Numerical simulation of sediment-laden flow on the Yarlung Zangbo River incorporating the climate change

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Abstract. The Yarlung Zangbo River originates from the Qinghai-Tibet Plateau, and runoff consists of the rainfall, melting of snow and glaciers in the upper high-altitude areas. The flow and sediment transport induced by flow in the Yarlung Zangbo River is highly sensitive to changes in climatic conditions. Changes in flow and sediment transport will also have an impact on the downstream wetland ecosystem. In order to study the changes of flow and sediment transport in the Yarlung Zangbo River, Niyang River wetlands under the changes of climatic conditions is used as the considered case. The two-dimensional shallow water equation and the non-equilibrium bedload sediment transport model are proposed in the Yarlung Zangbo-Niyang River. The model is discretized using the unstructured grid finite volume method (FVM). The model includes approximately 355 km length and covers an area of approximately 673 km$^2$. According to the measured time series of flow data at Nuxia hydrology station and the simulated data under the climate change conditions by the climate change model, the water level, flow velocity, erosion and siltation, and sediment gradation change in the river channel are calculated. The calculation results show that by the year 2025, the water level of Niyang River wetlands will increase by 2m under RCP8.5 (Representative Concentration Pathway), and accordingly the total area of the wetlands will decrease by 5%. The results show that climate change has a significant impact on the flow and sediment transport and downstream ecological environment of the Yarlung Zangbo River.

1. Introduction

The study of water and sediment transport is of great significance in the study of riverbed morphology and ecological environment. By studying the flow rate, water level, river erosion and siltation of rivers, we can fully grasp the evolution of rivers, changes in habitats of some important species, such as cupressus gigantea and black-necked cranes. We can also predict future changes in these indicators.

With the development of computer science and technology, the numerical simulation method of flow and sediment transport has become increasingly mature [1][2][3]. For the slender river channel, the 1-D numerical model can be used to calculate the flow and sediment transport and the river channel erosion and siltation along the length direction [4][5]. Based on the 1-D model, the planar 2-D numerical model adds the flow and sediment transport calculation along the width direction of the river channel, which can simulate the local river erosion and calculate the influence of cross-river buildings on the flow field and flow-sediment transport [6][7][8][9][10]. The 3-D numerical model is more precise, which can simulate the flow and sediment transport on the microscopic scale, which is suitable for the calculation of small-scale water and sediment transport [11][12][13][14][15].
The Yarlung Zangbo River is the longest plateau river in China and is one of the highest rivers in the world. The Yarlung Zangbo River Basin and Niyang River wetlands have many unique species. Changes in flow and sediment transport in the Yarlung Zangbo River have a great impact on the living environment of these organisms. Therefore, it is particularly important to study the impact of climate change on the flow and sediment transport of the Yarlung Zangbo River [16]. However, due to the complex terrain and varied climate conditions in the Yarlung Zangbo River Basin, it is difficult to carry out geological and hydrological surveys in the area. Therefore, it has been difficult to study the flow and sediment transport in the Yarlung Zangbo River.

The numerical models of flow and sediment transport have the advantage of being able to adapt to complex flow-sediment and topographic conditions and more accurate than empirical formulas [17][18]. Therefore, numerical models are widely used in flow and sediment transport in large rivers. However, due to the long-term lack of terrain and hydrological data, the numerical model is rarely used in the study of flow and sediment transport in the Yarlung Zangbo River. To compensate for the lack of hydrological data, the Tsinghua Representative Elementary Watershed (THREW) model [19] was introduced to predict changes in the flow under climate change conditions. At the same time, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) [20] was introduced to construct the digital terrain of the Yarlung Zangbo River.

In order to balance the computational efficiency and accuracy, we used a two-dimensional flow-sediment transport model based on unbalanced sediment transport mode [21], and constructed a finite volume discrete method based on unstructured grid. According to the flow sequences output by the THREW model, the flow and sediment transport and riverbed evolution of the Yarlung Zangbo River section from Langxian to Chilong Zangbo under the different climate change conditions were calculated.

2. Materials and methods

2.1. Numerical model

The major equation used in the flow calculation is the conservative form of 2-D shallow water equation (8):

$$\frac{\partial q}{\partial t} + \frac{\partial m(q)}{\partial x} + \frac{\partial n(q)}{\partial y} = b(q)$$

(1)

where $q=[h, hu, hv]^T$ is the conserved physical vector; $m(q)=[hu, hu^2+gh^2/2, hu v]^T$ is the flux vector in the $x$-direction; $n(q)=[hv, hv v, hv^2+gh^2/2]^T$ is the flux vector in the $y$-direction. The quantity $h$ (m) is water depth, and $u$ and $v$ (m/s) are the depth-averaged velocity components in the $x$- and $y$-directions, respectively. The quantity $g$ (m/s²) is the gravitational acceleration. The source/sink term $b(q)$ is written as [22]:

$$b(q)=[0, gh(s_{ux} - s_{ux}), gh(s_{uy} - s_{uy})]^T$$

(2)

where $s_{ux}$ and $s_{ux}$ are the bed slope and friction slope in the $x$-direction, respectively; $s_{uy}$ and $s_{uy}$ are the bed slope and friction slope in the $y$-direction.

The integral form of Eq. (1) can be written as [21]:

$$\iint_{\Omega} q d\omega = - \int_{\partial\Omega} F(q) \cdot ndL + \iint_{\Omega} b(q) d\omega$$

(3)

where $n$ is a unit outward vector normal to the boundary $\partial\Omega$; $d\omega$ and $dL$ are the area and arc elements, respectively. The integrand $F(q) \cdot n$ is the normal flux vector in which $F(q) = [f(q), g(q)]^T$. 
We assume that the vector quantity $q$ is constant over an element. Discretizing Eq. (5), the basic equation of the finite volume method (FVM) is [21]:

$$A \frac{dq}{dt} = - \sum_{j=1}^{m} F_j(q) L_j + Ab(q)$$

(4)

where $A$ (m$^2$) is area of an element; $m$ is the total number of sides for an element; $j$ is the index for the side of the element; $L_j$ (m) is the length of the side; $b(q)$ is the source term of the Eq. (1).

The governing equation of sediment calculation is the non-equilibrium bed load transport equation [8]:

$$\frac{\partial}{\partial x} (\alpha_s q_b) + \frac{\partial}{\partial y} (\alpha_s q_b) + \frac{1}{L_s} (q_b - q_{te}) = 0$$

(5)

where $\alpha_s$ is the cosine function of shear stress direction; $L_s$ (m) is the adjustment length of non-equilibrium bed load transport [23]; $q_{te}$ (N/s) is the equilibrium bed load transport rate given as [8]:

$$q_{te} = 9.31D^{0.5} \left( \frac{1.2U}{U_c} \right) \left( U - \frac{U_c}{1.2} \right) \left( \frac{D}{h} \right)^{0.25}$$

(6)

where $D$ (m) is diameter of sediment particles, $U$ (m/s) is the depth-averaged velocity, $U_c$ (m/s) is the incipient velocity of sediment.

2.2. Calculation region

![Figure 1](image1.jpg)  
Figure 1. Calculation region with grid data.

![Figure 2](image2.jpg)  
Figure 2. ASTER GDEM digital elevation model.
The calculation region covers the main stream of the Yarlung Zangbo River (from Langxian to the junction of the Yarlung Zangbo River and Chilong Zangbo) and the total area of the Niyang River wetlands, i.e. a length of approximately 355 km and an area of approximately 673 km². In order to ensure the accuracy and speed of the calculation, a grid size of 80 m × 80 m was used for the discretization of calculation region. The number of the cells is 92087 in total (Figure 1).

An elevation data was needed for each cell. Due to the lack of measured terrain data, the ASTER GDEM digital elevation model (Figure 2) was selected as the elevation data source [20].

The accuracy of the ASTER GDEM model is 30m, which satisfies the calculation accuracy requirements of the cell with a size of 80m. The elevation scatter of the digital elevation model is interpolated at the center of the cell to obtain the elevation value of each cell. The elevation difference between the highest point and the lowest point in the calculation area is 446m.

2.3. Boundary conditions.

The upstream boundary condition is the time series of the flow coming into the calculation region. We set the flow series data in Langxian and Gengzhang under current condition, under RCP4.5 condition, and under RCP8.5 condition [24] as the upstream boundary conditions of the main stream and Niyang River, respectively. The downstream boundary condition is the time series of water level at the exit of the calculation region. We set the water level series data at the junction of the Yarlung Zangbo River and Chilong Zangbo under the three types of conditions as the downstream boundary condition.

The current flow input data (average flow from 1955 to 2015) of the Yarlung Zangbo and Niyang River came from the flow-time series data provided by Nuxia hydrological station and Gengzhang hydrological station. The data shows that under the current climatic conditions, the maximum flow over a year in the main stream of the Yarlung Zangbo River is about 4000m³/s.

Moreover, the flow of the rivers by the year of 2025 under RCP4.5 (Representative Concentration Pathway) condition and RCP8.5 condition was obtained from the THREW model [19]. Under the condition of RCP4.5, the maximum flow of the Yarlung Zangbo River in 2025 is about 1.5 times that of the current, which is over 6000m³/s. If under the condition of RCP8.5, the maximum flow will exceed over twice the current, which is over 9000m³/s. Meanwhile, in the Niyang River, the maximum flow under the current climatic conditions is about 1500m³/s, and it is over 2000m³/s and 2500m³/s under the condition of RCP4.5 and RCP8.5, respectively.

Thus, changes in the water level (water depth), flow velocities in the x- and y-directions, and riverbed level can be obtained from the calculation.

3. Results

3.1. Water level changes in the Niyang River wetlands under different climate conditions

The calculation results show that the water depth of the Niyang River wetlands is approximately 6-8m on July 31 under current climate condition. In most areas of the wetlands, the velocity of the flow is 0.2-0.5m/s. Compared with the results under current condition, the calculation results on July 31, 2025, under RCP8.5 condition show that in most areas, the water level is 2m higher. Correspondingly, the water depth in the Niyang River Wetlands is 8-10m, which is about 2m deeper than that of current condition. The velocity of flow under RCP8.5 condition is almost the same as that of current condition in the Niyang River wetlands, which is 0.3-0.5 m/s. The results also show that the total area of wetlands (defined as an area with a water depth of less than 2m) will decrease by 5% by the year of 2025 under the condition of RCP8.5. Under RCP4.5 condition, the water level is 1.2m higher than that of current condition, and the flow velocity field is also almost the same as that of current condition.

3.2. Sediment transport changes in the Niyang River wetlands under different climate conditions

Figure 3 shows the calculation results of the erosion and siltation of the Niyang River wetlands under current condition.
Figure 3. Bed level changes in the Niyang River wetlands.

In most areas, the change of bed level in the Niyang River wetlands is between 0m and 0.2m under current climate condition. As previously described, the change of flow velocity is very low under all conditions, thus the changes of bed level under RCP4.5 condition and RCP8.5 condition are almost the same as those of under current condition.

4. Conclusions

In this study, we established a two-dimensional numerical model to calculate the changes in flow and sediment transport in the Yarlung Zangbo River and the Niyang River wetlands before and after climate changes. When the concentration of carbon dioxide in the atmosphere increases, the climate become warmer and the flow of the Yarlung Zangbo River increases, resulting in changes in the hydrodynamics and sediment transport.

The calculation results show that the water level of the Niyang River wetlands is sensitive to climate changes. When it becomes warmer, the water level will increase significantly. Under RCP8.5 condition, it will rise by a maximum of 2m. However, the flow velocity and sediment transport in the Niyang River wetlands are not sensitive to climate changes. This is mainly because the water surface of the Niyang River wetland is wide.

Due to the elevation of the water level, the *cupressus gigantea* that currently grows less than 2m above the surface of the the Yarlung Zangbo River will be inundated when the peaks of the flood come. The shrinking of the wetland area caused by climate change will also affect the habitats in the Niyang River wetlands.

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