{va}} = \left(\frac{h - y}{y} - \frac{a}{h - a}\right)^2$$ (1.3)

in which $a$ is the elevation from the bed of a reference point, $S_{va}$ is the concentration at the point and $z$ is a dimensionless number called the Rouse number\cite{9}, given by

$$z = \frac{\omega_s}{kU_*}$$ (1.4)

If the suspended particles move with the same velocity as the flow ($V$), the average transport rate of the suspended load per width ($q_s$) may be written as follows:

$$q_s = \int_a^h S_v V dy$$ (1.5)

1.2.2 Bed load

Bed load is the sediment that moves in the bed in vicinity to and in direct contact with the bed (Figure 1.3). The particles on the bed are subjected to a drag force from the flow and they slide or roll forward often in contact with the bed. These particles are called contact load. If the flow velocity is high, the contact load may move in a saltation way. Furthermore, if the drag force is extremely high a laminated load movement may occur. Laminated load movement is a special form of bed load transport with an extremely high intensity.

![Bed load movement in rivers\cite{10}](image)

To study the rate of bed load transport, the formulas of Meyer-Peter-Muller, Einstein, Bagnold, Engelund and Yalin are the most widely applied\cite{11}. The models have different variables, including shear stress, flow velocity and stream power. For bed load movement in a steady and uniform flow, Meyer-Peter and Muller\cite{12} derived the following formula:

$$g_b = 8g^{0.5} \gamma_s D^{1.5} \left[\left(\frac{K_b}{K_b'}\right)^{1.5} \frac{\gamma}{\gamma_s - \gamma}^{2/3} \frac{Rf}{D} - 0.047\left(\frac{\gamma_s - \gamma}{\gamma}\right)^{1/3}\right]^{1.5}$$ (1.6)

where $g_b$ is the rate of bed load transport per unit width in weight, $D$ is the diameter of the bed load and is usually represented by the median diameter $D_{50}$, $K_b/K_b'$ is the ratio of the roughness coefficient to that of the total resistance, $\gamma_s$ and $\gamma$ is the density of sediment and water in weight.
1.2.3 Sediment transport in tidal river

In tidal rivers, the amount of bed load is often negligibly small meaning that the sediment is mainly in suspension with the water, a common feature of many fluvial rivers[13]. The suspended sediment concentration is dependent on the flow discharge, showing an hourly variation. The sediment dynamics is closely linked to the flow dynamics described above.

As aforementioned, cohesive sediment of mud (silt and clay) has completely different dynamics than non-cohesive sediment of sand. In a tidal environment, cohesive sediment movement is somehow affected by the flocculation, leading to a lower settling velocity [14]. The difference arises from the electrochemical interactions of clay and silt particles, so the cohesiveness of sediment depends on their contents and also the salty water concentration. Laboratory experiments show that sediments becomes cohesive when the clay and silt contents are over 3–5% [15].

Interplaying with the freshwater flow, tides penetrating into the river lose energy in the bottom boundary layer, this energy dissipation is transformed into bed shear stress [16]. Deposition takes place when the shear stress is below a critical value while if it is above this value erosion occurs. The critical shear stress is determined by the bottom composition and cohesiveness augments the critical value by 2–5 times [15] as compared to a non-cohesive sediment. This implies that the flow to erode the bed layer with tidal effect, should has more momentum although the sediment is finer, which is not in line with the findings for non-tidal river regarding the fine sediment transport.

During flood tide, it is common to observe sediment in a high concentration advocating landward. The sediment deposits easily during the flow reversal, i.e. the shift between flood and ebb tides. A certain amount of particles consolidates and is not re-suspended during the ebb tide[17]. This is the main sediment transport patterns for rivers driven by strong tides. This transport scenario may become the opposite in stormy periods, becoming ebb dominated. For non-tidal rivers during wet season, the peak freshwater flow with high sediment concentration may govern the sediment transport in the river [18-20], suppressing the tides. There are also exceptions that are subject to the availability of sediment sources.

1.3 Fluvial processes

Three primary geomorphic processes govern the fluvial process, i.e., (a) erosion, the detachment of soil particles; (b) sediment transport, the movement of eroded particles in the flow volume; (c) deposition, settling of eroded particles to the river-bed. In these processes sediment, a bridge or media between flow and river-bed, plays the essential role.

To study the fluvial processes, the settling velocity of particles, being an important physical quantity characterising the sediment transport, is in focus. To simplify the problem, a single sphere falling with a constant velocity is considered. For this case the force of gravity $W$ and the resistance of the motion $F$ are equal, according to:

$$W = (\gamma_s - \gamma) \frac{\pi D^3}{6} \quad (1.7)$$
\[ F = C_D \frac{\pi D^2 \rho \omega_s^2}{4 \frac{2}{2}} \]  
\[ \omega_s^2 = \frac{4}{3} \times \frac{1}{C_D} \times \frac{\gamma_s - \gamma}{\gamma} gD \]

where \( D \) is the particle diameter and \( C_D \) is the drag coefficient being a function of the particle Reynold number:

\[ R_{e_p} = \frac{\omega_s D}{\nu} \]

in which \( \nu \) is the kinematic viscosity. For \( 1000 < R_{e_p} \), \( C_D \) is approximately constant at 0.5 \([21]\).

If the inertia force in the fluid is negligible, the Navier-equations can be linearized and solved and the following relationship is obtained\([22]\)

\[ F = 3\pi D \mu \omega_s \]

which is known as the Stokes Law and \( \mu \) is the dynamic viscosity. In this case, \( C_D \) is inversely proportional to \( R_{e_p} \) according to

\[ C_D = \frac{24}{R_{e_p}} = \frac{24}{\omega_s D/\nu} \]

Substituting Eq. (1.12) into Eq. (1.9), results in

\[ \omega_s = \frac{1}{18} \frac{\gamma_s - \gamma gD^2}{\gamma \nu} \]

Now notice that a group of particles falling in a liquid are affected by each other and behaves differently than a single particle. The theory behind this is tricky and an empirical formula has been proposed, based on extensive experiments \([7]\),

\[ \omega'_s = \omega_s (1 - S_v)^m \]

in which \( \omega'_s \) = the group settling velocity, \( m = 2-8 \) where \( m \) is a function of the \( R_{e_p} \).

In a tidal environment, there is not a universal formula to derive \( \omega_s \), so far. The empirical formula for \( \omega \) is usually obtained through laboratory or field experiments \([23]\). The values and ranges of \( \omega_s \) vary significantly in different rivers.
As for fluvial processes, sediment supply and transport capacity play dominant roles for the development of the plan-form geometry and bathymetry under specific environmental conditions[24]. The sediment carrying capacity ($S_c$ kg/m$^3$) reflects, as an index, the amount of entrained sediment transported by the flow if a river is in equilibrium. In comparison with the actual sediment centration ($S$) in the water, predictions are made for the fluvial process. If $S > S_c$, the flow is over-saturated with sediment and deposition occurs. If $S < S_c$, it is under-saturated and erosion takes place.

1.4 River confluence and meandering

1.4.1 River confluence

A river confluence is a key feature of a drainage basin in terms of hydrology and geomorphology, for geological records, as well as from a habitat point of view [25, 26]. In the confluence, where two tributaries meet, there is an enhanced turbulent mixing, which significantly affects the sediment transport and the amount of sediment delivered downstream. Local scouring is a typical morphological feature of the river confluence. In a long-term perspective, it is the flow patterns that govern the morphology changes, e.g., the erosion and sedimentation [26].

Mosley [27] pioneered the confluence research and Best [28] further developed it by dividing the confluence into six typical hydraulic regions [26, 28]. Those included areas of flow stagnation, flow deflection, flow separation, maximum velocity, gradual flow recovery, and shear layers (Figure 1.5). Yuan et al. [29] made a review of the state of the art in hydraulic research of run-off confluences.
In tidal environments, the confluence is, in addition to freshwater flow, also affected by the tides. The flow patterns thus differ from an overall unidirectional flow. As a result, the alluvial process in terms of erosion and deposition is different, which is an issue of concern for many practical applications, especially if the confluence is in an urban development area. To understand the morphodynamic changes of a tidal river confluence, field measurements and numerical modelling are performed, as reported in Paper 1.

1.4.2 Meandering river

In nature, meandering is one of the most common shapes formed by river streams, which is especially true for streams in lowland alluvial plains \(^{31}\). Leopold indicated that 90% of the alluvial rivers in the U.S. have meandering stream channels \(^{32}\).

Flow and sediment transport dynamics along meandering channels are controlled by changes in bed topography across the stream. Changes in channel curvature and bed topography are significantly interrelated, and the three-dimensional geometric properties of the channel need to be taken into account when assessing the effects of channel configuration on flow and sediment transport in meander bends \(^{33}\). The characteristic channel asymmetry at cross-sections in meander bends also favors the cross-sectional flow patterns, which in turn influence sediment transport (Figure 1.6).

Secondary circulation is generally observed in meander bends \(^{11}\). Secondary currents (laterally, across the channel) in curved channels are induced by a combination of two forces: centrifugal force and pressure gradient force. The former acting on water flowing around a bend causes a build-up of water adjacent to the bank known as water super-elevation. This, therefore, results in a slope of the water surface laterally across the channel. The magnitude of the change in water surface elevation \((Z)\) across the stream is determined from:

\[
Z = \frac{V^2 B}{gr} \tag{1.15}
\]

where \(B\) is the channel width, \(r\) is the radius of the bend curvature \(^{34}\).

In a tidal environment, the cross-sectional flow of a meander bend shows a different feature. The patterns are simulated and displayed in Paper 2.
1.5 Motivation and research objective

In this research, extensive field measurements are performed to record the flow and sediment data and to map the river bathymetry at selected occasions in a tidal river, including a confluence and a meandering reach. Both 2D and 3D morpho-dynamic models are established. The cohesive suspended sediment transport is simulated. The study focuses on such an alluvial river subjected to strong tides as compared to much lower fresh-water flow discharges.

The field data help understand the sediment movement characteristics in both the horizontal and vertical directions. By means of the field measurements and numerical simulations, the objectives are,

a) to elucidate the interplay between freshwater flows and tidal currents;
b) to reveal the relationship between the velocity and suspended sediment movement influenced by both the freshwater flow and the tides;
c) to illustrate circulatory patterns of suspended load transport during the tidal rising and falling;
d) to provide insight into the physical phenomenon that governs flow features of the tidal confluence;
e) to predict the evolution of a scour hole at the confluence.
f) to make predictions of the bed deformation associated with the meandering properties (curvature, cross-channel asymmetry etc.).
g) to derive a modified tidal flow carrying capacity formula based on the perturbation theory.
1.6 Outline of the thesis

This thesis is structured in five chapters. In addition to the introduction, it also contains four chapters that follow the objectives presented above.

Chapter 2 describes the field measurements, consisting of the arrangement of hydrological stations, the mainly used devices and method of raw data analysis.

Chapter 3 explains the two numerical models performed in 2D and 3D, respectively. In addition, detail explanations for some governing parameters and the method of calibration and validation are introduced.

Chapter 4 presents the results and discussions of the tidal confluence and meandering reach. An approach to derive a tidal flow carrying capacity for suspended load is also established.

Chapter 5 gives the concluding remarks based on the three papers appended. The future works in the next two years are also briefly proposed.
2. Field measurements

The study area is in Southeast China, featuring a water system with a confluence called Sanjiangkou. Upstream of it, the two merging rivers are Fenghua and Yao and downstream it is the Yong River flowing into the Pacific Ocean (Figure 2.1). The length of the Yong River is \( \sim 26 \) km from the confluence to the river mouth. The area is significantly affected by the interplay between the freshwater flow and tidal currents, experiencing semi-diurnal tides, i.e. two nearly equal high and low tides each day, and belonging to the category of incomplete standing waves. The river-bed profile from the confluence to the river mouth is shown in Figure 2.2.

![Figure 2.1 The water system, hydrological stations of water levels (WL) and of flow and sediment (FS).](image)

![Figure 2.2 The longitudinal bed profile from the confluence to the river mouth.](image)
To record the tidal hydrological data, extensive field surveys were carried out for the study area during June 2015 and January 2016. The hydrological data include water level, flow velocity, flow discharge, sediment concentration and grain-size distribution, etc. The water levels were monitored at seven cross-sections (WL1‒WL7), five of which were along Yong. To measure flow velocity and suspended sediment, seven corresponding cross-sections (FS1‒FS7) were arranged, each with three typical vertical lines A, B and C, from left to right, looking downstream (Figure 2.3). Their distances to the confluence as measured along the river centerline are given in Table 2.1. Along each line, sampling was made at six points, i.e., $h_i = 0, 20\%, 40\%, 60\%, 80\%$ and $100\%$ of the water depth $H_0$ ($i = 1, 2, ..., 6$). All data was recorded in a one-hour interval.

![Schematic diagram of cross-sectional measurement points (looking downstream).](image)

**Figure 2.3** Schematic diagram of cross-sectional measurement points (looking downstream).

**Table 2.1** Distance of field measurement stations to the confluence.

<table>
<thead>
<tr>
<th>Water Level station</th>
<th>WL1</th>
<th>WL2</th>
<th>WL3</th>
<th>WL4</th>
<th>WL5</th>
<th>WL6</th>
<th>WL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to confluence (km)</td>
<td>2.20</td>
<td>0.25</td>
<td>6.00</td>
<td>14.80</td>
<td>20.30</td>
<td>25.20</td>
<td>2.80</td>
</tr>
<tr>
<td>Flow &amp; sediment station</td>
<td>FS1</td>
<td>FS2</td>
<td>FS3</td>
<td>FS4</td>
<td>FS5 (FS6)</td>
<td>FS7</td>
<td></td>
</tr>
<tr>
<td>Distance to confluence (km)</td>
<td>2.20</td>
<td>0.25</td>
<td>9.70</td>
<td>18.10</td>
<td>24.70</td>
<td>3.20</td>
<td></td>
</tr>
</tbody>
</table>

Four-beam 600/1200-kHz RDI Workhorse Acoustic Doppler Current Profilers (ADCPs) were used to measure the velocities. These were put on a vessel having a speed less than 2.5 m/s, that was equipped with an GPS. The inaccuracy of the resulting flow discharges was below $\pm 5\%$. The YJD-1 type pressure sensors were used for water-level measurements, with an inaccuracy of $\pm 0.01$ m. Table 2.2 lists the parameters and inaccuracy of the main devices used in the field survey. Some photos are also displayed in Figure 2.4.

**Table 2.2** The parameters and inaccuracy of the main devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Parameter</th>
<th>Inaccuracy</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADCP</td>
<td>600/1200 kHz</td>
<td>$\pm 5%$</td>
<td>Flow velocity</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>YJD-1</td>
<td>$\pm 1$ cm</td>
<td>Water level</td>
</tr>
<tr>
<td>Electronic-Level</td>
<td>Topcon</td>
<td>$\pm 1.0$</td>
<td>Elevation</td>
</tr>
<tr>
<td>Echo sounder</td>
<td>HY1600</td>
<td>$\pm 1$ cm</td>
<td>Topographic survey</td>
</tr>
<tr>
<td>GPS</td>
<td>Trimble SPS461/BX982</td>
<td>$\pm 0.5$ m</td>
<td>Topographic survey</td>
</tr>
</tbody>
</table>

Efforts were made on sampling of the suspended load, using point-integrative water samplers. Samples of bed load, though small in amount, were also taken with Shipek grab samplers and their percentages were calculated. The grain-size distribution of the suspended load was analyzed using an automatic sieving device (SFY-D) and an automated Laser particle-size analyzer (Mastersizer2000). Particle sizes falling between the range $0.0002$ and $2$ mm were identified.
Figure 2.4 The devices photos mainly used during the field survey [36].

According to the field measurements, the bed load in the river is negligibly small in quantity (< 5 %) and suspended load dominates, a common feature of many fluvial rivers. Figure 2.5 shows the particle distributions for the suspended load at FS3 in wet and dry seasons, respectively. The particle size, in terms of $D_{50}$, is comparatively small.

Figure 2.5 The particle distributions at FS3: (a) wet season 2015; (b) dry season 2015.
For each WL and FS station, the time-series of the raw hydrological data were analyzed. For each time period, the average value of the FS sampling was first obtained for each line with the six points. Based on the three lines, cross-sectionally averaged sediment concentration, $S$ (kg/m$^3$), and flow velocity, $V$ (m/s), were then achieved by the weighted average method given below:

\begin{align*}
S &= \frac{\sum_i S_i V_i h_i}{\sum_i V_i h_i} \\
V &= \frac{\sum_i V_i h_i}{\sum_i h_i}
\end{align*} \tag{2.1, 2.2}

where $S_i$ and $V_i$ are the sediment concentration and the velocity of each measured points, respectively.

The obtained data is well suited for calibration and validation of numerical models. The field data acquired for the wet season, including one spring and one neap tide, in June 2015, are used in Paper 1 & 2. In addition to the wet season data, a set of data acquired for the dry season in January 2016 are used in Paper 3.
3. Modelling framework

3.1 Mathematical description

The Delft3D 4.04 package [37] is used to examine the complex flow features and morphology changes both in the confluence and the meandering. It is based on the finite-difference method and solves the Navier-Stokes equations. The governing equations include continuity, momentum, sediment transport and the bed deformation. No mathematical formulations of continuity and momentum are given here, since this is described in Paper 1 & 2.

For the 2D model, the depth-averaged flow parameters are obtained by Leibniz integration in the vertical direction. The vertical flow acceleration is neglected, leading to the hydrostatic pressure distribution. The turbulence shear stress is solved with the κ-ε turbulence model. For the 3D model, the vertical velocity component is computed using continuity.

From the field data, the bed-load amount is comparatively small, below 5%. To simplify, only the cohesive suspended sediment is considered in the sediment transport model. For mass balance and advection-diffusion, the equation in 3D reads as

\[
\frac{\partial s}{\partial t} + \frac{\partial}{\partial x}(us) + \frac{\partial}{\partial y}(vs) + \frac{\partial}{\partial \sigma}[(\omega - \omega_s)s] - \frac{\partial}{\partial x} \left( \varepsilon_{s,x} \frac{\partial s}{\partial x} \right) - \frac{\partial}{\partial y} \left( \varepsilon_{s,y} \frac{\partial s}{\partial y} \right) - \frac{\partial}{\partial \sigma} \left( \varepsilon_{s,z} \frac{\partial s}{\partial \sigma} \right) = -F_s
\]

where \( t \) is time, \( u \) and \( v \) are longitudinal and transversal velocity components, respectively while \( \varepsilon_{s,x}, \varepsilon_{s,y} \), and \( \varepsilon_{s,z} \) are the eddy diffusivity of sediment fraction in three directions and \( F_s \) is a function of the river-bed deformation, which is dependent on sediment erosion and deposition and is proposed as follows by Partheniades-Krone [38].

\[
\frac{\partial Z_b}{\partial t} = F_s \tag{3.2}
\]

\[
F_s = D_b - E_b \tag{3.3}
\]

\[
D_b = \begin{cases} 
\omega_s S_b \left( 1 - \frac{\tau}{\tau_d} \right) & \tau \leq \tau_d \\
0 & \tau_d < \tau 
\end{cases} \tag{3.4}
\]

\[
E_b = \begin{cases} 
M \left( \frac{\tau}{\tau_e} - 1 \right) & \tau \geq \tau_e \\
0 & \tau < \tau_e 
\end{cases} \tag{3.5}
\]

where \( Z_b \) (m) is the change in bed elevation, \( \gamma_0 \) is the dry weight of bed load, \( D_b \) is the sediment flux of deposition from suspended load, \( E_b \) is the sediment flux of erosion resulting in suspended load, \( S_b \) is the bottom sediment concentration, \( \tau \) is the bed shear stress, \( \tau_d \) and \( \tau_e \) are the critical stresses of deposition and erosion, respectively and \( M \) is the bed scouring rate.
The 2D transport equations for suspended load use a sediment diffusion coefficient \( u_s \) in the longitudinal and transversal directions, instead of \( \varepsilon_{xx} \), \( \varepsilon_{xy} \) and \( \varepsilon_{xx} \). For large-scale river simulations, the recommended \( u_s \) value is 10 m²/s and it is used in the simulations. The river bed deformation is dependent upon sediment erosion and deposition. Its derivation is also based on the shear stress, settling velocity and bed scouring rate, which is the same for the 3D model.

To predict the morphological changes in the long-term, a time scale factor, that accelerate the bed changes for each hydrodynamic time step, is used. Lesser et al.\[99\] conceptually described it as:

\[
\Delta t_{mor} = f_{mor} \Delta t
\]

where \( \Delta t_{mor} \) is the morphological time step, \( f_{mor} \) is the morphological scale factor and \( \Delta t \) is the hydrodynamic time step.

### 3.2 Calibration and validation

Calibration, as well as validation, is a prerequisite for modelling accuracy. By adjusting specific parameters, a reasonable match is achieved between observed and simulated results. In the study, varying roughness coefficient in space, time step and open boundary conditions and refining the mesh are the tuning aspects. As in many other studies, the results turn to be most sensitive to the roughness. Time steps (dependent on the grid density) and boundary conditions also have an influence on the model convergence; the grid density has a bearing on the accuracy of the results.

River-bed roughness, represented by Manning’s roughness equation \( n \), is an essential parameter dependent on such factors as river-bed morphology, flow patterns including water depth, etc. Based on the field investigations, a channel is separated into main channel and shore region with different \( n \) ranges. For a given position, linear interpolation is then made in light of water depth (Figure 3.1).

![Figure 3.1 Schematic diagram of river-bed roughness interpolation (adopted from internet).](image)

As shown in Table 3.1, three model criteria, i.e. Nash-Sutcliffe efficiency (NSE), R-Squared \( (R^2) \) and Percent bias (PBIAS) are often used for the model evaluation, where \( O_i \) are the
observed (in situ) values, $\bar{O}$ is the average of $O_i$, $P_i$ are the predicted values, $\bar{P}$ is the average of $P_i$ and $n$ is the total number of observed or predicted values.

**Table 3.1** Error parameters and accepted ranges for the model evaluation $^{[40,41]}$.  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Optimal value</th>
<th>Satisfactory if</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSE</td>
<td>$-\infty - 1$</td>
<td>$1$</td>
<td>$&gt; 0.5$</td>
<td>$E = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2}$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>$0 - 1$</td>
<td>$1$</td>
<td>$&gt; 0.5$</td>
<td>$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2 \sum_{i=1}^{n}(P_i-\bar{P})^2}}\right)^2$</td>
</tr>
<tr>
<td>PBIAS</td>
<td>$-\infty - +\infty$</td>
<td>$0$</td>
<td>$\pm 25%$ for flow $\pm 55%$ for sediment</td>
<td>$PBIAS = \frac{\sum_{i=1}^{n}(O_i-P_i) \times 100}{\sum_{i=1}^{n}O_i}$</td>
</tr>
</tbody>
</table>
4. Results and discussions

4.1 River confluence

When the maximum flood tide from the coastal area approaches the confluence, the confluence flow increases in magnitude. The flow field at the maximum flood tide is shown in Figure 4.1a, forming a flow bifurcation. The surface flow pattern is relatively smooth in the confluence without a recirculation. With the incoming maximum ebb tide from the two tributaries to the downstream, the flow velocity reaches its peak in the confluence and a large vortex is formed, see Figure 4.1b.

![Tidal flow fields during the 2nd half of June 2015: (a) at the max. flood tide; (b) at the max. ebb tide.](image)

The confluence flow at the maximum flood tide differs in both flow direction and magnitude from that at the maximum ebb tide, which depends on the tidal flow direction. And as mentioned at the ebb tide, there is a zone of flow separation close to left river bank (Figure 4.1b).

With the typical confluence flow features, the simulated results enable a scrutinization of the potential pattern of morphological changes. As time elapses, that the three river reaches are subjected to continuous siltation (Figures 18–20, Paper 2). The trend is not only in qualitative agreement with the study of the water system by Shen [42] and Chen et al. [13], but also it is in qualitatively agreement with the measured topography (Figure 4.2). These results all show that the rivers including the confluence, especially the scour hole, suffered from gradual siltation of the suspended load.
4.2 Meandering river reach

In the meandering reach (Figure 4.3), the flow features vary a lot with the stratified currents, in which cross-sectional velocity distributions often deviate from the logarithmic profile being typical of straight reaches. Meanwhile, the bi-directional currents induced by flood and ebb tides also make the flow patterns more complex.

In addition to cross-sectional and streamwise changes of bed forms, the velocity distributions in the cross-sections are also influenced by the rise and fall of the tides, which is different from non-tidal situations with only run-off. To exemplify this, cross-section WL5, being located at the bend apex, is studied. Figure 4.4 shows, during spring tide, both the velocity magnitude and the direction of the falling period (b) and the rising period (e), respectively. Other velocity distributions are displayed in Paper 2 (Figure 11).
Dependent on the rise and fall of the tides, the cross-sectional flow patterns in a meander differ in both flow direction and magnitude. Relative to the main stream, the major feature is an outward movement of water with the falling tide and an inward movement with the rising tide.

Predictions are made to display potential sediment patterns in the meander (Figure 4.5). For a given cross-section, its inner bank is exposed to heavier deposition than the outer bank. The mainstream tends to switch more to the outer bank, aggravating the curvature of the bend. The flow regime and imbalance of sediment transport are the main drivers of the meander reach evolution. The simulations suggest that the bed-level changes are closely related to the interactions between the run-off and tides. The latter plays a dominating role and governs the sedimentation.
4.3 Tidal flow carrying capacity

Perturbation theory (Paper 3), combined with dimensional analysis, multivariate linear analysis and least squares method results in an approach to estimate the sediment carrying capacity. This approach is presented for a tidal river and a capacity formula is established (Eq. 4.1). The procedure includes such factors as flow turbulence intensity ($U^2/gh$), gravity action ($U/\omega$), relative roughness ($D_{50}/h$), median grain size ($D_{50}$) and tidal effect ($\Delta h/h$).

$$S_c = F^2 \left( 0.026 \frac{D_{50}}{h} + 0.019 \frac{U}{\omega} + 0.013 \frac{\Delta h}{h} \right) + 1.025$$

where $F = U/(gh)^{0.5}$, the Froude number. Based on the field data from the wet season, values of the coefficients in the formula are obtained. The data of the dry season are then used for verification (Figure 4.6).

Figure 4.6 Comparison of $S_c$ and $S$ during ST and NT in the dry season (the 1st half of January 2016)
The derived formula has relatively good prediction accuracy. It is an improvement compared with previous studies considering fewer parameters. It is advisable to take into consideration the median grain size and tidal effects in determination of the sediment carrying capacity.
5. Concluding remarks and future work

5.1 Summary

This thesis work involves three parts:

In the first part (Paper 1), a tidal river confluence is surveyed and simulated. In a river confluence subjected also to strong tidal currents, its flow and morphological changes are dependent on a number of factors, showing a complex pattern in both time and space. The study deals with the typical features of such a confluence by means of field studies and numerical modeling.

In the second part (Paper 2), field and numerical studies are made to examine a tidal meander reach. If freshwater flow and strong tides co-exist in a meander reach, its flow and morphological changes exhibit both spatial and periodical changes, which differ significantly from non-tidal meandering reach.

In the third part (Paper 3), theoretical analysis is applied to examine the tidal flow carrying capacity. Based on the perturbation theory, the study considers seven major factors and a modified sediment carrying capacity formula is computed. The values of the coefficients of this model are obtained through multivariate linear regression analysis. Field data from a wet and dry season of a typical tidal river are collected to establish and verify the model.

The results provide reference to behaviors of tidal currents, sediment transport patterns and fluvial process in similar situations.

5.2 Future work

The following tasks have been considered for future work to be included in my study:

- Research on flow patterns and fluvial processes in a river reach shaped with both bifurcation and confluence; a 3D model with 10 vertical layers is expected to be setup.
Figure 5.1: (a) Numerical grids over the domain and with a local enlargement at the bifurcation and confluence; (b) Bathymetry.

- Sediment bypasses a dam. Sustainable structure design is examined and then applies it to some reservoirs exposed to high suspended sediment yield. The research is proposed to be carried out for some hydropower plants in Sweden or Norway.
- Investigation of vanes and submerged dams in river management. In addition to theoretical analysis, numerical simulation is also to be performed.
References


Part II
Papers
Paper A

Understanding Morphodynamic Changes of a Tidal River Confluence through Field Measurements and Numerical Modeling
Understanding Morphodynamic Changes of a Tidal River Confluence through Field Measurements and Numerical Modeling

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Abstract: A confluence is a natural component in river and channel networks. This study deals, through field and numerical studies, with alluvial behaviors of a confluence affected by both river run-off and strong tides. Field measurements were conducted along the rivers including the confluence. Field data show that the changes in flow velocity and sediment concentration are not always in phase with each other. The concentration shows a general trend of decrease from the river mouth to the confluence. For a given location, the tides affect both the sediment concentration and transport. A two-dimensional hydrodynamic model of suspended load was set up to illustrate the combined effects of run-off and tidal flows. Modeled cases included the flood and ebb tides in a wet season. Typical features examined included tidal flow fields, bed shear stress, and scour evolution in the confluence. The confluence migration pattern of scour is dependent on the interaction between the river currents and tidal flows. The flood tides are attributable to the suspended load deposition in the confluence, while the ebb tides in combination with run-offs lead to erosion. The flood tides play a dominant role in the morphodynamic changes of the confluence.

Keywords: tidal river confluence; flow features; morphological changes; field measurements; numerical simulations

1. Background

A river confluence is a key feature of a drainage basin in terms of hydrology and geomorphology, for geological records, as well as from a habitat point of view [1]. In the confluence, two merging run-off streams often result in enhanced turbulent mixing. This has a bearing on transported sediment and its amount delivered downstream. In a long-term perspective, the flow patterns govern the morphology changes of the confluence, e.g., the scouring and sediment deposition [2].

Many studies focused on hydrodynamic patterns and morphology changes in run-off confluences. Mosley [3] was a pioneer in the research, which was further developed by Best who defined six distinct hydraulic regions in a confluence [2,4]. Those included areas of flow stagnation, flow deflection, flow separation, maximum velocity, gradual flow recovery, and shear layers. With advanced instrumentation and novel experimental design, research of river confluences evolved and focused on the separation zone and the shear layer [5–8]. Yuan et al. [9] made a review of the state of the art in hydraulic research of run-off confluences. Best [2] examined principal morphological features
such as deep scour holes, bank-attached lateral bars, tributary-mouth bars, and a region of sediment accumulation in a river confluence. Other similar studies looked at the sediment and morphological aspects at non-tidal alluvial confluences [10–12]. They contributed to the understanding of the confluence scouring. A literature review shows that limited attention is drawn to tidal confluences with bi-directional flows [4].

In tidal environments, the confluence is also affected by tidal currents. As a result, the alluvial process in terms of erosion and deposition is different, which is an issue of concern for many practical applications, especially if the confluence is in an urban development area. Pittaluga et al. [13] investigated the morphodynamic equilibrium of alluvial estuaries, where river flows and tides meet. The complexity in a tidal confluence does not draw much attention [4,14,15]. In bi-directional flows, the shift of the dominant processes between river run-off and tides, featuring periodical changes in both magnitude and direction, induces more degrees of complexity in terms of flow patterns, sediment transport, and bed morphology change in the confluence. Ferrarin et al. [16] identified 29 scour holes at tidal channel confluences by examining their geomorphological characteristics and comparing them with scours in rivers. As a consequence of changes in the flow regime, their findings revealed, on a century scale, the morphological dynamics of scouring.

Field studies [10–12] and laboratory experiments [17–20] are major tools for studying sediment transport and the hydromorphic process in a confluence. In some studies, field measurements were made with tides; their purpose was to examine transport of the bed load [21–23]. The study of suspended load in tidal confluences is limited. One reason is attributable to the fact that it is not easy to, in a controlled manner in the laboratory, produce flow conditions of suspended load in combination with tides. Due to the complexity of the process, erosion and deposition are still not well understood [18]. Hypotheses are usually made that the origin of mid-stream scour is related to high flow velocity, strong turbulence, and the effect of shear layer or curvature-induced helical circulation [2,18–20].

Numerical modeling allows duplications of complex boundary conditions and prediction of different scenarios in a short time [24–29], which is also true for the study of tidal river confluences. Previous attempts were made with three-dimensional (3D) models for simulations of secondary circulations and flow variations in the vertical direction [30,31]. For a shallow confluence with a large width-to-depth ratio, a depth-averaged model is an acceptable compromise if necessary corrections of cross-circulatory motion are made [32–35].

In this research, field measurements of flow and sediment were made in the study area including the confluence. A two-dimensional (2D) morpho-dynamic model was set up, in which the cohesive suspended sediment transport was simulated. The objective was, by means of field measurements and simulations, to provide insight into the physical phenomenon that governs flow features of the tidal confluence, to describe circulatory patterns of suspended load transport, and to predict the scour-hole evolution. This study reveals the relationship between the velocity and suspended sediment movement influenced by both the run-off and the tides. The results provide reference to behaviors of tidal currents, sediment transport patterns, and fluvial process in similar situations.

The paper includes a description of the study area, field measurements of flow and sediment and data analyses, numerical formulation, model set-up with calibration and validation, major flow features, and morphological changes of the confluence.

2. Study Area

The confluence in question is called Sanjiangkou, formed by the Fenghua and the Yao River in southeast China. The stream after the confluence is called the Yong River. It is approximately 26 km upstream from the mouth into the Pacific Ocean (Figure 1). The Yao River runs into the junction roughly at a 90° angle with the other two rivers. The confluence is significantly affected by combined actions of river run-off and tidal currents. The bed load is negligibly small; the sediment transport in the rivers is mainly in form of suspended load, a common feature of many fluvial rivers [36].
Measured at the normal water surface, the width of the Fenghua River ranges from 90 to 180 m, and its average bed slope is 0.81%. The reach near the confluence is almost straight; its cross-section is nearly U-shaped. The yearly averaged run-off is 53.6 m³/s; the annual sediment discharge is 4.35 × 10⁴ tons [36].

The normal width of the Yao River ranges from 180 to 230 m. About 500 m before the confluence, a local constriction exists, with its water-surface width expanding from 140 to 180 m at the confluence. The daily run-off, as well as sediment transport, is controlled by the sluice gates located 3.3 km upstream of the confluence; the annual sediment discharge is comparatively small.

![Figure 1](image_url)

**Figure 1.** The water system, locations of the river confluence, and hydrological stations of water levels (WL) and of flow and sediment (FS).

The Yong River runs roughly in the west–east direction, with its normal width ranging from 150 to 250 m. The average river-bed slope is 0.117%. Its annual mean run-off is approximately 92 m³/s (annual average run-off 2.912 × 10⁹ m³). The peak discharge of run-off and tides occurs normally during the second half of June, amounting to about 1800 m³/s. The field recording stations for river water levels (WL) and of flow and sediment (FS) are also marked in Figure 1. At the river mouth, e.g., at station WL6, the annual mean tidal range is 1.91 m; the flood and ebb durations are almost the same, approximately 6 h. The tidal asymmetry aggregates from the river mouth to the upstream. In the confluence, the ebb duration is 40 min longer than the flood duration. At station WL7, the duration difference becomes 60 min [36]. On the Yao River, the sluice gates stop the tidal propagation further upstream. As for the location of the upstream limit of current reversals along the Fenghua River, the tides affect approximately 15 km upstream of WL7/FS7; no records are available to show the run-off influence. The sediment in the river is mainly from the coastal area and is carried by the tides.

Local scouring is a typical morphological feature of the river confluence. Our concern of the bed morphology is its scour-hole evolution (Figure 1). Previous field measurements show that a scour hole, like a narrow and deep crater along the Fenghua–Yong River, exists in the confluence and its deepest point is more than 10 m below the confluence bed elevation. During the earlier years, scouring dominated the river sedimentation process. Since the 1980s, the study area was affected by a number of factors, such as the construction of the sluice gates on the Yao River and other human activities. These changes modified the hydraulic conditions and affected the erosion potential in the water system, including the confluence. Bathymetric surveys, although irregular and fragmental, show that the morphology tends to shift from erosion to deposition.
3. Field Measurements

3.1. Data Collection

To map the river and confluence topography and to record the tidal hydrological data, field surveys were carried out during two major periods, i.e., June 2015 and January 2016. The former was used for this study. The river bathymetry used in the simulations was mapped from June 2015–January 2016, which was achieved using an HY1600 bathymetric profiler (SunNav Technology Co., Ltd., Tianjin, China). The hydrological data included water level, flow velocity, flow discharge, sediment concentration, grain-size distribution, water quality, and salinity.

The water levels were monitored at seven cross-sections (WL1–WL7), five of which were along the Yong River. To measure flow velocity and suspended sediment, seven corresponding cross-sections (FS1–FS7) were arranged, each with three plumb lines (Figure 2). Their distances to the confluence (measured along the river centerline) are given in Table 1. FS5 and FS6 are a few meters apart from each other and are treated as the same section. Along each line, the sampling was made at six depths from the water surface, i.e., \( h = 0, 0.2H_0, 0.4H_0, 0.6H_0, 0.8H_0, \) and \( 1.0H_0 \), where \( H_0 \) (m) is the water depth at each line. All the data were recorded in one-hour intervals.

Table 1. Distance of field measurement stations to the confluence.

<table>
<thead>
<tr>
<th>Water Level Station</th>
<th>WL1</th>
<th>WL2</th>
<th>WL3</th>
<th>WL4</th>
<th>WL5</th>
<th>WL6</th>
<th>WL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to confluence (km)</td>
<td>2.20</td>
<td>0.25</td>
<td>6.00</td>
<td>14.80</td>
<td>20.30</td>
<td>25.20</td>
<td>2.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow and Sediment Station</th>
<th>FS1</th>
<th>FS2</th>
<th>FS3</th>
<th>FS4</th>
<th>FS5 (FS6)</th>
<th>FS7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to confluence (km)</td>
<td>2.00</td>
<td>0.25</td>
<td>9.70</td>
<td>18.10</td>
<td>24.70</td>
<td>3.20</td>
</tr>
</tbody>
</table>

With a four-beam 600/1200-kHz RDI Workhorse acoustic Doppler current profilers (ADCPs) (Nortek group, Rud, Norway), water-flow velocities and discharges were measured. They were attached to the measurement vessels that were anchored on land. The uncertainty of the flow measurements was below \( \pm5\% \). The YJD-1-type pressure sensors (Tekscan, Inc., South Boston, MA, USA) were used for the water-level measurements and their accuracy is \( \pm1 \) cm. Major efforts were made to sample the suspended sediment, using point-integrative water samplers (Hoskin Scientific, Ltd., Saint-Laurent, QC, Canada). Samples of the bed load, although limited in amount, were also taken with Shipek grab samplers (Envco, Auckland, New Zealand) and their amount was calculated.

The grain-size distribution of the suspended load was analyzed using an automatic sieving device (SFY-D) (Zhonghu Scientific Ltd., Nanjing, China) and an automated laser particle-size analyzer (Mastersizer2000) (Malvern Panalytical Ltd., Worcestershire, UK). Particle sizes falling in the range between 0.0002 and 2 mm were identified. The obtained data are well suited for calibration and validation of numerical models. The field data acquired during the wet season, i.e., the second half of June 2015, were analyzed to determine the sediment features in the study area including the confluence. They are also used for calibration and validation.
3.2. Features of Suspended Sediment

For each WL and FS station, the time series of the raw measurement data were analyzed. For each time period, the average value was first obtained for each plumb line with the six points. Based on the results of the three lines, the cross-sectionally averaged value was achieved using the weighted average method.

According to the grain-size distribution, the sediment is classified as sand (0.05–2 mm), silt (0.005–0.05 mm), and clay (<0.005 mm) [37]. The field measurements show that approximately 95% of the river sediment is suspended load of cohesive silt and clay, most of which is carried into the river by the tides from the coastal area, as shown later. Table 2 shows their median grain sizes ($D_{50}$) from the field data. In the spring tide, the $D_{50}$ values vary from 0.005–0.009 mm for the suspended load, and from 0.008–0.017 mm for the bed load. In the neap tide, the corresponding ranges are 0.006–0.009 mm and 0.009–0.020 mm, implying that the $D_{50}$ values are slightly larger.

<table>
<thead>
<tr>
<th>Station</th>
<th>Spring Tide, $D_{50}$ (mm)</th>
<th>Neap Tide, $D_{50}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspended Load</td>
<td>Bed Load</td>
</tr>
<tr>
<td>FS1</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>FS2</td>
<td>0.007</td>
<td>0.013</td>
</tr>
<tr>
<td>FS3</td>
<td>0.007</td>
<td>0.011</td>
</tr>
<tr>
<td>FS4</td>
<td>0.008</td>
<td>0.019</td>
</tr>
<tr>
<td>FS5 (FS6)</td>
<td>0.008</td>
<td>0.011</td>
</tr>
<tr>
<td>FS7</td>
<td>0.009</td>
<td>0.017</td>
</tr>
</tbody>
</table>

The study area experiences a semi-diurnal tide—two nearly equal high and low tides each day, belonging to the category of incomplete standing waves. The second half of June 2015 includes 30 semi-diurnal tides, with 30 flood and ebb tides. $S$ (kg/m$^3$) denotes the mean sediment concentration at a cross-section. To look at its spatial changes during the period, Table 3 summarizes the time-averaged $S$ values at FS1–FS7. The following features were observed:

1. Going upstream from FS4, including the confluence, the suspended sediment experiences a trend of decrease in concentration during the semi-diurnal tides. The maximum value of $S$ along the Yong River always occurs at FS4, with a peak value of 2.341 kg/m$^3$ during the spring tides.

2. At the same location during the semi-diurnal tides, the sediment concentration during the spring tide is 3–8 times higher than that during the neap tide.

3. For either the spring or neap tide at the same location, the sediment concentration of the flood tides differs from that of the ebb tides; the spring tides feature higher values than the neap tides. This implies that the spring tides govern the transport of the suspended sediment from the coastal area.

4. At FS2, the flood tides carry more sediment than the neap tides, which means that the former dominates the sediment to the confluence.

<table>
<thead>
<tr>
<th>Station</th>
<th>Spring Tide (kg/m$^3$)</th>
<th>Neap Tide (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flood Tide</td>
<td>Ebb Tide</td>
</tr>
<tr>
<td>FS1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FS2</td>
<td>0.780</td>
<td>0.541</td>
</tr>
<tr>
<td>FS3</td>
<td>1.247</td>
<td>1.615</td>
</tr>
<tr>
<td>FS4</td>
<td>2.341</td>
<td>2.117</td>
</tr>
<tr>
<td>FS5 (FS6)</td>
<td>1.673</td>
<td>1.476</td>
</tr>
<tr>
<td>FS7</td>
<td>0.895</td>
<td>0.920</td>
</tr>
</tbody>
</table>
To further unveil the streamwise influence of the tides on the sediment, cross-sections FS5 (FS6) and FS2 were selected on the Yong River. The former is close to the river mouth and the latter to the confluence. Figures 3 and 4 compare, for the spring and neap tides, their relationship between $S$ and $V$, where $V$ (m/s) refers to the mean flow velocity at a river cross-section, positive toward the sea [38]. A negative $V$ value implies tidal reversal of the current.

![Figure 3](image-url) Station FS5 (FS6), mean flow velocity vs. mean sediment concentration ($V-S$) relationship for spring and neap tides: (a) Spring tide; (b) Neap tide.

![Figure 4](image-url) Station FS2, $V-S$ relationship for spring and neap tides: (a) Spring tide; (b) Neap tide.

The $V$ and $S$ values in the spring tides are larger than in the neap tides. $S$ varies significantly during a tidal period, with two peaks, implying that the sediment concentration is dominated by the tides along the river. The flood tidal $V$ and $S$ are always out of phase with one another; the peak $S$ appears during the flood tides. Along the river, the peak of $S$ almost synchronizes with that of $V$ except for during the neap tide at the river mouth. This implies that the sediment concentration is subjected to modifications by the tides at the river mouth and other oceanic processes like coastal up- and downwelling, storm surges, etc.

During the spring tide, it is the strong tidal currents that dominate the river flow and that transport the sediment toward the confluence. During the neap tide, the tide is comparatively weak; its $S$ values are much lower (Figures 3b and 4b). Judging from this, one can say that the run-off plays a major role. This leads to the non-similarity of $S$ and $V$ between the spring and neap tides. The tidal currents are essential for stirring sediment, modifying its peak duration, as well as its transport. If there was no tide, $S$ would be directly proportional to the river discharge and sediment would only be diverted downstream [39].

4. Numerical Modeling

Based on the Delft3D package [40], a 2D depth-averaged model was used to help understand the complex flow features and morphology changes of the confluence. Delft3D-Flow is a separate module in the package, in which sediment motion and morphology change are coupled with the flow to simulate flow patterns and morphological changes.

4.1. Mathematical Formulation

The governing equations are based on the Navier–Stokes equations, with Leibniz integration in the vertical direction, to obtain depth-averaged flow parameters. The vertical flow acceleration
is neglected, leading to the hydrostatic pressure. The turbulence shear stress is solved by the $k-\varepsilon$ turbulence model. The river-bed stability coefficient and resistance are parameters that govern the sediment scouring and deposition. The governing equations include, therefore, mass continuity, flow motion, sediment transport, and bed deformation.

The depth-averaged continuity equation is

$$ \frac{\partial \xi}{\partial t} + \frac{1}{G_{\xi\xi}G_{\eta\eta}} \frac{\partial (HU_\xi G_{\eta\eta})}{\partial \xi} + \frac{1}{G_{\xi\xi}G_{\eta\eta}} \frac{\partial (HU_\eta G_{\xi\xi})}{\partial \eta} = q, $$

(1)

where $H$ is water depth, $U_\xi(\xi, \eta)$ and $U_\eta(\xi, \eta)$ (m/s) are the depth-averaged velocities in the $\xi$ and $\eta$ coordinate system, $G_{\xi\xi}$ and $G_{\eta\eta}$ (m) are coefficients for transformation of the curvilinear to orthogonal coordinates, $q$ (m/s) is the global source or sink term per unit area, and $t$ (s) is time.

The momentum equations in the $\xi$ and $\eta$ directions are

$$ \frac{\partial U_\xi}{\partial t} + \frac{U_\xi}{G_{\xi\xi}} \frac{\partial U_\xi}{\partial \xi} + \frac{U_\eta}{G_{\eta\eta}} \frac{\partial U_\xi}{\partial \eta} - \frac{U_\eta^2}{G_{\eta\eta}G_{\eta\eta}} \frac{\partial G_{\eta\eta}}{\partial \xi} + \frac{U_\eta U_\xi}{G_{\eta\eta}G_{\eta\eta}} \frac{\partial G_{\xi\xi}}{\partial \xi} - fU_\xi = - \frac{1}{\rho_0 G_{\xi\xi}} P_\xi + F_\xi + M_\xi, $$

(2)

$$ \frac{\partial U_\eta}{\partial t} + \frac{U_\xi}{G_{\xi\xi}} \frac{\partial U_\eta}{\partial \xi} + \frac{U_\eta}{G_{\eta\eta}} \frac{\partial U_\eta}{\partial \eta} - \frac{U_\eta^2}{G_{\eta\eta}G_{\eta\eta}} \frac{\partial G_{\eta\eta}}{\partial \xi} + \frac{U_\eta U_\xi}{G_{\eta\eta}G_{\eta\eta}} \frac{\partial G_{\xi\xi}}{\partial \xi} + fU_\eta = - \frac{1}{\rho_0 G_{\eta\eta}} P_\eta + F_\eta + M_\eta, $$

(3)

where $\rho_0$ (kg/m$^3$) is water density (except in the baroclinic pressure terms, variations in $\rho_0$ are neglected), $P_\xi$ and $P_\eta$ (kg/(m$^2$s$^2$)) are pressure gradients, $f$ (1/s) is the Coriolis parameter (i.e., inertial frequency), $M_\xi$ and $M_\eta$ (m/s$^2$) refer to contributions from external sources or sinks of momentum (within the computational domain $M_\xi = M_\eta = 0$), $F_\xi$ and $F_\eta$ (m/s$^2$) are horizontal Reynolds stresses based on the eddy viscosity concept and change in both space and time, and $F_\xi = \frac{1}{\xi \xi} \frac{\partial \xi \xi}{\partial \xi} + \frac{1}{\xi \xi} \frac{\partial \xi \eta}{\partial \eta}$, $F_\eta = \frac{1}{\eta \eta} \frac{\partial \eta \eta}{\partial \xi} + \frac{1}{\xi \eta} \frac{\partial \xi \eta}{\partial \eta}$, and $\tau_{\xi \xi}$, $\tau_{\xi \eta}$, $\tau_{\eta \eta}$ (N/m$^2$) are turbulence shear stresses.

As noted from the in situ data, the bed load amount is small (below 5%). For the sake of simplification, only the cohesive suspended sediment is considered in the sediment model. The 2D transport equations for suspended load are given by

$$ \frac{\partial (HS)}{\partial t} + \frac{1}{G_{\xi\xi}} \frac{\partial (HSU_\xi)}{\partial \xi} + \frac{1}{G_{\eta\eta}} \frac{\partial (HSU_\eta)}{\partial \eta} = \frac{1}{G_{\xi\xi}} \frac{\partial}{\partial \xi} \left( v_s \frac{H}{G_{\xi\xi}} \frac{\partial S}{\partial \xi} \right) + \frac{1}{G_{\eta\eta}} \frac{\partial}{\partial \eta} \left( v_s \frac{H}{G_{\eta\eta}} \frac{\partial S}{\partial \eta} \right) - F_S, $$

(4)

where $F_S$ is the function of the river-bed deformation and $v_s$ (m$^2$/s) is the sediment diffusion coefficient. For large-scale river simulations, the recommended $v_s$ value is 10 m$^2$/s and it was used in the simulations.

The river-bed deformation is dependent upon sediment erosion and deposition and it is expressed as

$$ \gamma_0 \frac{\partial Z_b}{\partial t} = F_s, $$

(5)

$$ F_s = D_b - E_b, $$

(6)

$$ D_b = \begin{cases} \omega_s S_b \left( 1 - \frac{\tau_b}{\tau_d} \right) & \tau_b \leq \tau_d \\ 0 & \tau_d < \tau_b \end{cases} $$

(7)

$$ E_b = \begin{cases} M \left( \frac{\tau_b}{\tau_e} - 1 \right) & \tau_b \geq \tau_e \\ 0 & \tau_b < \tau_e \end{cases} $$

(8)

where $Z_b$ (m) is the bed elevation, $\gamma_0$ (N/m) is the dry weight of suspended load, $D_b$ (kg/(m$^2$s)) is the sediment flux of deposition from suspended load, $E_b$ (kg/(m$^2$s)) is the sediment flux of erosion resulting in suspended load, $\omega_s$ (m/s) is the particle settling speed, $S_b$ (kg/m$^3$) is the sediment
concentration at \( h = H \), \( \tau_b \) (N/m\(^2\)) is the bed shear stress, \( \tau_d \) and \( \tau_e \) (N/m\(^2\)) are the critical stresses of deposition and erosion, and \( M \) (kg/m\(^2\)s) is the bed scouring rate.

4.2. Grid and Bathymetry

In an orthogonal curvilinear grid, the finite-difference method solves the partial differential equations in Delft3D-Flow. The variables of water stage, bed level, and flow velocity were arranged in a staggered grid. Delft3D-Rgfgrid, a module of the package, generated the computational grid. A quality grid is the prerequisite for reliable simulations. It should be smooth enough to minimize discretization errors; the cells should be as orthogonal as possible, with a non-orthogonal factor less than 0.02 [40]. Figure 5 shows the grid generated for the modeled area with the confluence. The total river length of the study area was about 32.5 km; the area was covered by a grid of 102,600 cells, with 760 streamwise cells and 135 transverse cells. Several grids of varying cell sizes were tested to ensure grid independent solutions. Grid independence was checked through steady-state flow calculations. From a relatively coarse grid, the mesh refinement was made both globally and locally. A larger cell density was given to the confluence area, with a minimum cell size of 5 m.

![Computational domain with cells.](image1.png)

Figure 5. Computational domain with cells.

The module Delft3D-Quickin generated the river bathymetrical data. The bathymetry of the study area with the confluence is shown in Figure 6.

![Bathymetry of the study area with confluence.](image2.png)

Figure 6. Bathymetry of the study area with confluence.

4.3. Boundary and Initial Conditions

There were three open boundaries in the model: two upstream inflows and one outflow. For the former (FS1 and FS7), the time series of the tributary flow discharges were specified; for the latter
(WL6), the time series of the water level was given. The change in sediment concentration as a function of time was also specified at all the boundaries. Figure 7 displays the measured $Q$, $Z$, and $S$ profiles at the three boundaries, where $Q$ (m$^3$/s) and $Z$ (m) denote flow discharge and the water stage at a cross-section, respectively. The wetting and drying functions of cells in the domain were activated to reflect the rise and fall of the tides.

![Figure 7](image-url)

**Figure 7.** Boundary conditions with measured data: (a) Flow discharge ($Q$); (b) Water stage ($Z$); (c) $S$.

Initial conditions referred to specifications of water flow and sediment in the domain. The water level was first patched and the corresponding flow velocity was estimated by the program. Approximately one hour was taken to reach a steady-state flow. Then, the sediment concentration was patched. After another hour, the sediment conditions became steady, based on which the dynamic changes of flow and bathymetry governed by the boundary conditions were then updated. This is shown in Figure 8.

![Figure 8](image-url)

**Figure 8.** Schematic diagram of the coupled flow and sediment calculations.

Table 4 summarizes the additional parameters, $\omega_s$, $\tau_d$, $\tau_e$, $M$, and $\gamma_0$, in the set-up.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_s$ (m/s)</td>
<td>0.0005</td>
<td>Measurements</td>
</tr>
<tr>
<td>$\tau_d$ (N/m$^2$)</td>
<td>0.06–0.10</td>
<td>Equation (7) [39]</td>
</tr>
<tr>
<td>$\tau_e$ (N/m$^2$)</td>
<td>0.10–0.20</td>
<td>Equation (8) [41]</td>
</tr>
<tr>
<td>$M$ (kg/m$^2$ s)</td>
<td>0.0002–0.02</td>
<td>Equation (8) [41]</td>
</tr>
<tr>
<td>$\gamma_0$ (kg/m$^3$)</td>
<td>1600</td>
<td>Measurements</td>
</tr>
</tbody>
</table>
4.4. Time Step

The choice of the time step (Δt) was based on the Courant number (C), the value of which should be less than 10 [42]. It is defined as

$$C = 2\Delta t \sqrt{gh\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right)},$$

(9)

where $g$ (m/s$^2$) is the acceleration due to gravity; Δt = 0.3 s was selected.

5. Model Calibration and Validation

5.1. Model Calibration

Model calibrations were based on the hourly observed data for the spring tide in 2015, occurring between 10:00 a.m. on 17 June and 4:00 p.m. on 18 June, representing 30 h in total. The model was tested with several options for boundary conditions—bed roughness, grid size, and time step. The purpose was to find a reasonable match between the observed and calculated values of flow discharge, water level, and sediment concentration. The commonly used criteria including Nash–Sutcliffe efficiency, the $R^2$-squared method, and the percent bias were also used here for the model calibration [43,44]. Table 5 shows the definitions of the error parameters and their ranges, where $O_i$ = measured value, $P_i$ = predicted value by the model, $\bar{O}$ = average of measured values, $\bar{P}$ = average of predicted values, and $n$ = the total number of values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optimal Value</th>
<th>Satisfactory</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSE</td>
<td>1</td>
<td>&gt;0.5</td>
<td>$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>1</td>
<td>&gt;0.5</td>
<td>$R^2 = \frac{\left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$</td>
</tr>
<tr>
<td>PBIAS</td>
<td>0</td>
<td>±25% for flow rate ±55% for sediment</td>
<td>$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i) \times 100}{\sum_{i=1}^{n}O_i}$</td>
</tr>
</tbody>
</table>

The river-bed roughness ($n$) is a key parameter of concern that is governed by factors, such as the river-bed morphology, flow patterns, etc. Based on trial and error, its range was finally set between 0.015 and 0.030, with 0.015–0.018 for the main channel and 0.018–0.030 for the shore beach. Figures 9–11 show the final calibration results of $V$ and $S$ at FS2, FS3, and FS4.

Figure 9. Model calibration, numerical vs. field results at FS2 (spring tide, June 2015): (a) $|V|$; (b) $S$.  

![Figure 9](image-url)
were negligibly small for all the stations. For matches were generally satisfactory. The four reproduced, in terms of both magnitude and phase. For FS2, FS3, and FS4, Table 6 shows the calibration results of the error parameters. All the values fell within the ranges required by the criteria.

In the validation, the procedure for result evaluations was the same as for in the calibration. The validation results are shown in Figures 12–14. The calculated profiles matched well with the measured data series. Table 7 shows the validation results of the error parameters for the three stations. All the values met the requirements of the criteria. The model generated acceptable results and is suitable for prediction of flow and morphology changes of the area including the confluence.

5.2. Model Validation

The model was validated against a neap tide that occurred during a 31-h period between 3:00 p.m. on 24 June and 10:00 p.m. on 25 June of the same year. In the validation, the procedure for result evaluations was the same as in the calibration.

The validation results are shown in Figures 12–14. The calculated $V$ and $S$ profiles matched well with the measured data series. Table 7 shows the validation results of the error parameters for the three stations. All the values met the requirements of the criteria. The model generated acceptable results and is suitable for prediction of flow and morphology changes of the area including the confluence.
According to the statistics of the whole-year water-level data at WL6 during 2015, the tidal frequency in the wet season (the 2nd half of June) was 10%, 40%, and 25% for the spring, mid, and neap tides, respectively [45]. Under the combined action of the run-off and tides, the maximum flood and ebb tides of the spring tides dominate the sediment transport; they also characterize the flow features and they were selected to show the results.

### 6. Typical Flow Features

According to the statistics of the whole-year water-level data at WL6 during 2015, the tidal frequency in the wet season (the 2nd half of June) was 10%, 40%, and 25% for the spring, mid, and neap tides, respectively [45]. Under the combined action of the run-off and tides, the maximum flood and ebb tides of the spring tides dominate the sediment transport; they also characterize the flow features and they were selected to show the results.

#### 6.1. Tidal Current Fields

When the maximum flood tide from the Yong River approached the confluence, the confluence flow saw an increase in magnitude. The flow field at the maximum flood tide is shown in Figure 15a.
Current reversals occurred because the tides were stronger than the river run-off. It was a flow bifurcation. The surface flow pattern was relatively smooth in the confluence. In the Yong River, the depth-averaged flow velocities were largest (0.6–0.8 m/s). In the Fenghua and Yao rivers, the tidal currents were weak; the corresponding velocities amounted to 0.4–0.6 and 0.2–0.3 m/s, respectively. Furthermore, the tidal current flowing into the Yao River was influenced by the bend. Due to the centrifugal force [46], its mainstream was close to the concave river bank.

In summary, parting from the water levels, the confluence flow at the maximum flood tide differed from the nearby velocities in the river streams. The discrepancy was attributed to the effect of the momentum offsetting. If two flows merge with each other, there is momentum exchange, which enhances the turbulent mixing, leading to energy dissipation. Moreover, the water depths in the confluence were larger, also explaining the smaller velocities.

In the confluence, comparison of the velocities at the maximum flood and ebb tides show that the latter was approximately 0.2 m/s larger than the former, which was due to the addition of the ebb tide to the run-off. The volume of the ebb tide was also larger than that of the flood tide, while, for the flood tide, the run-off and the tide were in opposite directions, thus offsetting each other. The prevalence held that the velocity of the ebb tide was higher than that of the flood tide.

In summary, parting from the water levels, the confluence flow at the maximum flood tide differed in both flow direction and magnitude from that at the maximum ebb tide, which depended on the tidal flow direction. At the ebb tide, a zone of flow separation also existed close to left river bank.
6.2. Bed Shear Stress

For a location in question, \( \tau_b \) relates the flow regime to deposition and erosion patterns. It is a function of a quadratic of \( \bar{U} \) and the 2D Chézy coefficient \( C_{2D} \) (m\(^{0.5}$/s) or an equivalent roughness length [48]. For 2D depth-averaged flows, \( \tau_b \) is given by

\[
\tau_b = \frac{||\bar{U}|| \rho g \bar{U}}{C_{2D}^2},
\]

where \( ||\bar{U}|| \) (m/s) is the magnitude of \( \bar{U} = \bar{U}_z + \bar{U}_y \). \( C_{2D} \) is expressed as

\[
C_{2D} = \frac{\sqrt{H}}{n}.
\]

Collins et al. [48] pointed out the variability of these parameters. In a tidal confluence, the \( \tau_b \) determination is complicated by factors such as confluence geometry, bed topography, and sediment. Flow perturbations make it difficult to measure \( \tau_b \) in the field. Therefore, numerical models are often used for obtaining \( \tau_b \) in tidal environments.

\( \tau_b \) is proportional to \( ||\bar{U}|| \) and is also affected by \( H \). In the confluence, the \( ||\bar{U}|| \) and \( H \) values were between 0.4–0.6 m/s and 6.0–17.3 m (exclusive of the scour hole). At the maximum flood and ebb tides, Figure 16 shows the distribution of the peak \( \tau_b \) values. Their distributions of \( \tau_b \) were similar, with some local differences. For each tide, the spatial distribution and magnitude followed the pattern of the velocity gradient distribution. For a given river, a decay was exhibited from the mainstream to the bank.

\( \tau_b \) reflects the velocity gradient and is affected by both run-off and tides. The peak \( \tau_b \) values occurred away from the confluence in the Fenghua and Yong rivers, which was true for both the flood and ebb tides. The occurrence of these areas was similar to the situation with only the run-off in the rivers [1,4,9].

Low \( \tau_b \) values occurred in such areas as along the Yao River and in the confluence. At the confluence, the Yong and Fenghua rivers run almost along a straight line, while the Yao River intersects them at almost a right angle. As the tide comes from the Yong River, the tides are bathymetrically constrained and the bending accounts for the low \( \tau_b \) values in the Yao River. \( \tau_b \) links the flow conditions with sediment transport, providing indications of morphology change.

![Figure 16. Distributions of \( \tau_b \) during the second half of June 2015: (a) At the maximum flood tide; (b) At the maximum ebb tide.](image-url)
7. Morphological Changes

With the typical confluence flow features, predictions were made to look at the potential pattern of morphological changes. The construction of the sluice gates on the Yao River interrupted the natural run-off downstream. Another factor is that many wading structures were built on both rivers upstream of the confluence, which also affected the run-off in the water system. This means that the tides interact with the run-off in a different way than before; the intrusion of the tidal waves is further upstream, which probably results in more sediment deposition. Simulations were carried out to estimate the possible scenarios.

As shown earlier, the tidal currents, especially for the spring tides in wet seasons, dominate the sediment transport in the area. During the second half of June 2015, the 30-h spring tide was selected for the purpose. Along the rivers including the confluence, the start condition of the river bed corresponded to the bathymetry obtained at 10:00 a.m. on 17 June 2015. As shown in Figure 17, a long, oval-shaped scour hole exists in the confluence and extends into the Yong River. Its depth is 10.8 m at the maximum (the river bed is 6.5 m below the mean sea level, with a bed elevation of $-6.5$ m). In the simulation, a morphological scaling factor was used to accelerate the bed erosion and deposition, a method of common practice [39,49–51]. The scaling factor was set to 100, implying that the prediction period covered 125 days.

Figure 17. Contours of the confluence in June 2015 ($T = 0$).

Figure 18 illustrates, in the confluence and its close vicinity, the bed evolution from $T = 0$, 30, 60, 90, 120, and 125 days. The results show, as time elapses, that the three river reaches were subjected to continuous siltation. The trend is in qualitative agreement with the study of the water system by Chen et al. [36], in which the cumulative influence of the wading structures, including the Yao sluice gates, bridges, and wharfs, was analyzed. Their results showed that the rivers including the confluence also suffered from gradual siltation of suspended load. Figure 19 illustrates the change in scour-hole depth and the averaged elevation of the river bed around the hole. Figure 20 shows, as a function of time, the simulated longitudinal profiles of the bed-level changes along each river at the confluence. Both the river bed and the scour hole show a tendency of gradual deposition. The hole depth was initially 10.8 m and became 9.25 m at $T = 125$ days.
Both the flood and ebb tides contributed to shaping the confluence scour hole. The former gave rise to deposition, while the latter led to erosion. However, the flood tide played a dominant part in the process. As a result, the scour hole shrank both upstream and downstream as time elapsed. Two factors accounted for the morphological feature. On one hand, the change was associated with the sediment availability in each river. The field measurements indicated that the flood tides carry a large amount of suspended load upstream. When flow velocity fell below 0.8 m/s, deposition occurred in the confluence area. Using morpho-sedimentological and seismo-stratigraphic data, Silva et al. explained a similar phenomenon of confluence deposition [15]. They found that the river sediment was deflected back into the river by the flood tides, thus producing the sediment deposition on the scour hole’s gentle side (downstream slope). On the other hand, the cumulative effect of river run-off and ebb tides was also attributable to the scour changes. During the ebb tides, the deposited sediment in the confluence became re-suspended and resulted in slight bed erosion. The dominance of the flood tide eventually led to the sediment deposition along the rivers inclusive of the confluence.

Figure 18. River-bed morphology changes in the confluence: (a) $T = 0$; (b) $T = 30$ days; (c) $T = 60$ days; (d) $T = 90$ days; (e) $T = 120$ days; (f) $T = 125$ days.
strong tides are closely related to the interactions between the run-off and tidal currents. However, the periodic changes in the tidal flow direction induce a complex morphological regime that are dependent on a number of factors, showing a complex pattern in both time and space. This study dealt with the typical features of such a confluence by means of field studies and numerical modeling. The Yao River also features gradual siltation, which changes its river-bed slope and lowers the sediment carrying capacity. This was also observed in the field [38]. Two plausible reasons account for it. One is ascribed to the construction of the sluice gates and the wading structures upstream. As a result, it not only intercepts the river run-off, but also deforms the tidal waves in the river. According to measurements [38], the mean high tidal level increased by 0.17 m; the mean low tidal level decreased by 0.11 m. The flood tide duration became 9 min shorter and the ebb tide duration became 9 min longer. The other reason is due to the bending toward the confluence. The flow, either during the flood or ebb tides, fails to transport the sediment downstream, thus leading to deposition along the river.

The periodic changes in the tidal flow direction induce a complex morphological regime that does not occur in unidirectional run-off flows. Concerning the sedimentation pattern, the morphologic features migrate streamwise with run-off flows [3,49]. With tidal waves, the pattern migrates both ways, which agrees with previous findings of the tides that both deposition and re-suspension take place in the confluence [52]. The analysis showcases that the flow regime is the main driver of the confluence scour evolution. The morphological changes in the confluence subjected to the latter plays a dominant role and governs the sedimentation pattern.

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place in the confluence [52]. The analysis showcases that the flow regime is the main driver of the
confluence scour evolution. The morphological changes in the confluence subjected to strong tides are
closely related to the interactions between the run-off and tidal currents. However, the latter plays a
dominant role and governs the sedimentation pattern.

8. Conclusions

In a river confluence subjected also to strong tidal currents, its flow and morphological changes
are dependent on a number of factors, showing a complex pattern in both time and space. This study
dealt with the typical features of such a confluence by means of field studies and numerical modeling.

From the sea into the Yong River, the sediment is transported by the tidal currents,
especially during the spring tides. During the selected period of two years, field measurements
were made to examine the sediment behaviors. The data show that approximately 95% of the sediment
in the study area is suspended load. From the river mouth to its upstream including the confluence,
the flow and sediment changes are not always in phase with one another; the sediment movement
is significantly modified by the tides. The peak values of sediment concentration occur during both
the flood and ebb tides in the rivers. Tidal currents are essential for stirring sediment, modifying
its concentration and transport. If there was no tide, the sediment concentration would be directly
proportional to the river flow, with the sediment diverted only downstream.

With the field measurements in the background, numerical modeling helps understand the
alluvial features of the confluence. Two-dimensional simulations of suspended sediment transport
were performed to simulate the sediment patterns. At the confluence, the flow at the maximum flood
tides differs, in both flow direction and magnitude, from that at the maximum ebb tides. During the
ebb tides, a small zone of flow circulations exists close to the left bank of the confluence. The bed
shear stress is proportional to the water depth and flow velocity, and it is affected by the river-bed
topography. Its distribution reflects the sediment erosion potential in the confluence.

By means of a morphological scale factor, the scour formation in the confluence was predicted.
The initial hole in the confluence, extending along the Fenghua and Yong rivers, becomes gradually
deposited as time elapses. The shifting tidal directions induce a complex morphological pattern that
does not exist in unidirectional run-off flows. The erosion and deposition migrate in both directions.
The flood tides govern the sediment transport and deposition, while the ebb tides with run-offs lead to
erosion. For the scour-hole development, the flood tides play a dominant role.

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with participation from S.L., J.Y., and W.D. The manuscript was written by Q.X. and J.Y. The research of river flow
and sedimentation was supervised by J.Y. and S.L.

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Paper B

Field Studies and 3D Modelling of Morphodynamics in a Meandering River Reach Dominated by Tides and Suspended Load.
Field Studies and 3D Modelling of Morphodynamics in a Meandering River Reach Dominated by Tides and Suspended Load

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Abstract: Meandering is a common feature in natural alluvial streams. This study deals with alluvial behaviors of a meander reach subjected to both fresh-water flow and strong tides from the coast. Field measurements are carried out to obtain flow and sediment data. Approximately 95% of the sediment in the river is suspended load of silt and clay. The results indicate that, due to the tidal currents, the flow velocity and sediment concentration are always out of phase with each other. The cross-sectional asymmetry and bi-directional flow result in higher sediment concentration along inner banks than along outer banks of the main stream. For a given location, the near-bed concentration is $2-5$ times the surface value. Based on Froude number, a sediment carrying capacity formula is derived for the flood and ebb tides. The tidal flow stirs the sediment and modifies its concentration and transport. A 3D hydrodynamic model of flow and suspended sediment transport is established to compute the flow patterns and morphology changes. Cross-sectional currents, bed shear stress and erosion-deposition patterns are discussed. The flow in cross-section exhibits significant stratification and even an opposite flow direction during the tidal rise and fall; the vertical velocity profile deviates from the logarithmic distribution. During the flow reversal between flood and ebb tides, sediment deposits, which is affected by slack-water durations. The bed deformation is dependent on the meander asymmetry and the interaction between the fresh water flow and tides. The flood tides are attributable to the deposition, while the ebb tides, together with run-offs, lead to slight erosion. The flood tides play a key role in the morphodynamic changes of the meander reach.

Keywords: tidal meandering river; field measurements; 3D numerical model; flow features; sediment transport; erosion-deposition patterns

1. Introduction

Meandering is one of the most common shapes formed by river streams, which is especially true for streams in the lowland alluvial plains [1]. Due to meandering, the characteristics of water flow, sediment transport and the resulting bed deformation are more complex than in relatively straight river reaches. For a coastal river, the tidal currents interact with the fresh-water run-off and they form a bidirectional flow, which also plays an essential role in the fluvial process. This is especially true if the tides are much stronger than the fresh-water discharges. With a landward decline in strength, the tidal influence descends.

At the meander bend apex, its cross-sectional shape is usually asymmetrical, with a deep portion of channel along the outer bank and a broad, shallow section extending towards the inner bank.
The plane curvature and cross-sectional asymmetry topography are shown to produce significant secondary currents and transverse water-surface slopes \[2,3\]. The secondary currents derive from the centrifugal acceleration acting on the stratification between the upper and lower flow layers.

It has also been proved that strong stratified currents have significant impacts on the distribution of bed shear stresses along the wetted perimeter of river, and thereby play an essential role in the sediment transport as well as morphology changes \[3–6\]. The bed changes induced by erosion and deposition affect the flow, which in turn influences the shear-stress distribution, sediment component and bed topography \[7\]. Therefore, the coupling of the stratified currents, sediment movement and bed-form changes makes up an interactive response that characterizes the meandering morphodynamics.

Given its scientific and practical significance, the dynamic process in a meandering river, among several other issues, has to date been the object of numerous theoretical and experimental studies \[8–11\]. These contribute to the understanding of the meandering phenomena. Recently, the use of an acoustic doppler current profiler (ADCP) has permitted direct estimations of Reynolds stress in tidal environment rivers \[12\]. Further research, especially of field measurements, that focuses on river curvature and cross-sectional asymmetry and deals with the interaction between river run-off and tidal currents \[3\], is necessary.

In recent years, many numerical simulations have been performed of tidal flow and sediment transport in meandering rivers. Instead of simplifications and assumptions in physical model tests, complex river geometries and boundaries are directly modelled. In a meander, its flow is three dimensional \[13\]. As compared with 2D depth-averaged models, an application of a 3D model generates, in terms of sediment transport, more reliable results \[14\].

For meandering rivers, most 3D models applied to simulations are based on the Reynolds-Averaged Navier-Stokes (RANS) equations assuming time-independent flow and isotropic turbulence \[4,6\]. A recent development is the application of large and detached eddy simulation (LES, DES) models to meandering flows \[15,16\]. LES aims to capture the time-dependent flow and resolves the large-scale anisotropy of turbulence. Limited by central processing unit (CPU) time and convergence, it is often used for issues with low Reynolds numbers and of limited domain dimensions \[6\]. In contrast, Delft3D (Version 4.04, Delft, The Netherlands) has the advantage of time-effective computations when applied to large-scale river and ocean simulations.

Meandering with large curvatures is a characteristic of many streams in low-land coastal regions. Changes in both river curvature and bed topography are interrelated, and their geometric shapes need to be considered when assessing the effects of channel configuration on flow and sediment transport. In a tidal environment, the river reach is affected by both run-off and tides, in which shifts between flood and ebb tides induce, with regard to flow patterns and sediment transport, more complexity. As a result, in terms of erosion and deposition, the alluvial process is different, an issue of concern for practical applications, especially if the river is in an urban development area.

The study focuses on a meandering reach of an alluvial river subjected to strong tidal currents (compared to much lower fresh-water discharges). Suspended load accounts for approximately 95% of the sediment in the river. Field measurements are performed to record the flow and sediment data and to map the river bathymetry at selected occasions. The field data help understand the sediment movement characteristics in both horizontal and vertical directions. A 3D suspended-load transport model is incorporated into a hydrodynamic model and computes the flow patterns and morphological changes. By means of the two approaches, the objective of the study is to provide insight into the interplay between fresh-water flows and tidal currents, to illustrate the circulatory patterns of suspended load transport during the tidal rising and falling, and to make predictions of the bed deformation associated with the meandering properties (curvature, cross-channel asymmetry, etc.). The results provide a reference for studies of tidal fluvial processes in similar situations.

The paper includes a study area description, field measurements of flow and sediment, field data analyses, mathematical formulation, model setup with calibration and validation, major flow features and morphological changes.
2. Study Area

The study aims to examine an approximately sinusoidal meandering reach, with two successive, nearly S-shaped meander loops (Figure 1). The river runs into the sea and is subjected to strong tides.

![Study area: (a) Location; (b) examined meandering reach of the Yong River; (c) measurement stations of water levels (WL) and flow & sediment (FS).](image)

The study area is part of the Yong River, located in Southeast China. The total area of the catchment is 42.94 km² (the area above the FS3 gauge is approximately 29 km). The river runs roughly in the SW–NE direction. The river length and width are about 26.5 km and 150–250 m measured on the normal water surface. The average river-bed slope is 1.17%. The annual average rainfall is 1505 mm; the annual flow volume is 2.91 × 10⁷ m³; its annual average fresh-water discharge is 92 m³/s [17]. In a pronounced way, the flow and sediment transport in the river are affected by the tides from the coastal area. The annually averaged tidal flux is 946 m³/s, approximately 11 times the fresh-water flow discharge. The tides are the dominating factor for the sediment movement. Due to deposition, the river-bed rises, and the width narrows in many sections. This water system has been well managed since 1959, with regular dredging for navigation [18]. A single water course features the river mouth, without multiple branches, either at present or in the past.

The tide in the river is a semi-diurnal tide, i.e., two nearly equal high and low tides each day, belonging to the category of incomplete standing waves. According to the yearly statistics of hydrological stations, the average range of tidal levels is 0.29–0.44 m within one circle. The mean river depth is about 8 m, with tidal peak velocities close to 1 m/s; the tidal range increases landwards with the narrowing river width, with an average range falling between 1.62–1.84 m. During flood tides, sediment follows the currents and is transported from the outer sea area to the inland. This flow and sediment transport process reverse during ebb tides.

The meandering reach of interest has three consecutive parts of significant curvature (Figure 2). From up- to downstream, the radius of curvature is $R \approx 700, 500$ and 300 m; their angles are $\theta \approx 80^\circ$, $100^\circ$ and $120^\circ$, respectively. The typical river width and water depth are about 200 m and 10 m. In addition, the meandering reach features large areas of shoals associated with high tidal levels, especially close to the apex positions. With these geometrical features, it is a typical site to understand the cross-sectional currents and asymmetric bed forms and their effects on sediment movement along the reach.
Further upstream of the study area, a confluence exists, where the Yao and Fenghua Rivers merge into the Yong River (Figure 1). Its sedimentation pattern, associated with different flow regimes, is also an issue of concern [19].

To record the hydrological data and map the river bathymetry, extensive field surveys were carried out for the study area during the period June 2015–January 2016. The hydrological data used were acquired for a typical wet season in June 2015. The collected parameters included water levels, water-flow velocity, flow discharge, sediment concentration and grain-size distributions. The river bathymetry used for the study was achieved using an HY1600 bathymetric profiler.

Also marked in Figure 1 are the recording stations for water levels (WL), at three locations (denoted as WL4, WL5 and WL6), and for flow & sediment (FS), also at three locations (denoted as FS3, FS4 and FS5). At each FS, three typical plumb lines (A, B and C, from left to right, looking downstream) were arranged (Figure 3). Along each line, sampling was made at six points, i.e., \( h_i = 0, 20\%, 40\%, 60\%, 80\% \) and 100% of the water depth \( H_0 \) \((i = 1, 2, \ldots, 6)\). All the data were recorded in a one-hour interval.

Fourbeam 600/1200-kHz RDI Workhorse Acoustic Doppler Current Profilers (ADCPs) (Nortek group, Rud, Norway), measured flow velocities. Each ADCP was attached to its measurement vessel. The inaccuracy of the resulting flow discharges was below \( \pm 5\% \). The YJD-1 type pressure sensors (Tekscan, Inc., South Boston, MA, USA) were used for water-level measurements, with an inaccuracy of \( \pm 1 \) cm. Efforts were made on sampling of the suspended load, using point-integrative water samplers (Hoskin Scientific, Ltd., Saint-Laurent, QC, Canada). Samples of bed load, though small in amount,
were also taken with Shipek grab samplers (Envco, Auckland, New Zealand) and their percentages were calculated.

The grain-size distribution of the suspended load was analyzed using an automatic sieving device (SFY-D) (Zhonghu Scientific Ltd., Nanjing, China) and an automated Laser particle-size analyzer (Mastersizer2000) (Malvern Panalytical Ltd., Malvern, UK). Particle sizes falling between the range 0.0002 and 2 mm were identified. The obtained data are well suited for calibration and validation of numerical models. The field data acquired for the wet season, including one spring and one neap tide, in June 2015 were used in the study.

For each WL and FS station, the time-series of the raw hydrological data were analyzed. For each time period, the average value of the FS sampling was first obtained for each line with the six points. Based on the three lines, cross-sectionally averaged sediment concentration, \( S \) (kg/m\(^3\)), and flow velocity, \( V \) (m/s), were then achieved by the weighted average method given below:

\[
S = \frac{\sum S_i V_i h_i}{\sum V_i h_i}
\]

\[
V = \frac{\sum V_i h_i}{\sum h_i}
\]

where \( S_i \) and \( V_i \) = sediment concentration and velocity of each measured points, respectively.

3.2. Suspended versus Bed Load

Based on grain-size distribution, river sediment is classified as sand (0.05–2 mm), silt (0.005–0.05 mm) and clay (<0.005 mm) [20]. The field measurements show that suspended load consists of cohesive silt and clay and accounts for approximately 95% of the sediment. Table 1 shows their median grain sizes (\( D_{50} \)), which differ during spring and neap tides. For the former, the \( D_{50} \) values vary between 0.007–0.008 mm for the suspended load and between 0.011–0.019 mm for the bed load. For the latter, the corresponding ranges are 0.006–0.008 mm and 0.011–0.020 mm.

<table>
<thead>
<tr>
<th>Station</th>
<th>Spring Tide, ( D_{50} ) (mm)</th>
<th>Neap Tide, ( D_{50} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suspended Load</td>
<td>Bed Load</td>
</tr>
<tr>
<td>FS3</td>
<td>0.007</td>
<td>0.011</td>
</tr>
<tr>
<td>FS4</td>
<td>0.008</td>
<td>0.019</td>
</tr>
<tr>
<td>FS5</td>
<td>0.008</td>
<td>0.011</td>
</tr>
</tbody>
</table>

3.3. Cross-Sectional Difference in Sediment Concentration

The second half of June 2015 includes 30 semi-diurnal tides, with 30 flood and ebb tides, respectively. To reveal the spatial changes of \( S \) at FS3, FS4 and FS5, Table 2 summarizes their time-averaged \( S \) values, with the following observations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Spring Tide (kg/m(^3))</th>
<th>Neap Tide (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flood Tide</td>
<td>Ebb Tide</td>
</tr>
<tr>
<td>FS3</td>
<td>1.247</td>
<td>1.615</td>
</tr>
<tr>
<td>FS4</td>
<td>2.341</td>
<td>2.117</td>
</tr>
<tr>
<td>FS5</td>
<td>1.673</td>
<td>1.476</td>
</tr>
</tbody>
</table>

(1) Going upstream from the river mouth, the \( S \) value is largest at FS4, with \( S = 2.341 \) kg/m\(^3\) during the spring tide.
3.3. Vertical Difference in Sediment Concentration

concentration (denoted as \( S \)) along lines A, B, C at each FS location. Table 3 shows, for each line, the time-averaged sediment concentration (3) during the spring tide, its distribution.

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For lines A, B and C at FS3, FS4 and FS5, Figure 4 displays, during the spring tide, the asymmetry in cross-channel shape.

As a showcase, Figure 5 illustrates, at FS4, its distribution along the lines.

The following features are evident.

1. For each line, the spring-tide \( S \) value is significantly larger than the neap-tide one. This further indicates the former dominates the sediment transport from the coastal area.

2. At FS4, line A is nearest to the outer bank. In the spring tide, FS4-B exhibits the largest \( S \) value, followed by FS4-C and FS4-A. This shows that, around this bend apex, the water along the inner bank carries more sediment than along the outer bank. This is mainly ascribable to the asymmetry in cross-channel shape.

3. During the neap tide, the \( S \) values are much lower and are close at the same cross-section.

3.4. Vertical Difference in Sediment Concentration

To look at the sediment distribution in the vertical direction, the measured results are analyzed along lines A, B, C at each FS location. Table 3 shows, for each line, the time-averaged sediment concentration (denoted as \( \bar{S}_i \)) at \( h = 0, 0.2H_0, 0.4H_0, 0.6H_0, 0.8H_0 \) and \( H_0 \). As a showcase, Figure 5 illustrates, at FS4, its distribution along the lines.

Table 3. Time-averaged sediment concentration (\( \bar{S}_i \)) along lines A, B and C during the wet season (2nd half of June 2015).

<table>
<thead>
<tr>
<th>Vertical Line</th>
<th>( 0 )</th>
<th>( 0.2H_0 )</th>
<th>( 0.4H_0 )</th>
<th>( 0.6H_0 )</th>
<th>( 0.8H_0 )</th>
<th>( H_0 )</th>
<th>( 0 )</th>
<th>( 0.2H_0 )</th>
<th>( 0.4H_0 )</th>
<th>( 0.6H_0 )</th>
<th>( 0.8H_0 )</th>
<th>( 1.0H_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS3-A</td>
<td>0.872</td>
<td>0.871</td>
<td>1.062</td>
<td>1.233</td>
<td>1.581</td>
<td>1.996</td>
<td>0.157</td>
<td>0.177</td>
<td>0.191</td>
<td>0.202</td>
<td>0.214</td>
<td>0.279</td>
</tr>
<tr>
<td>FS3-B</td>
<td>0.643</td>
<td>0.786</td>
<td>0.941</td>
<td>1.151</td>
<td>1.320</td>
<td>1.761</td>
<td>0.189</td>
<td>0.206</td>
<td>0.216</td>
<td>0.226</td>
<td>0.239</td>
<td>0.273</td>
</tr>
<tr>
<td>FS3-C</td>
<td>0.633</td>
<td>1.201</td>
<td>1.509</td>
<td>1.773</td>
<td>2.187</td>
<td>2.925</td>
<td>0.156</td>
<td>0.192</td>
<td>0.215</td>
<td>0.249</td>
<td>0.310</td>
<td>0.390</td>
</tr>
<tr>
<td>FS4-A</td>
<td>0.809</td>
<td>1.201</td>
<td>1.509</td>
<td>1.773</td>
<td>2.187</td>
<td>2.925</td>
<td>0.156</td>
<td>0.192</td>
<td>0.215</td>
<td>0.249</td>
<td>0.310</td>
<td>0.390</td>
</tr>
<tr>
<td>FS4-B</td>
<td>0.783</td>
<td>1.193</td>
<td>1.775</td>
<td>2.249</td>
<td>3.018</td>
<td>4.292</td>
<td>0.158</td>
<td>0.188</td>
<td>0.241</td>
<td>0.296</td>
<td>0.426</td>
<td>0.611</td>
</tr>
<tr>
<td>FS4-C</td>
<td>1.097</td>
<td>1.246</td>
<td>2.050</td>
<td>1.902</td>
<td>2.903</td>
<td>2.962</td>
<td>0.172</td>
<td>0.201</td>
<td>0.252</td>
<td>0.241</td>
<td>0.375</td>
<td>0.423</td>
</tr>
<tr>
<td>FS5-A</td>
<td>0.876</td>
<td>1.135</td>
<td>1.443</td>
<td>1.739</td>
<td>1.989</td>
<td>2.349</td>
<td>0.133</td>
<td>0.174</td>
<td>0.278</td>
<td>0.343</td>
<td>0.493</td>
<td>0.600</td>
</tr>
<tr>
<td>FS5-B</td>
<td>0.906</td>
<td>1.200</td>
<td>1.490</td>
<td>1.717</td>
<td>1.982</td>
<td>2.409</td>
<td>0.119</td>
<td>0.146</td>
<td>0.246</td>
<td>0.348</td>
<td>0.483</td>
<td>0.747</td>
</tr>
<tr>
<td>FS5-C</td>
<td>0.564</td>
<td>-</td>
<td>1.547</td>
<td>-</td>
<td>2.048</td>
<td>0.061</td>
<td>-</td>
<td>0.202</td>
<td>-</td>
<td>0.385</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
The following patterns are observed:

1. The S distribution from the water surface to the river bed exhibits an increasing tendency. Close to the bed, the S value reaches a maximum. The value close to the bed is 2–5 times that close to the surface.

2. For a given line, the S values at h = 0.6H₀ are approximately equal to the line-averaged value.

3. At the same cross-section, the averaged S values along the B line are the largest. This implies that the main-channel flow carries most sediment.

4. For the same point, the S value during the spring tide is 3–7 times during the neap tide. This means that much more sediment is transported by the spring tide, which is a potential source of sedimentation in the area. The observations are consistent with the findings by Chen et al. [17] and Shen [18].

3.5. Tidal Effects

To further unveil the time dependence of sediment transport, Figure 6 illustrates, for the spring and neap tides, the relationship between S and V at cross-section FS5 (close to the river mouth). A positive V value indicates flow towards the sea and a negative V implies a reversal of the current. The FS3 and FS4 results are shown later in the numerical part.

At the river mouth, the V and S values in the spring tide are larger than in the neap tide. S varies greatly during a tidal period, with two peaks, implying that the tides govern the sediment concentration. The flood tidal V and S are always out of phase with each other; the S peak appears during the flood tides. The S is modified by the tides and other oceanic processes.

The spring tide dominates the river flow and transports the sediment in the river. The neap tide being relatively weak, the run-off plays a dominant role. As a result, S and V exhibit non-similarity
between the spring and neap tides. The tides stir sediment, affects its peak duration and transport. Without the tides, sediment would be diverted directly downstream [21].

4. Numerical Modeling

3D numerical modeling of flow and sediment is performed for the tidal reach and it considers the following typical aspects: (1) bidirectional flow environment under the interaction between river run-off and tides; (2) spatial variations of roughness and bed asymmetry topography; (3) submergence and exposure of shoals due to tidal rising and falling; (4) stratified currents in meanders; and (5) graded suspended load.

4.1. Mathematical Formulation

The Delft3D 4.04 package [22] is used to examine the complex flow features and morphology changes. It is based on the finite-difference method and solves the Navier-Stokes equations. To simulate river-bed changes, it is necessary to supplement such control conditions as bed stability coefficient and riverbed resistance. Therefore, the governing equations include equations for flow continuity, flow momentum, sediment transport and the bed deformation.

The flow continuity equation is

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU_x)}{\partial x} + \frac{\partial (HU_y)}{\partial y} = q \tag{3}$$

where \( U_x (m/s) \) and \( U_y (m/s) \) = depth-averaged velocities in the \( x \) and \( y \) coordinate system, \( \zeta (m) \) is the tidal level, \( d (m) \) is the still water depth, \( H (m) \) is the total water depth \((H = \zeta + d)\), \( q (m/s) \) is the global source or sink term per unit area and \( t (s) \) is time. The momentum equations in the \( x \) and \( y \) directions are

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} - f v = -\frac{1}{\rho_0} F_u + F_v + \frac{1}{H^2} \frac{\partial}{\partial \sigma} \left( \frac{\partial u}{\partial \sigma} \right) \tag{4}$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{\partial u}{\partial t} + \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + f u = -\frac{1}{\rho_0} F_v + F_u + \frac{1}{H^2} \frac{\partial}{\partial \sigma} \left( \frac{\partial v}{\partial \sigma} \right) \tag{5}$$

where \( \rho_0 (kg/m^3) \) = water density, \( \nu_0 (m^2/s) \) = vertical eddy viscosity, \( P_u \) and \( P_v \) (kg/(m^2s^2)) = pressure gradients, \( F_u \) and \( F_v \) (m/s^2) = Coriolis parameter (inertial frequency) and \( \nu \) and \( \omega \) (m/s) = longitudinal and transversal velocity components. The vertical velocity \( \omega (m/s) \) component is computed from the mass balance:

$$\frac{\partial \omega}{\partial \sigma} = \frac{\partial \zeta}{\partial t} - \frac{\partial (Hu_x)}{\partial x} - \frac{\partial (Hu_y)}{\partial y} + H(q_{in} - q_{out}) + P - E \tag{6}$$

where \( q_{in} \) and \( q_{out} \) (m/s) = local source and sink per unit volume, \( P \) (m/s) = precipitation and \( E \) (m/s) = evaporation.

As seen from the field data, the bed-load amount is comparatively small (below 5%). To simplify, only the cohesive suspended sediment is considered in the sediment transport model. For mass balance and advection-diffusion, the equation in 3D reads as

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(us) + \frac{\partial}{\partial y}(vs) + \frac{\partial}{\partial \sigma}[(\omega - \omega_x)S] - \frac{\partial}{\partial x} \left( \epsilon_{s,x} \frac{\partial S}{\partial x} \right) - \frac{\partial}{\partial y} \left( \epsilon_{s,y} \frac{\partial S}{\partial y} \right) - \frac{\partial}{\partial \sigma} \left( \epsilon_{s,\sigma} \frac{\partial S}{\partial \sigma} \right) = -F_s \tag{7}$$

where \( \omega_x (m/s) \) = sediment settling velocity, \( \epsilon_{s,x}, \epsilon_{s,y} \) and \( \epsilon_{s,\sigma} (m^2/s) \) = eddy diffusivity of sediment fraction in three directions and \( F_s \) = function of the river-bed deformation, which is dependent on sediment erosion and deposition and is proposed as follows by Partheniades-Krone [23].
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\[
\frac{\partial Z_b}{\partial t} = F_s \tag{8}
\]

\[
F_s = D_b - E_b \tag{9}
\]

\[
D_b = \begin{cases} 
\omega_b S_b \left(1 - \frac{\tau}{\tau_0}\right) & \tau \leq \tau_d \\
0 & \tau_d < \tau 
\end{cases} \tag{10}
\]

\[
E_b = \begin{cases} 
M \left(\frac{\tau}{\tau_c} - 1\right) & \tau \geq \tau_c \\
0 & \tau < \tau_c 
\end{cases} \tag{11}
\]

where \(Z_b\) (m) = change in bed elevation, \(\gamma_0\) (N/m) = dry weight of bed load, \(D_b\) (kg/(m\(^2\)s)) = sediment flux of deposition from suspended load, \(E_b\) (kg/(m\(^2\)s)) = sediment flux of erosion resulting in suspended load, \(S_b\) (kg/m\(^3\)) = bottom sediment concentration, \(\tau\) (N/m\(^2\)) = bed shear stress, \(\tau_d\) and \(\tau_c\) (N/m\(^2\)) = critical stresses of deposition and erosion and \(M\) (kg/m\(^2\)s) = bed scouring rate.

4.2. Grid and Bathymetry

The river reach of interest is composed of three consecutive bends. The bathymetry is based on the measured topography data in June 2015 (Figure 1c). The computational domain is 13.2 km long and includes 1000 m upstream and 1200 m downstream to reduce boundary effects. Several grids of varied cell sizes are evaluated to ensure grid independence. Grid independence is checked through steady-state calculations. Based on a coarse mesh (Figure 7a), both global and local refinements are made to achieve a finer mesh. Figure 7b,c show the local refinements of two sections.

After refinement, the domain is covered by 10 500 cells, comprising 350 streamwise cells and 30 transverse cells. Grid size varies between 10 and 20 m, a typical range for most river simulations \cite{7,13,22}. Denser cells, with a minimum cell size of 5 m, are given to the outer bank to account for large flow velocity gradients. As recommended by the Deltares systems \cite{22}, 10 layers are specified in the vertical direction, with a thickness of 2%, 3%, 4%, 6%, 8%, 10%, 12%, 15%, 20% and 20% of \(H\). The difference between two neighboring layers should not exceed the lower layer’s thickness.

4.3. Boundary Conditions

For flow computations, time-series of boundary conditions are specified with discharge, \(Q\) (m\(^3\)/s), at the upstream end (FS3) and with water level, \(Z\) (m), at the downstream end (WL6) (Figure 8a).
The time series of sediment concentration needs also be specified at both ends (Figure 8b). For the closed sediment boundary (river bed and banks), a non-entry condition specifies a zero normal gradient of sediment content. The wetting and drying function of cells is activated to account for the tidal rise and fall.

River-bed roughness, represented by Manning’s roughness equation, is an essential parameter dependent on such factors as river-bed morphology, flow patterns including water depth, etc. The range of Manning’s roughness falls within \( n = 0.015 \) to \( 0.030 \) \( \text{m}^{-1/3} \) \( \text{s} \), with \( 0.015 - 0.018 \) \( \text{m}^{-1/3} \) \( \text{s} \) for the main channel and \( 0.018 - 0.030 \) \( \text{m}^{-1/3} \) \( \text{s} \) for the shore beach, which is based on field investigations. For a given position, interpolation is made in light of water depth. Table 4 summarizes the additional parameters, \( \omega_0 \), \( \tau_d \), \( \tau_e \), \( M \) and \( \gamma_0 \), in the model setup.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_0 ) (m/s)</td>
<td>0.0005</td>
<td>Field measurements</td>
</tr>
<tr>
<td>( \tau_d ) (N/m²)</td>
<td>0.06-0.10</td>
<td>Equation (10) [23]</td>
</tr>
<tr>
<td>( \tau_e ) (N/m²)</td>
<td>0.10-0.20</td>
<td>Equation (11) [24]</td>
</tr>
<tr>
<td>( M ) (kg/m²s)</td>
<td>0.0002-0.02</td>
<td>Equation (11) [24]</td>
</tr>
<tr>
<td>( \gamma_0 ) (kg/m³)</td>
<td>1600</td>
<td>Field measurements</td>
</tr>
</tbody>
</table>

To achieve numerical stability, the chosen time step is 0.3 s. For each time step, the flow is first calculated and the sediment transport and the resulting bed-level change are updated accordingly.

5. Model Calibration and Validation

Calibration, as well as validation, is a prerequisite for modelling accuracy. By adjusting specific parameters, a reasonable match is achieved between observed and simulated results. In the study, varying roughness coefficient in space, time step and open boundary conditions and refining the mesh are the tuning aspects. As in many other studies, the results turn out to be most sensitive to the roughness. Time steps (dependent on the grid density) and boundary conditions also have an influence on the model convergence; the grid density has a bearing on the accuracy of the results.

As shown in Table 5, three model criteria, i.e., Nash-Sutcliffe efficiency (NSE), R-Squared (\( R^2 \)) and Percent bias (PBIAS) are often used for model evaluation, where \( O_i \) = observed (in situ) value, \( \overline{O} \) = average of \( O_i \), \( P_i \) = predicted value, \( \overline{P} \) = average of \( P_i \) and \( n \) = total number of observed or predicted values.

The model calibration is based upon the hourly data observed for the spring tide occurring between the period from 10:00 2015-06-17 to 16:00 2015-06-18; totally 30 h. Comparisons of water levels at WL4 and WL5 and of \( V \) and \( S \) at FS4 are shown in Figure 9.
Table 5. Error parameters and accepted ranges for model evaluation [25–27].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Optimal value</th>
<th>Satisfactory if</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSE</td>
<td>−∞−1</td>
<td>1</td>
<td>&gt; 0.5</td>
<td>$E = 1 - \frac{\sum_i (O_i - P_i)^2}{\sum_i (O_i - \bar{O})^2}$</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0−1</td>
<td>1</td>
<td>&gt; 0.5</td>
<td>$R^2 = \left( \frac{\sum_i (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_i (O_i - \bar{O})^2} \sqrt{\sum_i (P_i - \bar{P})^2}} \right)^2$</td>
</tr>
<tr>
<td>PBIAS</td>
<td>−∞→∞</td>
<td>0</td>
<td>±25% for streamflow, ±55% for sediment</td>
<td>$PBIAS = \frac{\sum_i (O_i - P_i) \times 100}{\sum_i O_i}$</td>
</tr>
</tbody>
</table>

Figure 9. Model calibration with measured versus predicted for the spring tide (June 2015): (a) Z at WL4; (b) Z at WL5; (c) V at FS4; (d) S at FS4.

The calibration results show that the calculated Z and V are in good agreement with the measured ones. All their error parameters meet the criteria. For S, the calculated and simulated results do not exhibit the exactly same pattern. However, the sediment peaks are, in terms of phase and magnitude, reasonably reproduced.

The model validation is performed with a neap tide that occurred during the period between 15:00 2015-06-24 and 22:00 2015-06-25, lasting a total of 31 hours. It follows the same principle as model calibration. The validation results are shown in Figure 10.

The calculated Z, V and S profiles match relatively well with the measured data series. All the error parameter values also meet the requirements. As in other numerical simulations, the match between the measured and simulated parameters is better for Z and V than for S. The interplay between fresh-water flows and tides accounts for the difference in peak sediment concentration. The model generates acceptable results and it is suitable for prediction of flow and morphology changes of the meandering river reach.
6. Typical Flow Features

In the meandering reach, the flow features are of significant variations with stratified currents, in which cross-sectional velocity distributions often deviate from the logarithmic profile typical of straight reaches. Meanwhile, the bi-directional currents induced by flood and ebb tides also make the flow patterns more complex. A 2D depth-averaged model, with the assumption of a logarithmic velocity structure, would lead to inaccurate prediction in terms of, e.g., bed shear stress [22]. A 3D model is, therefore, necessary for prediction of such a tidal meander reach.

6.1. Cross-Sectional Flow Patterns

In addition to cross-sectional and streamwise changes of bed forms, the flow patterns in cross-section are also influenced by the rise and fall of the tides, which is different from non-tidal situations with only run-off. Cross-section WL5 is at the bend apex and is chosen to illustrate the issue. Figure 11 shows, during the spring tide, its patterns of the falling period (a,b), low water slack (c), rising period (d,e) and high water slack (f), respectively. Major flow patterns are summarized below:

(1) During the tidal fall and rise, the cross-sectional flows behave differently in direction and magnitude. For the former, the flow moves from the main stream of higher velocity toward the banks. For the latter, the cross-sectional currents are driven in the opposite direction; the water flowing from the banks are likely to offset each other. The alternating flow causes deposition or erosion at a bend.

(2) At the low and high water slacks, as shown in Figure 11c,f, the flow strength decreases to its minimum. The reason is that the motion reverses in the subsequent changes, so that the residual motion from the previous tide counteracts the motion in the next period.

(3) At the bend apex, secondary circulations in cross-section do not occur as commonly observed in non-tidal meandering rivers [4,6]. The difference is mainly ascribed to the tidal level changes, resulting in cross-sectional currents moving away from or toward the streamwise mainstream.
(4) At the maximum ebb and flood tides, the flow velocity of the mainstream reaches its peak, amounting to 0.8−1.0 m/s and 0.5−0.8 m/s (Figure 11b,e). The former is some 0.2 m/s larger than the latter, which is due to the addition of the ebb tide to the run-off. For the flood tide, the run-off and the tide run in the opposite direction, thus offsetting each other. It holds true that the velocity of the ebb tide is higher than that of the flood tide.

(5) The flow along the outer bank, during the falling period, is much stronger than that along the inner bank. With the rising tide, the flow pattern shifts and the flow along the inner bank becomes stronger instead. Along the banks in a bend, the opposing and offsetting flows are also visualised by Fenies and Faugeres [28].

Figure 11. Cross-sectional flow patterns during the spring tide: (a,b) Falling period; (c) Low water slack; (d,e) Rising period; and (f) High water slack.
In summary, dependent on the rise and fall of the tides, the cross-sectional flow patterns in a meander differ in both flow direction and magnitude. Relative to the main stream, the major feature is an outward movement of water with the falling tide and an inward movement with the rising tide.

6.2. Bed Shear Stress Distribution

For the flood and ebb tides, the bed shear stress ($\tau_b$) is useful to judge flow regime and to interpret the resulting patterns of deposition and erosion. For 3D flows, $\tau_b$ is expressed in terms of a quadratic function of the $u_b$ and a drag coefficient [22,29].

$$\tau_b = \frac{\rho_0 g |u_b|}{C_{3D}^2}$$ (12)

where $u_b$ (m/s) = horizontal velocity in the first layer above the river bed and $C_{3D}$ = a 3D-Chézy coefficient. For a relatively wide and shallow river, $C_{3D} = \sqrt{H/n}$.

Determination of $\tau_b$ is influenced by such factors as river curvature, cross-sectional asymmetry and sediment composition, etc. Due to flow perturbations, it is not straightforward to directly measure it in the field. Numerical modeling is employed for its analysis of the meandering stream. For the wet season (June 2015), Figure 12 displays $\tau_b$ distributions at four instants, i.e., (a) high water, (b) maximum ebb tide, (c) low water and (d) maximum flood tide. $\tau_b$ varies with discharge, bend curvature, cross-sectional asymmetry, etc., demonstrating the following features.

Figure 12. Distributions of $\tau_b$ during the wet season (June 2015): (a) High tide; (b) Maximum ebb tide; (c) Low water; (d) Maximum flood tide.
(1) \( \tau_b \) is proportional to \( u_b^+ \) and is also a function of \( H \). In the meander reach, the \( u_b^+ \) and \( H \) values are between 0.2–0.6 m/s and 6.0–14.0 m (exclusive of the scour hole at WL5). At the low and the high water, a similar \( \tau_b \) distribution is exhibited (Figure 12a,c), with minor local discrepancy. \( \tau_b \) reflects the velocity gradient, governed by the run-off and tides. At the maximum ebb and flood tides, the peak \( \tau_b \) values are shown in Figure 12b,d.

(2) Due to erosion, a deep hole exists at bend apex WL5. Its \( \tau_b \) distribution features low values. This is ascribed to the large water depth. Shoaling areas along the inner banks show always low \( \tau_b \) values.

(3) The spatial distribution is also affected by the curvature. A salient feature is, following the main stream, a band of high \( \tau_b \) values. In the flow direction, it shifts from the outer bank in one bend to the outer bank in the subsequent bend. This is true for both flood and ebb tides. The occurrence of the band is similar to the situation with a non-tidal meander reach [30,31].

6.3. Sediment Carrying Capacity

The sediment carrying capacity \((S_c, \text{kg/m}^3)\) reflects, as an index, the amount of entrained sediment transported by the flow if erosion and deposition are in equilibrium. In comparison with the actual \( S \) in the water, predictions are made of morphological changes. If \( S > S_c \), the flow is over-saturated with sediment and deposition occurs. If \( S < S_c \), it is under-saturated, and erosion takes place. \( S_c \) is shown to have a linear relationship with \( F^2 \) (Froude number \( F = V^2/(gH) \)) [17,32,33], with the following expression

\[
S_c = S_0 + f(F^2) = S_0 + kF^2
\]

(13)

where \( k = \text{coefficient} \) and \( S_0 = \text{background sediment concentration, i.e., the amount of sediment left from the previous tide.} \) The multivariate linear regression analysis and the least square method are used for their estimations. At each time interval, a cross-section has \( 3 \times 6 = 18 \) measured values. For the 30-h measurement period, 30 sets of the data are analysed. For the flood and ebb tides of the wet season in June 2015, Figure 13 shows the obtained \( S-F^2 \) relationship.

![Figure 13](image)

**Figure 13.** \( S-F^2 \) relationship for the wet season (June 2015): (a) Flood tides; (b) Ebb tides.

The \( S_c \) expression for the meander reach is written as

\[
\text{Flood tide, } S_c = 103.86F^2 + 1.09 \\
\text{Ebb tide, } S_c = 58.67F^2 + 0.92
\]

(14) (15)

The \( k \) value for the flood tides is almost twice as high as for the ebb tides. It is, therefore, reasonable to separately determine \( S_c \)—the former carries more sediment than the latter. Chen et al. [17,32] examined \( S_c \) during wet and dry seasons, which also show significantly different \( S_c \) values.
In a meander subjected to the interaction of run-off and tides, $S_c$ depends on a few factors and shows its complexity in both time and space. In consideration of the nature of the issue, it is not straightforward to find a unified $S_c$ formula with accuracy. Though there are other forms of expressions, the commonly accepted expression is based on $F$, implying that $S_c$ is mainly dependent on turbulence intensity [33,34].

6.4. Erosion-Deposition Patterns

Predictions are made to look at the potential sediment patterns in the meander. The tidal currents, especially the spring tide in a wet season, dominate the sediment transport. During the 2nd half of June 2015, the 30-h spring tide is chosen for the purpose, corresponding to a critical scenario of interest. Compared with river flow conditions, morphological changes are a slower process. When only simulating a 30-hr period, changes in the bed level are hardly noticeable. A morphological scaling factor is thus used to amplify the bed-form change, a method of common practice [21,35,36]. It is set to 24, leading to a one-month prediction. A longer time series of measured sediment data is not available.

The start condition corresponds to the measured bathymetry at 10:00 on 17 June 2015. Figure 14a−c illustrates the bed-form evolution from $T = 0$, 15 to 30 days. As time elapses, the results show that, except for the slight erosion in the vicinity of WL4, gradual deposition features the meander reach. The trend is in qualitative agreement with the observation made by Chen et al. [17,32], in which the influence of the wading structures, including bridges and wharfs, was also included. Figure 14d−f illustrates, as a function of time, the cross-sectional bed profiles at WL4, FS4 and WL5.

For a given cross-section, its inner bank is exposed to heavier deposition than the outer bank. The mainstream tends to switch more to the outer bank, aggravating the curvature of the bend.

Figure 14. Cont.
During a tidal circle, sediment transport into and out of the reach is not in balance, leading to sediment storage along the reach. As shown in the field measurements, the flood tide carries more sediment and results in deposition. For an ebb tide, its low bed shear stress can only re-suspend a limited amount of the deposited sediment from the flood tides, only slight erosion occurs. The flood tide plays a dominant role. An oblong scour hole exists at WL5. At maximum, its hole depth is initially 14.0 m and becomes 13.05 m at $T = 30$ days. The hole shrinks both up- and downstream as time elapses. Both the flood and ebb tides contribute to shaping the scour hole.

Sediment deposition occurs easily around the flow reversal, i.e., the shift between flood and ebb tides, which is dependent on the duration of slack waters. As shown earlier (Figure 11c,e), the cross-sectional flow momentum during the slacks decreases to a minimum. The offsetting effect between the flood tide and run-off results in a long slack duration around the high water. As a result, more suspended sediment settles at the reversals.

To sum up, the flow regime and imbalance of sediment transport are the main drivers of the meander reach evolution. Though there is no complete bathymetry data available to calibrate the morphological change for the reach, the simulation suggests that the bed-level changes are closely related to the interactions between the run-off and tides. The latter plays a dominating role and governs the sedimentation.

7. Conclusions

If river run-off and strong tides co-exist in a meander reach, its flow and morphological changes are governed by several factors and exhibit both spatial and periodical changes. Field and numerical studies are made to examine such a tidal meander reach.

Field measurements show that approximately 95% of the river sediment is suspended load, most of which is transported upstream into the reach by the flood tides, especially during the spring-tide period. Tidal currents stir sediment and modify its concentration, which leads to the fact that the flow velocity and sediment concentration are out of phase with one another. The asymmetry in cross-section and bi-directional flow affect the re-distribution of suspended load, leading to a higher concentration in the inner banks than in the outer banks. Additionally, the near-bottom values are usually 2-5 times the surface ones. Based on the extensive filed data, a formula of sediment carrying capacity is formulated as a function of the Froude number, with which deposition and erosion patterns can be judged.

Based on the Delft3D software, a 3D model of suspended sediment transport is setup to simulate the alluvial behavior of the reach. The flow exhibits significant vertical stratifications; the velocity distribution differs from the logarithmic profile valid for a non-tidal straight river reach. During the tidal rise and fall, the cross-sectional flow moves in the opposite direction. At the water slacks, the momentum decreases to a minimum. Sediment settles mainly during the flow reversal and the
durations of slack water affects the deposited amount. The spatial distribution of the bed shear stress follows the pattern of velocity gradient and is also affected by the meander asymmetry.

With a morphological scale factor, the bed-form change of the meander reach is predicted. The results show that, during a tidal circle, the suspended load transport in and out of the reach is not in balance and gives rise to gradual siltation, which is mainly owing to the flood tides that carry most of the load. The offsetting effect between the flood tide and run-off results in a long slack duration around the high water, facilitating the sediment deposition when the current reverses between the flood and ebb tides.

The tides interact with the fresh-water run-off and lead to varied sediment patterns in space and time, generating a different morphological regime from a non-tidal meander reach. The study, especially the collected field data, contributes to the understanding of the fluvial behaviors and is of reference to other investigations of similar tidal meander rivers.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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Paper C

Perturbation Theory and Sediment Carrying Capacity of Suspended Load in a Tidal River
Perturbation Theory and Sediment Carrying Capacity of Suspended Load in a Tidal River

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Abstract

In a fluvial river, coastal tides often carry suspended load that dominates the sediment transport. The sediment carrying capacity (SCC) is the amount of suspended load transported by the flow, reflecting the erosion and deposition equilibrium in the water body. Based on the perturbation theory the study modifies a method to determine the SCC and apply it to a natural river where tidal currents are predominant. In terms of flow velocity, water depth, particle settling velocity, median grain size and tidal range, an approach is established by means of dimensional analysis and multivariate linear regression. Field data are collected to determine and validate the coefficients of the SCC formula. Compared to previous studies with fewer parameters for the correlation analysis, the procedure is an improvement and can be used to estimate the SCC in similar situations.

Keywords: Sediment carrying capacity; Tidal river; Perturbation theory; Suspended load; Field measurements.

1 Introduction

The sediment carrying capacity (SCC) is an index characterizing the interplay between the flow and sediment transport in a river. It is often used for predictions of the river bedform evolution. During the past decades, many studies have been dedicated to the SCC estimations, leading to numerous theoretical and empirical formulas that contribute to the understanding of the issue (Zhang 1961; Engelund and Hansen 1967). For suspended load, most of the formulas involve four factors i.e., average flow velocity, average water depth, median grain size and particle settling velocity (Milhous 2005; Yang et al. 2007). Affected by river bathymetry, flow and sediment features, the formulas differ in the way of combination of these contributing factors, which is natural. During recent years, the SCC approach has been extended to the research of estuaries and coastal areas. In a tidal environment, it is not straightforward to make estimations due to the flow complexity, involving the river run-off and tidal currents at different spatial and temporal scales. Hence, the effect of tides including the periodic feature should also be included in the SCC predictions.

The perturbation theory refers to a mathematical tool used to obtain an approximate solution to a complex system. It starts with a simplified form of the original problem, simple enough to be solved analytically. A feature of the approach is, by means of dimensionless analysis, to break down the problem into several perturbation parts. The theory is widely used in fluid mechanics and other physical disciplines.

Based on the perturbation theory, the study considers seven major factors and derives a modified SCC formula. Its coefficients are obtained through multivariate linear regression analysis. Field data from a wet and dry season of a typical tidal river are collected to establish and verify the formula. The procedure provides reference for determination of suspended sediment transport in similar situations.
2 Methodology description

For suspended load transport in a tidal river, the SCC, denoted by $S_c$, is affected by several factors.

$$S_c = f (U, h, g, \nu, \gamma_s, \gamma, \omega, D_{50}, B, \Delta h, \bar{h})$$  \hspace{1cm} (1)

where $U$ (m/s) = flow velocity, $h$ (m) = water depth, $g$ (m/s$^2$) = gravity acceleration, $\nu$ (m$^2$/s) = water viscosity, $\gamma_s$ (N/m$^3$) = volumetric mass density of suspended load, $\gamma$ (N/m$^3$) = water density, $\omega$ (mm/s) = particle settling velocity, $D_{50}$ (mm) = median grain size, $B$ (m) = river width, $\Delta h$ (m) = water-level difference between two adjacent instants (usually one-hour interval), and $\bar{h}$ (m) = tidal range, i.e. the difference between the high and low tides within a tidal period. The flow parameters $U$, $h$, $B$, $\Delta h$ and $\bar{h}$ refer to the cross-sectionally averaged values.

By dimensionless analysis, Eq. (1) is rewritten as:

$$S_c = f \left( \frac{U^2}{gh}, \frac{D_{50}}{h}, \frac{U}{\omega}, \frac{\gamma_s}{\gamma}, \frac{h}{B}, \frac{U h}{\nu}, \frac{\Delta h}{\bar{h}} \right)$$  \hspace{1cm} (2)

Term $\gamma_s/\gamma$ is considered as a constant. If the river is wide and the water is shallow, the $h/B$ ratio becomes small and is therefore neglected. The Reynolds effect, $R = U h/\nu$ is also excluded for flows in a natural river. Eq. (2) thus becomes

$$S_c = f \left( \frac{U^2}{gh}, \frac{D_{50}}{h}, \frac{U}{\omega}, \frac{\Delta h}{\bar{h}} \right)$$  \hspace{1cm} (3)

In light of the perturbation theory, the contrast relations between flow turbulence intensity ($U^2/(gh)$), relative roughness ($D_{50}/h$), gravity action ($U/\omega$) and tidal effect ($\Delta h/\bar{h}$) are written as

$$S_{c1} = S_1 + k_1 \frac{U^2 D_{50}}{gh^2} + k_2 \frac{U^2 D_{50}}{gh^2} + k_3 \frac{U^2 D_{50}}{gh^2} + ...$$  \hspace{1cm} (4)

$$S_{c2} = S_2 + k_2 \frac{U^3}{gh \omega} + k_2 \frac{U^3}{gh \omega} + k_2 \frac{U^3}{gh \omega} + ...$$  \hspace{1cm} (5)

$$S_{c3} = S_3 + k_3 \frac{U^2 \Delta h}{gh \bar{h}} + k_3 \frac{U^2 \Delta h}{gh \bar{h}} + k_3 \frac{U^2 \Delta h}{gh \bar{h}} + ...$$  \hspace{1cm} (6)

where $S_1$, $S_2$ and $S_3$ = constants and $k_1$, $k_2$ and $k_3$ = infinitesimal perturbation variables. The second- and higher-order terms are neglected. Introducing the above expressions into Equation (3) leads to:

$$S_c = S_{c1} + S_{c2} + S_{c3} = S_1 + S_2 + S_3 + k_1 \frac{U^2 D_{50}}{gh^2} + k_2 \frac{U^3}{gh \omega} + k_3 \frac{U^2 \Delta h}{gh \bar{h}}$$  \hspace{1cm} (7)

Replacing $S_1 + S_2 + S_3$ with $k_4$, Equation (7) becomes

$$S_c = k_1 \frac{U^2 D_{50}}{gh^2} + k_2 \frac{U^3}{gh \omega} + k_3 \frac{U^2 \Delta h}{gh \bar{h}} + k_4$$  \hspace{1cm} (8)

The coefficients are determined using the least-square method (Ni et al. 2014). The objective function reads
\[ f = \sum_{i=1}^{n} \left( k_1 \frac{U_{2i}^2 D_{50i}}{gh_i^2} + k_2 \frac{U_{2i}^3}{gh_i \omega_i} + k_3 \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} + k_4 - S_i \right)^2 \]  

where \( n \) is the total number of data sets included in the analysis, and subscript \( i \) refers to the corresponding parameters of the \( i \)th data set.

The following conditions are satisfied if the objective function reaches the minimum:

\[ \frac{\partial f}{\partial k_1} = 0 \Rightarrow 2 \sum_{i=1}^{n} \frac{U_{2i}^2 D_{50i}}{gh_i^2} (k_1 \frac{U_{2i}^2 D_{50i}}{gh_i^2} + k_2 \frac{U_{2i}^3}{gh_i \omega_i} + k_3 \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} + k_4 - S_i) = 0 \]  

\[ \frac{\partial f}{\partial k_2} = 0 \Rightarrow 2 \sum_{i=1}^{n} \frac{U_{2i}^3}{gh_i \omega_i} (k_1 \frac{U_{2i}^2 D_{50i}}{gh_i^2} + k_2 \frac{U_{2i}^3}{gh_i \omega_i} + k_3 \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} + k_4 - S_i) = 0 \]  

\[ \frac{\partial f}{\partial k_3} = 0 \Rightarrow 2 \sum_{i=1}^{n} \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} (k_1 \frac{U_{2i}^2 D_{50i}}{gh_i^2} + k_2 \frac{U_{2i}^3}{gh_i \omega_i} + k_3 \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} + k_4 - S_i) = 0 \]  

\[ \frac{\partial f}{\partial k_4} = 0 \Rightarrow 2 \sum_{i=1}^{n} (k_1 \frac{U_{2i}^2 D_{50i}}{gh_i^2} + k_2 \frac{U_{2i}^3}{gh_i \omega_i} + k_3 \frac{U_{2i}^2 \Delta h_i}{gh_i h_i} + k_4 - S_i) = 0 \]

A multivariate linear regression analysis is usually made to estimate \( k_1, k_2, k_3 \) and \( k_4 \).

### 3 Study area with data collection

The study area is in Southeast China. The water system includes a confluence called Sanjiangkou. Upstream of it, the two merging rivers are Fenhua and Yao; downstream it is the Yong River flowing into the Pacific Ocean (Figure 1). The Yong river length is ~26 km from the confluence to the river mouth. The area is significantly affected by the interplay between the river run-off (freshwater flow) and tidal currents, experiencing semi-diurnal tides (two nearly equal high and low tides each day) and belonging to the category of incomplete standing waves. The bed load in the area is negligibly small in quantity and the suspended load dominates, which is a common feature of many fluvial rivers.

![Figure 1. Hydrological stations of water levels (WL) and flow & sediment (FS) of the water system, with a cross-sectional sketch of measurement points.](image-url)
Fenghua is 90‒180 m in width and its average bed slope is 0.81%. The annual averaged runoff is 53.6 m³/s; the annual sediment discharge is 4.35×10⁴ ton (Chen et al. 2013). Yao is 180‒230 m wide. Its daily runoff, as well as the sediment transport, is controlled by the sluice gates located 3.3 km upstream of the confluence. The annual sediment inflow to the study area is comparatively small. Yong runs roughly in the West-East direction, with a 150‒250 m normal width. Its average river-bed slope is 0.117%; the annual mean runoff is ~92 m³/s (Chen et al. 2013).

In the wet seasons, the peak discharge of the run-off and tides occurs normally during the 2nd half of June, amounting to ~1800 m³/s. In the dry seasons, the peak occurs during the 1st half of January, equal to ~1100 m³/s (Wang et al. 2015). The field stations for water levels (WL) and flow & sediment (FS) are also marked in Figure 1. At the river mouth, e.g., at WL6, the annual mean tidal range is 1.91 m; the flood and ebb durations are approximately the same, ~6 hrs. From the river mouth, the tidal asymmetry aggregates up the river. In the confluence, the ebb duration is 40 min longer than the flood duration. At WL7, the duration difference becomes 60 min. On Yao, the sluice gates stop the tidal currents to propagate further upstream. As for the location of the upstream limit of current reversals along Fenghua, the tides affect a reach of approximately 15 km upstream of WL7/FS7. The sediment in the area is mainly from the coastal area and is carried by the tides.

To record the tidal hydrological data, field surveys were carried out for the study area during the period June 2015 and January 2016. The data include water stage, flow velocity, flow discharge, sediment concentration and grain-size distribution, etc. The water levels were monitored at seven cross-sections (WL1–WL7), five of which were along Yong. To measure flow velocity and suspended sediment, seven cross-sections (FS1–FS7) were selected (Figure 1). FS5 and FS6 are a few meters apart from each other and are treated as the same section. At each cross-section, three plumb lines were arranged. Along each line, the sampling was made at six depths from the water surface, i.e., \( h = 0, 0.2H_0, 0.4H_0, 0.6H_0, 0.8H_0 \) and 1.0\( H_0 \), where \( H_0 \) (m) is the water depth along each line. All the data were recorded at one-hour intervals.

For each station, either WL or FS, the time-series of data were analyzed. For each measurement interval, the time-averaged value was first obtained for each plumb line. The cross-sectionally averaged value was then achieved by the weighted average method.

4 Results

The measured data cover one wet season (the 2nd half of June 2015) and one dry season (the 1st half of January 2016). Due to difficulties in sediment measurements, data for only two typical tidal periods are available for each season, i.e. the spring tide (ST) and neap tide (NT). They are selected for the analysis.

Figure 2 shows the wet-season time-series of water levels \( Z \) (m) at the river mouth (WL6) and two upstream locations (WL1 & WL7). The ST occurs between 10:00 June 17 and 16:00 June 18, totaling 30 hrs. The NT occurs during a 31-hour period between 15:00 June 24 and 22:00 June 25 the in the same month. Based on the field data of the wet season, the coefficients of the formula are obtained. The data of the dry season are used for its verification.

**Figure 2.** Time-series of \( Z \) at WL6, WL1 and WL7 in the wet season 2015
To investigate the spatial-periodical changes of the governing factors that affect the SCC, Table 1 summarizes the parameter ranges at FS1–FS7 during the ST and NT from the wet season. The following features are observed. S denotes the averaged sediment concentration in a cross-section.

| Table 1. Parameter ranges during the ST and NT in the wet season (the 2nd half of June 2015) |
|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|
| Station | Tide | U (m/s) | h (m) | D_{50}(mm) | ω (mm/s) | Δh (m) | h (m) | S (kg/m³) |
| FS1     | ST   | 0.04–0.47 | 1.50–4.40 | 0.003–0.007 | 0.35–0.49 | -0.60–0.63 | 1.66–2.63 | 0.14–0.62 |
|         | NT   | 0.02–0.21 | 1.90–3.40 | 0.005–0.011 | 0.31–0.44 | -0.30–0.30 | 0.93–1.48 | 0.03–0.10 |
| FS2     | ST   | 0.08–0.90 | 6.57–9.47 | 0.006–0.008 | 0.47–0.52 | -0.60–0.90 | 1.46–2.90 | 0.28–1.23 |
|         | NT   | 0.11–0.69 | 6.97–8.47 | 0.005–0.009 | 0.41–0.49 | -0.30–0.30 | 0.93–1.50 | 0.03–0.18 |
| FS3     | ST   | 0.07–1.01 | 6.20–9.00 | 0.006–0.009 | 1.55–1.66 | -0.60–0.70 | 1.68–2.97 | 0.28–3.15 |
|         | NT   | 0.13–0.72 | 6.50–7.90 | 0.005–0.012 | 0.36–0.56 | -0.37–0.30 | 0.93–1.47 | 0.12–0.32 |
| FS4     | ST   | 0.23–1.25 | 5.07–8.57 | 0.007–0.009 | 0.72–3.43 | -0.70–0.90 | 1.98–3.51 | 0.59–4.48 |
|         | NT   | 0.15–0.98 | 5.97–7.37 | 0.004–0.009 | 0.54–2.46 | -0.43–0.40 | 1.06–1.59 | 0.11–0.64 |
| FS5     | ST   | 0.33–1.30 | 6.67–10.17 | 0.007–0.009 | 1.32–2.02 | -0.60–0.87 | 1.93–3.53 | 0.64–2.95 |
|         | NT   | 0.15–0.97 | 7.57–8.97 | 0.005–0.008 | 0.53–0.77 | -0.80–0.77 | 1.02–1.56 | 0.11–0.96 |
| FS6     | ST   | 0.05–1.01 | 5.83–8.53 | 0.008–0.010 | 0.45–0.51 | -0.50–0.80 | 1.48–2.70 | 0.37–1.54 |
|         | NT   | 0.10–0.84 | 6.33–7.77 | 0.006–0.013 | 0.41–0.48 | -0.30–0.30 | 0.81–1.46 | 0.07–0.26 |

(1) During the ST, the range of $U$ is 0.04–1.30 m/s; during the NT, it is 0.02–0.98 m/s. The $h$ and $Δh$ ranges during the ST are both larger than those during the NT. The $\tilde{h}$ range for the former is almost twice the value for the latter. This implies that the ST is comparatively strong.

(2) The $D_{50}$ values vary between 0.003–0.010 mm during the ST; it is between 0.004–0.013 mm for the NT. The $D_{50}$ values of the latter are slightly larger.

(3) $S$ exhibits an increase from FS5 (FS6) to FS4; it then decreases up the river. The maximum $S$ value on Yong occurs at FS4. For a given location, the ST shows higher $S$ values than the NT. This indicates that the former governs the transport of the suspended sediment from the coastal area.

(4) At FS4 and FS5 (FS6), $ω$ is larger than at the other stations. It implies that the flocculation effect of the suspended load is more intense at the estuary, which accelerates $ω$. During the ST, $ω$ is larger than during the NT. This also illustrates that ST not only dominates the sediment transport but also increases the sediment collision and flocculation.

With the $30 + 31 = 61$ temporal data sets at each cross-section, multivariate linear regression analysis is made in combination the least square method. Each set is cross-sectionally averaged. The resulting coefficients are: $k_1 = 0.026$, $k_2 = 0.019$, $k_3 = 0.013$ and $k_4 = 1.025$

Then the SCC formula takes the form

$$S_c = 0.026 \frac{U^2 D_{50}}{gh^2} + 0.019 \frac{U^3}{ghω} + 0.013 \frac{U^2 Δh}{ghh} + 1.025$$

which is rewritten as

$$S_c = F^2 \left(0.026 \frac{D_{50}}{h} + 0.019 \frac{U}{ω} + 0.013 \frac{Δh}{h} \right) + 1.025$$

where $F = U/(gh)^{0.5}$, the Froude number. Obviously, it considers flow turbulence, sediment property and tidal effects. In a tidal environment, the tides stir the sediment in water and modify its peak duration and transport. Field measurements show that the flow velocity and sediment concentration within a tidal period are always out of phase with each other (Xie et al. 2018, 2019). The peak-tide method (Sun, 2017) and the half-tide method (Pan et al. 2013) don’t include the lag effect between the sediment and flow. The proposed whole-tide method overcomes this and is therefore preferable.

The reliability of the derived formula is verified with the aid of the $30 + 32 = 62$ sets of the hourly measured data from the dry season. Figure 3 presents the corresponding $Z$ values. The ST occurs...
between 16:00 January 9 and 22:00 January 10 (30 hrs) and the NT between 9:00 January 3 and 17:00 January 4 (32 hrs).

![Figure 3. Time-series of Z at WL6, WL1 and WL7 in the dry season 2016](image)

Table 2 shows the parameter ranges during the ST and NT in the dry season. Compared to the wet season, the spatial-periodical features of the flow and sediment are similar. However, $U$, $\omega$ and $S$ are smaller in magnitude, implying that both the run-off and the tides are weaker.

**Table 2. Parameter ranges during the ST and NT in the dry season (the 1st half of January 2016)**

<table>
<thead>
<tr>
<th>Station</th>
<th>Tide</th>
<th>$U$ (m/s)</th>
<th>$h$ (m)</th>
<th>$D_{50}$ (mm)</th>
<th>$\omega$ (mm/s)</th>
<th>$\Delta h$ (m)</th>
<th>$\bar{h}$ (m)</th>
<th>$S$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1</td>
<td>ST</td>
<td>0.02–0.43</td>
<td>1.60–4.70</td>
<td>0.003–0.006</td>
<td>0.33–0.45</td>
<td>−0.43–0.63</td>
<td>1.41–2.18</td>
<td>0.07–0.30</td>
</tr>
<tr>
<td></td>
<td>NT</td>
<td>0.02–0.19</td>
<td>1.87–3.53</td>
<td>0.004–0.009</td>
<td>0.27–0.42</td>
<td>−0.35–0.37</td>
<td>0.87–1.30</td>
<td>0.03–0.08</td>
</tr>
<tr>
<td>FS2</td>
<td>ST</td>
<td>0.05–0.83</td>
<td>6.57–9.43</td>
<td>0.005–0.008</td>
<td>0.27–0.71</td>
<td>−0.50–0.70</td>
<td>1.69–2.80</td>
<td>0.10–0.66</td>
</tr>
<tr>
<td></td>
<td>NT</td>
<td>0.04–0.69</td>
<td>7.03–8.53</td>
<td>0.005–0.007</td>
<td>0.31–0.65</td>
<td>−0.30–0.40</td>
<td>0.89–1.54</td>
<td>0.06–0.20</td>
</tr>
<tr>
<td>FS3</td>
<td>ST</td>
<td>0.20–1.10</td>
<td>3.47–6.07</td>
<td>0.005–0.008</td>
<td>1.23–1.35</td>
<td>−0.60–0.80</td>
<td>1.73–2.83</td>
<td>0.22–1.60</td>
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<tr>
<td></td>
<td>NT</td>
<td>0.02–0.82</td>
<td>3.67–5.27</td>
<td>0.004–0.005</td>
<td>0.36–0.54</td>
<td>−0.40–0.30</td>
<td>0.95–1.55</td>
<td>0.07–0.35</td>
</tr>
<tr>
<td>FS4</td>
<td>ST</td>
<td>0.08–1.35</td>
<td>5.20–8.70</td>
<td>0.006–0.007</td>
<td>1.53–2.66</td>
<td>−0.40–0.80</td>
<td>2.03–3.52</td>
<td>0.59–2.37</td>
</tr>
<tr>
<td></td>
<td>NT</td>
<td>0.07–0.79</td>
<td>6.00–7.70</td>
<td>0.004–0.006</td>
<td>0.48–2.14</td>
<td>−0.40–0.40</td>
<td>0.98–1.71</td>
<td>0.05–0.30</td>
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<tr>
<td>FS5</td>
<td>ST</td>
<td>0.08–1.28</td>
<td>7.37–10.87</td>
<td>0.006–0.007</td>
<td>1.02–1.85</td>
<td>−0.60–0.80</td>
<td>2.89–3.52</td>
<td>0.52–1.33</td>
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<tr>
<td></td>
<td>NT</td>
<td>0.15–0.79</td>
<td>8.27–9.87</td>
<td>0.005–0.007</td>
<td>0.48–0.63</td>
<td>−0.40–0.80</td>
<td>0.97–1.69</td>
<td>0.04–0.61</td>
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<tr>
<td>FS7</td>
<td>ST</td>
<td>0.09–0.91</td>
<td>5.53–8.13</td>
<td>0.007–0.010</td>
<td>0.38–0.48</td>
<td>−0.50–0.70</td>
<td>1.53–2.66</td>
<td>0.08–0.59</td>
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<tr>
<td></td>
<td>NT</td>
<td>0.05–0.72</td>
<td>5.83–7.33</td>
<td>0.005–0.007</td>
<td>0.36–0.45</td>
<td>−0.30–0.30</td>
<td>0.81–1.52</td>
<td>0.07–0.20</td>
</tr>
</tbody>
</table>

Figure 4 shows the comparison between the prediction and measurements. The horizontal and vertical axes refer to the measured ($S$) and predicted values ($S_p$), respectively. Suppose that the total number data used for the ST or NT analysis is $n$. Within a deviation band $\pm e$ from the SCC formula, the total data number is denoted as $n_x$. Let $P(\%) = n_x/n$, representing the percentage of data within the interval. At each station in the dry season, the accuracy of prediction is further illustrated in Table 3, with $e = 5\%$ and $10\%$. Even the overall error is given for each station. This indicates that the derived SCC formula reasonably reproduces the data in the tidal river.
Figure 4. Comparison of $S_c$ and $S$ during ST and NT in the dry season (the 1st half of January 2016)

Table 3. Accuracy of prediction applied to the tides during the dry season.

<table>
<thead>
<tr>
<th>Period</th>
<th>Station</th>
<th>$P(%)$</th>
<th>Overall error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$e = 5%$</td>
<td>$e = 10%$</td>
</tr>
<tr>
<td>ST</td>
<td>FS1</td>
<td>83</td>
<td>90</td>
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<td>FS7</td>
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<td>90</td>
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<td>FS1</td>
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<td>FS5(FS6)</td>
<td>85</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>FS7</td>
<td>83</td>
<td>87</td>
</tr>
</tbody>
</table>

5 Conclusions
In a river subjected to the interaction of run-off and tidal currents, the carrying capacity of suspended load is dependent on a number of factors, exhibiting complex features in both time and space. With the field measurements in the background, the study deals with the typical features of such a river by means of theoretical analysis.

Based on the perturbation theory, combined with dimensional analysis, multivariate linear analysis and least squares method, an approach to estimate the sediment carrying capacity is presented for a tidal river and a capacity formula is established. The procedure includes such factors as flow turbulence intensity ($U^2/gh$), gravity action ($U/\omega$), relative roughness ($D_{50}/h$), median grain size ($D_{50}$) and tidal effect ($\Delta h/h$). It is an improvement compared with previous studies considering fewer parameters. The derived formula has relatively good prediction accuracy. It is advisable to take into consideration the median grain size and tidal effects in determination of the sediment carrying capacity.

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