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Article

Sustainability of the Dujiangyan Irrigation System for over 2000 Years—A Numerical Investigation of the Water and Sediment Dynamic Diversions

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Abstract: The Dujiangyan Irrigation System (DIS), located in the western portion of the Chengdu Plain at the transitional junction between the Qinghai-Tibet Plateau and Sichuan Basin, has been in operation for about 2300 years. The system automatically uses natural topographical and hydrological features and provides automatic water diversion, sediment drainage and intake flow discharge control, thus preventing disastrous events in the region in a ‘natural’ way. Using a numerical modeling approach, this study aims to investigate the reasons behind this natural behavior of the system and provide a better understanding of the complex mechanisms which have caused the sustainability of the DIS for over two millennia. For this purpose, a two-phase flow model based on the Shallow Water Equations (SWEs) is developed to simulate the fluid and sediment motions in the DIS. A coupled explicit-implicit technique based on the Finite Element Method is applied for the fluid flow and a Sediment Mass (SM) model in the framework of the Lagrangian particle method is proposed to simulate the sediment motion under different flow discharge conditions. The results show how different components of the DIS make full use of the hydrodynamic and topographical characteristics of the river to effectively discharge sediment and excess flood to the downstream and create an environmentally sustainable irrigation system.

Keywords: Dujiangyan; sediment mass model; hydraulic properties; sediment diversion; sustainable development

1. Introduction

The ancient water conservancy projects, such as the control project of Nel-Hammurabi on the Euphrates River built by the Babylon Kingdom, the manmade canals constructed by the ancient Roman Empire [1], and the agricultural irrigation systems dating back to the 1st-6th centuries in Israel [2] have long fallen into disuse. However, there are some old irrigation structures that are still in operation, such as the irrigation in sediment-laden rivers developed in ancient Peru [3]. Moreover, the qanat system, a subterranean aqueduct used to convey water for irrigation and domestic consumption, originated in Iran as early as the 7th century BCE [4], was brought to Spain in the 8th century, and then to the New World in the 16th century [5,6]. This system still irrigates farmlands in Iran at the present day.

The Dujiangyan Irrigation System (DIS) is one of the ancient irrigation systems which are still in operation. This system began in the 3rd century BCE, is characterized by the non-dam intake project

and is still discharging its functions perfectly [1]. It was listed as a World Cultural Heritage Site in 2000 and a World Heritage Irrigation Structure in 2018. The main headworks of the DIS are located in the transitional region, where the river flows from a gorge to an alluvial plain. The location has a 50 km distance and 273 m elevation difference from Chengdu City, China (Figure 1). This is on the commanding point of the alluvial plain so as to prevent floodwater flowing directly to the Chengdu Plain [7]. Natural topographical and hydrological features are used to exclude sediment and divert water for irrigation without the use of dams. The system has produced benefits in flood prevention, agricultural irrigation, and water consumption for many years [8].

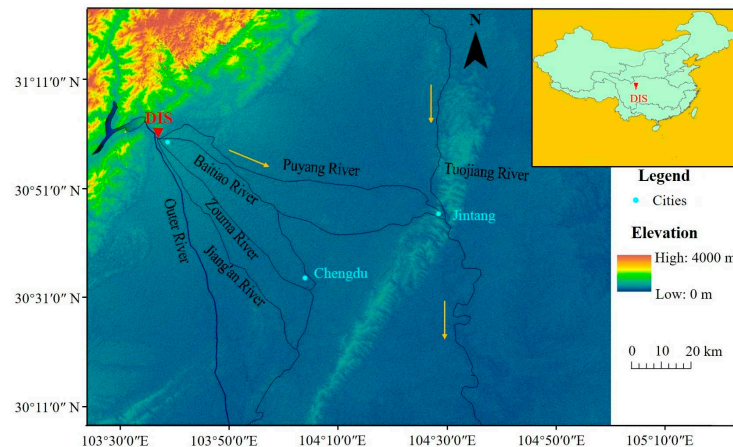


Figure 1. Sketch map of the study area. The inset map (top right) shows the location of the Dujiangyan Irrigation System (DIS) in China. The Puyang, Baotiao, Zouma, and Jiang'an Rivers all flow from the Baopingkou (the bottle-neck channel of the DIS).

Recently, a dam was constructed upstream of the DIS (about 4 km from the Fish Mouth). The reservoir of the dam can be seen in Figure 1. The dam construction was completed in 2006, and since then, it has provided a more stable water supply to the Dujiangyan areas during the dry season, and also reduced the peak flow discharge of the river during the flood season. Since this dam is a relatively new structure and the focus of the present study is on the historical performance of the DIS based on its natural and topographical characteristics during the past 2000 years, the effect of the dam is not taken into consideration in this study.

The headworks of the DIS are composed of three primary components: (1) The Fish Mouth (the front end looks like a fish mouth), a diversion embankment dividing the Minjiang River into the Inner River, primarily for irrigation, and the Outer River, mainly for flood and sediment discharge; (2) Feishayan, a low spillway dam removing sediment and excess water from the Inner River into the Outer River; and (3) Baopingkou (bottle-neck channel), a water intake automatically controlling intake discharge from the Inner River (Figure 2).

The need to understand how the DIS has preserved its functionality for more than 2000 years and the need for protecting it have urged researchers and engineers to investigate the hydrodynamics of the system, such as flow motion, sediment transport, and riverbed evolution. They have been conducting research in the last few decades on the mechanisms of water and sediment diversion under different discharge conditions in order to improve the methods of protecting the system. Since the first physical model experiment of the DIS conducted in 1941 [9], scholars have studied the characteristics of the water and sediment transport by using the prototype survey [10,11], physical hydraulics model [12], and numerical model [13–15]. As for the dynamic water diversion process, based on the ancients' experience, more than 60% of the Minjiang River typically goes into the Inner River for the use of the Chengdu Plain during the low discharge period, while in the flood period, this ratio can reduce to less than 40% [16]. The analysis of the prototype data carried out by Sun et al. suggested that after the construction of the check gate across the Outer River in 1974, the water distribution into the Inner

River was close to 75% in spring time and only 37.5% in the flood season [10]. Later, as a complement to the laboratory experiments conducted in Sichuan University [12], a two-dimensional (2D) numerical model has been used to study the performance of the system under different inflow conditions [13].

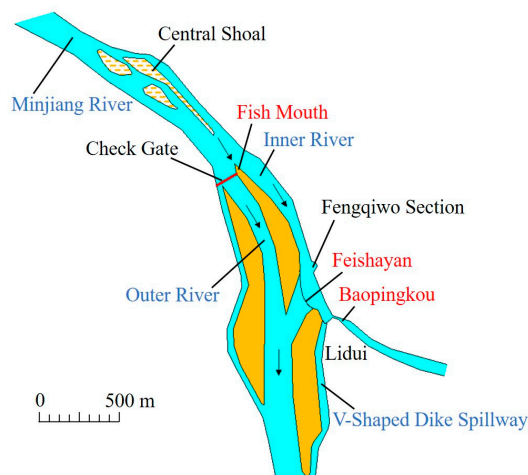


Figure 2. General layout of the DIS.

Many irrigation projects in history were abandoned due to sedimentation. The long-term vitality of the DIS project is linked to the fact that sediment is automatically excluded by natural characteristics of the system. Sediment deposition is primarily formed by the moving bed load from May to October [11]. Based on the distorted movable model, the amount of bed load entering the Inner River through the Fish Mouth is only about 29% of the total load in the Minjiang River [17]; and that is 26% based on the results of the prototype observations [18]. The Feishayan begins to discharge sediment to the Outer River when the flow rate of the Inner River is over $500 \text{ m}^3/\text{s}$ [12]. The larger the flood discharge is, the higher is the discharge diversion ratio at the Feishayan and the more efficient is the system in discharging sediment from the Inner River. Under the function of the Feishayan, over 90% of the bed load carried into the Inner River can be discharged to the downstream area of the Outer River [19]. In addition, the V-Shaped Dike Spillway, an auxiliary project of the DIS, also diverts sediment and excess water during periods of flood [20]. Finally, less than 8% of the total sediment of the Minjiang River can reach the Baopingkou, ensuring that the irrigation lands receive clear water [17]. It is notable that there have also been small amounts of sediment deposition in the Inner River section which have been dredged annually (probably since the irrigation system was first constructed).

At present, the prototype observations and model experiments can only explain the basics of the sediment discharge process in the DIS. On the other hand, the one-dimensional (1D) [14] and 2D [15] numerical models used for simulating riverbed evolution in the DIS have difficulty in describing the ‘dynamic’ sediment diversion, which has a key role in the understanding of the dynamics of the sediment discharge processes in the system. For 1D models, this is due to the one dimensionality of the model being able to describe the bed load movement process only in one channel while ignoring it in the other DIS channels. For 2D models, when considering only the continuity of the bed load, there is often a large time scale difference between flow and sediment motion, which results in non-accurate estimation of riverbed morphology. In addition, the grid-based models, due to the Eulerian description of the sediment medium, are unable to provide details of the motion of sediment particles between different channels.

In this study, to tackle these difficulties, the fluid flow in the DIS is simulated by solving the Shallow Water Equations (SWEs), which can effectively deal with the large scale of the study area, coupled with a newly proposed Sediment Mass (SM) model for the bed load transport. The fluid model is based on the coupled explicit-implicit solution algorithms of the SWEs and the SM model is developed from the Lagrangian particle modeling concept, considering the orderly movement (in

the form of bed load transport belt) of large amounts of sediment. With the SM model, due to its Lagrangian framework, we can understand how sediment particles move from one channel to another, i.e., 'dynamic' sediment diversion. Examples of such particle modeling approaches in fluid flow simulation and sediment transport process were developed by Pu et al. [21], Ran et al. [22], and Zheng et al. [23].

The developed coupled model is used to simulate the sediment motion in the DIS under different flow conditions; and the results are discussed to explain why the DIS has operated for 2300 years and is still functioning well.

2. Fluid Flow Model

The 2D Shallow Water Equations (Equations (1) and (2)) are solved for the fluid flow:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \quad (1)$$

$$\frac{D(h\mathbf{u})}{Dt} = A_H h \nabla^2 \mathbf{u} - gh \nabla \eta - \frac{g\mu^2 |\mathbf{u}| \mathbf{u}}{h^{1/3}} \quad (2)$$

where: η = water surface; t = time; h = flow depth; \mathbf{u} = the velocity vector with the longitudinal and transversal components of u and v , respectively; A_H = the horizontal eddy viscosity coefficient; g = gravitational acceleration; and μ = the bed roughness coefficient.

The solution is based on the method used in Zheng et al. [24]. The water level and flow velocity are calculated by the implicit Eulerian-Lagrangian method (ELM), i.e., the quantities at time $t + dt$ are updated using those at time t , implicitly, where dt is the time step size in the flow model; and then the temporary ELM traced lines are corrected explicitly by using the Characteristics-based Splitting method, i.e., the intermediate values between times t and $t + dt$ are explicitly computed. This leads to the enhancement of the computational efficiency of the model as the detailed flow information lost in the implicit computation can be recovered by increasing the number of explicit intermediate computational steps. In fact, the coupled method merges the merits of the high computational accuracy from the explicit scheme with the high numerical efficiency and stability from the implicit scheme.

For the ELM computations, the computational domain is discretized by triangular mesh elements, and the governing equations are solved by using the Finite Element Method. For the boundary conditions, three types of boundaries are considered:

- (1) an open boundary applied in the flow inlet and outlet;
- (2) a land boundary satisfying slip and non-penetration conditions; and
- (3) a moving boundary relating to the continuous changes of flow and sediment transport. More details on the numerical discretization and boundary conditions can be found in Zheng et al. [24] and Chen et al. [25].

The model has previously been used for a few applications including dam-break flow [24], long-term river meandering process [24], and unsteady flow propagation [26].

Due to the bending section of the Minjiang River and the diversion of flow at the Fish Mouth, the effect of secondary flow is not negligible in the present application, an effect which is often neglected in 2D SWE models. To include the secondary flow effect in the present model, a transversal velocity v_r is computed at the nodes of the computational domain by using the Rozovskii formula (Equation (3), [27]), and added to the transversal component of \mathbf{u} (i.e., v) with the magnitude of velocity $|\mathbf{u}|$ being unchanged. This applies a modification to the direction of the velocity vector, while its magnitude remains unchanged.

$$v_r = u \frac{1}{\kappa^2} \frac{h}{R} \left[F_1(\lambda) - F_2(\lambda) \frac{\mu \sqrt{g}}{\kappa h^{1/6}} \right] \quad (3)$$

where: κ = von Karman constant (~ 0.4); R = radius of curvature; λ = normalized vertical co-ordinate (which is set to 0.3 here); $F_1(\lambda) = -2 \left(\int_0^\lambda \frac{\ln^2 \lambda}{1-\lambda} d\lambda + 1 \right)$; and $F_2(\lambda) = \left(\int_0^\lambda \frac{\ln^2 \lambda}{1-\lambda} d\lambda \right)^2 - 2$.

3. Sediment Transport Model

In the present study, bed load is considered as the dominant form of sediment transport, and a particle-based SM model is proposed to model the convection motion of bed load in a disk-like form, considering sediment as a discrete medium and bed load as a motion of a group of sediment grains. In the following, a description of the SM model is presented.

Taking only the convective motion into account, in order to minimize the error caused by the omission of the sediment diffusion, a time step size smaller than the one used in the flow model is set for the calculation of sediment motion, i.e., $\Delta T = dt/N$, where N is the number of segments determined based on the velocity gradient (set to 2~10 in this study). Disks, representing SMs, are used to discretize the sediment domain. Each disk contains a number of sediment particles virtually, with a circular bottom area defining the influence domain of the SM, and a height (thickness) equal to the multiplication of the porosity of sediment medium by the mean diameter of the sediment grains within the disk influence area. The disks can overlap each other and move over the fluid domain based on their velocity, which is determined as follows.

Firstly, in each sub-step ΔT , the velocity of a virtual sediment particle is calculated as follows:

$$\mathbf{u}_{t+\Delta T} = \mathbf{u}_t + \mathbf{u}_a \quad (4)$$

where: \mathbf{u}_t and $\mathbf{u}_{t+\Delta T}$ = the sediment particle velocity vector at times t and $t+\Delta T$, respectively; and \mathbf{u}_a = the increase in the velocity of the sediment particle during ΔT . The magnitude of \mathbf{u}_a , i.e., u_a , is calculated by Equation (5); and its direction is determined by considering a normal distribution for the angle between it and the streamline (as depicted in Figure 3a) based on the assumption that the direction of \mathbf{u}_a is random due to the randomness of sediment particle collisions during bed load transport:

$$u_a = (u_w - u_c) \times \beta \quad (5)$$

where u_c = critical incipient velocity computed by the Sharmove formula [28]:

$$u_c = 1.14 \sqrt{\frac{\gamma_s - \gamma}{\gamma}} g D \left(\frac{h}{D}\right)^{\left(\frac{1}{6}\right)} \quad (6)$$

and u_w = mean flow velocity at the center of the SM, calculated as the arithmetic average of flow velocity at the nodes located inside the influence area of the disk. In addition, β = correction coefficient (which is set to 0.1 in the present simulations), γ_s = specific weigh of sediment grains (= 26.5 kN/m³ here), γ = specific weigh of flow (= 10 kN/m³ for water), and D = diameter of sediment grains.

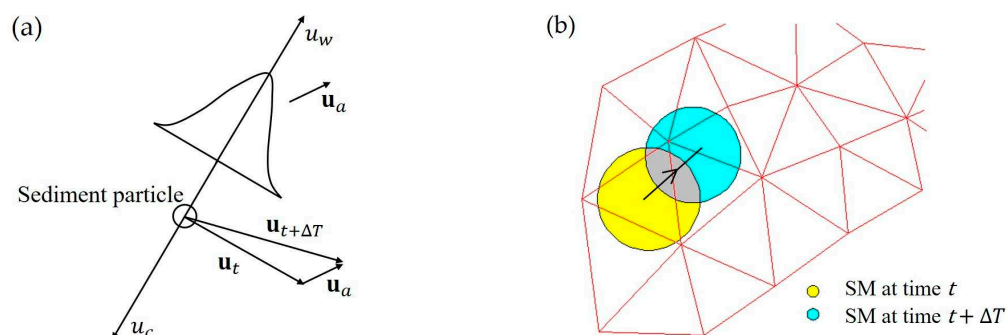


Figure 3. Bed load velocity and mass motion: (a) sediment particle resultant velocity; and (b) sediment mass motion over the fluid domain (which is discretized by triangular elements).

To determine the direction of the velocity vector \mathbf{u}_a a normal distribution is considered for the angle between the streamline and the direction of the \mathbf{u}_a vector (as depicted in Figure 3a). Then, the velocity of the SM is calculated as $\mathbf{u}_{SM} = \mathbf{u}_{t+\Delta T} \times P$, where the Einstein bed load theory is used to estimate the incipient probability P :

$$P = 1 - \frac{1}{\sqrt{\pi}} \int_{-\frac{1}{2}\psi-2}^{\frac{1}{2}\psi-2} e^{-t^2} dt \quad (7)$$

in which $\psi = \frac{(\gamma_s - \gamma) D}{\gamma h J}$ and $J =$ the bed slope. The displacement of the SM in each sub-step is then evaluated as $\Delta \mathbf{x} = \mathbf{u}_{SM} \times \Delta T$. Figure 3 shows the resultant velocity of a sediment particle and the motion of an SM according to its velocity.

After the position of the SM disks is updated, the calculated properties of the sediment domain are transported to the fluid domain. For this, the velocity and thickness of each disk is converted to the flow domain nodes that are located inside the influence domain of the disk using a weighting function (Spline here), and then the converted values at each node are summed up. This yields the average thickness h_s and velocity \mathbf{u}_s of the sediment layer at the position of the nodes. Then, the bed load transport rate \mathbf{q}_b is estimated using Equation (8), and the change of the riverbed elevation from t to $t + \Delta T$ is computed by using Equation (9):

$$\mathbf{q}_b = h_s \times \mathbf{u}_s \quad (8)$$

$$(1 - \xi) \frac{\partial z_b}{\partial t} + \nabla \cdot \mathbf{q}_b = 0 \quad (9)$$

where $\xi =$ porosity; and $z_b =$ thickness of the movable bed layer.

Then, the fluid model equations are solved in the next sub-step, and this process is repeated until the number of sub-steps reaches N . Then, for the next time step, i.e., at $t + dt$, SMs are regenerated instead of turning the node information back to them. This will reduce the error related to the diffusion effect without increasing extra calculation.

4. Model Applications in the DIS

In this section, the numerical model is applied to simulate the sediment processes in the DIS. The flood control discharge and the 1000-year flood of the area are 800 m³/s and 10,120 m³/s, respectively. Besides, if the Inner River discharge exceeds 1000 m³/s, a large amount of sediment can be discharged into the Outer River via the Feishayan [12]. Considering these factors, three flow rates, i.e., 800 m³/s (low discharge), 1800 m³/s (medium discharge), and 10,120 m³/s (high discharge), are selected to simulate different sediment diversion conditions. At the initial time of each simulation, a number of SM disks are placed at the inlet boundary with their velocity being determined according to the desired flow discharge. The total simulation time is 7 days, and the grid and time step sizes are set to 3 m and 10 s, respectively. Sections 4.1 and 4.2 present the results of the fluid flow and sediment motion, respectively.

4.1. Simulation of Fluid Flow

Figures 4–6 show the results of velocity of the numerical model for flow rates of 800, 1800 and 10,120 m³/s, respectively. The water diversion ratio, i.e., the ratio of the flow discharge in the Inner River to that of the Minjiang River, is automatically regulated at the Fish Mouth due to the central shoal located upstream of it (Figure 2). In the dry season, the central shoal is unsubmerged. As a result, according to the historical record (Figure 7), more than 60% of the total discharge runs into the Inner River, which is beneficial for the water intake of the irrigation area. In the wet season, the shoal is fully submerged, and the current tends straight into the Outer River, so the water diversion ratio is reverse. Due to these, the DIS, naturally, has functions of water intake and flood drainage during the dry and wet seasons, respectively. Figure 7 presents the water diversion ratio of the Inner River obtained from

the present simulations for different flow discharges in the Minjiang River in comparison with the historical records in the site, where good agreement is observed. It clearly shows that the diversion ratio of the Inner River decreases when the Minjiang River flow discharge goes up.

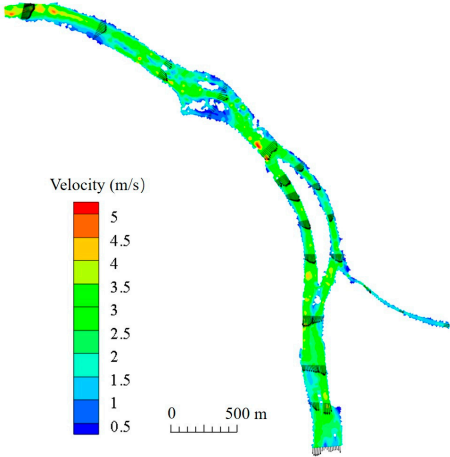


Figure 4. Flow velocity field under a flow discharge of 800 m³/s.

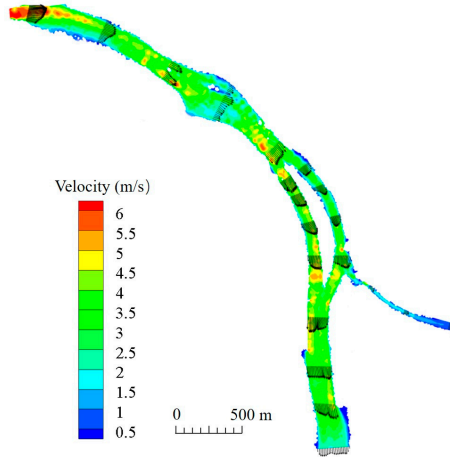


Figure 5. Flow velocity field under a flow discharge of 1800 m³/s.

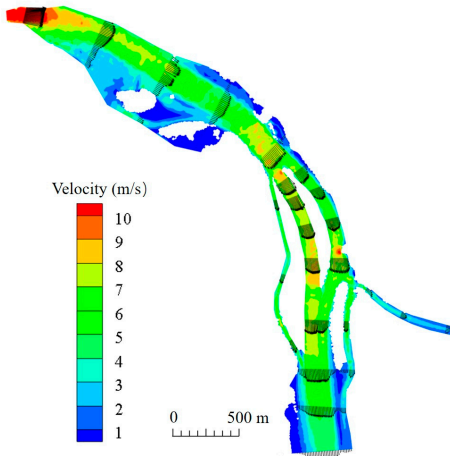


Figure 6. Flow velocity field under a flow discharge of 10,120 m³/s.

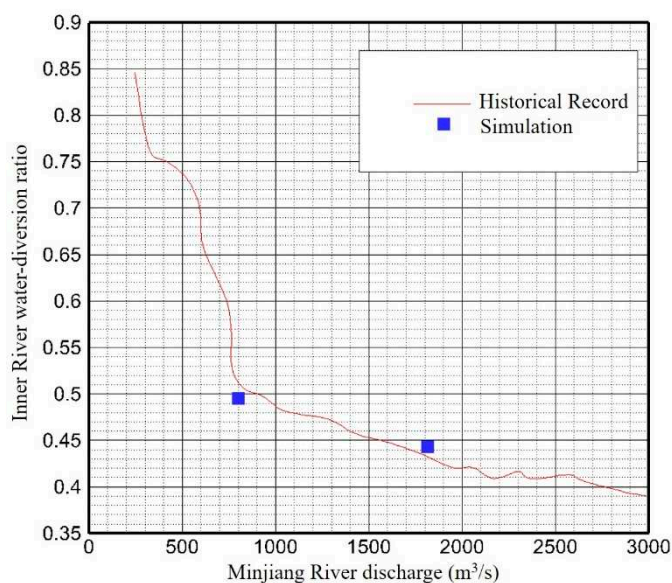


Figure 7. Computed and measured water diversion ratio for different flow discharges. There is no historical record for the high discharge condition (10,120 m³/s). The historical record is from field measurements in the DIS [10].

4.2. Simulation of Sediment Processes

In order to understand how under different flow regimes, the sediment transport is distributed over the channels of the DIS, i.e., the Inner and Outer Rivers, the results of the bed load movement simulated by the proposed model in Section 3 are presented. Figures 8–10 show these results under the low, medium, and high flow discharge conditions (800, 1800, and 10,120 m³/s, respectively).

As seen in Figure 4, when the discharge is low (800 m³/s), the flow velocity in the Inner River is not significant (the average velocity in the middle of the channel is about 3 m/s). Therefore, only a small amount of sediment moves through the Inner River (see Figure 8).

During the medium flow discharge condition (1800 m³/s), the sediment and surplus water are discharged through the Feishayan (Figure 5; Figure 9). This can be explained by the mutual functionality between the Feishayan and the Baopingkou. The Feishayan is a low spillway weir with a width of 240 m, average weir crest elevation of 728.25 m, and distance of 710 m away from the Fish Mouth; the Baopingkou, with a width of 20.4 m, bottom elevation of 716.3 m, and a distance of 120 m away from the Feishayan, serves as a water intake throat to the downstream irrigation areas (Figure 2). The width of the Baopingkou is only one-tenth of that of the Feishayan. Therefore, once the discharge in the Inner River exceeds the intake capacity of the Baopingkou, most of the excess flood flows out into the Outer River via the Feishayan (Figure 5). Another important function of the Feishayan is sediment diversion. The Minjiang River carries large amounts of materials flowing into the Inner River and may cause the siltation of the Baopingkou, changes in the elevation of the riverbed, and reduction of the irrigation water intake. However, due to the diversion of sediment at the Feishayan, these impacts are effectively mitigated. The reason behind that the Feishayan is able to discharge sediment to the Outer River is that it is located on the convex bank of the slightly curved Inner River section. Under the function of the centrifugal force, the surface flow with low sediment concentration flows to the Baopingkou located on the concave bank, whereas the bottom water containing high concentration moves to the Feishayan located on the convex bank (see Reference [29]). The larger the flood discharge is, the higher is the water division ratio of the Feishayan and the more efficient is the sediment diversion of the Feishayan.

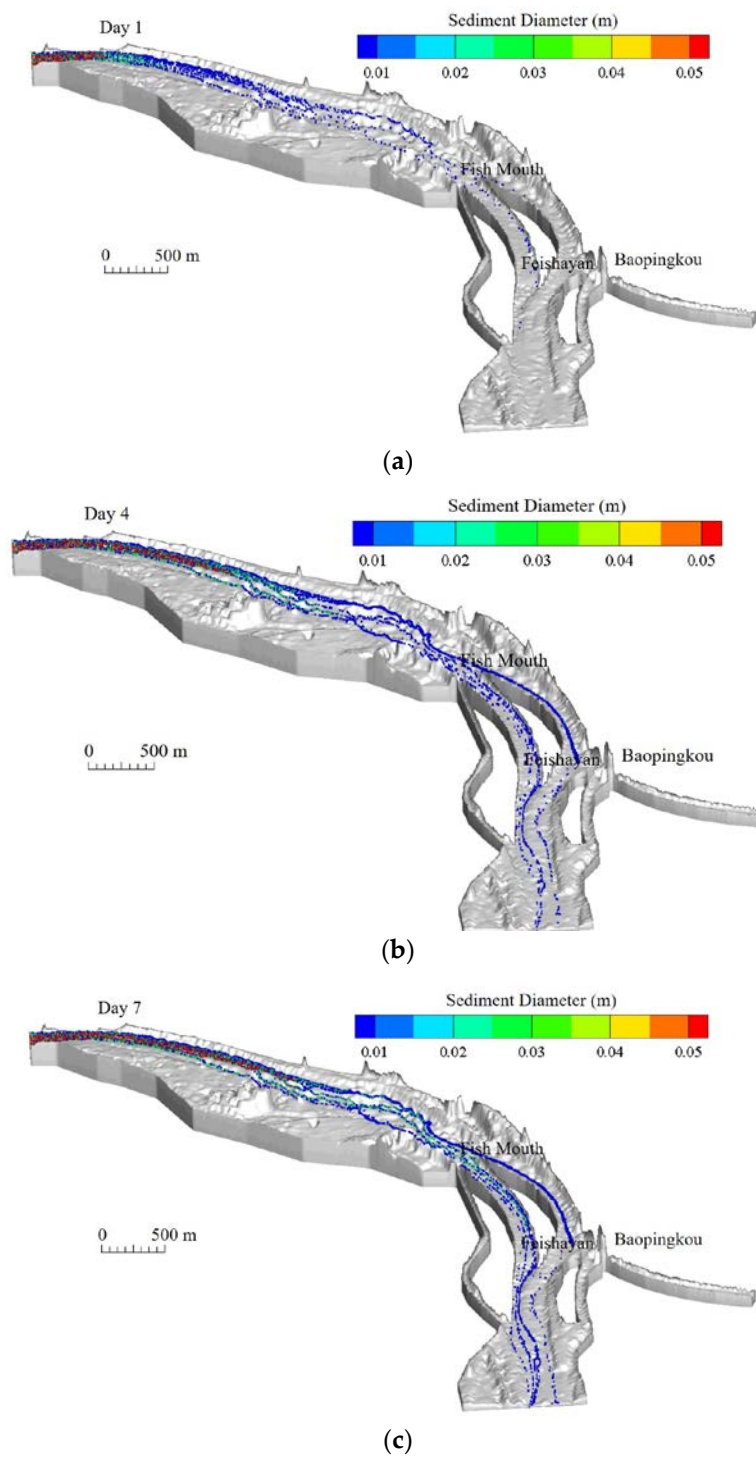


Figure 8. Bed load movement process under the discharge of $800 \text{ m}^3/\text{s}$ on: (a) Day 1; (b) Day 4; and (c) Day 7.

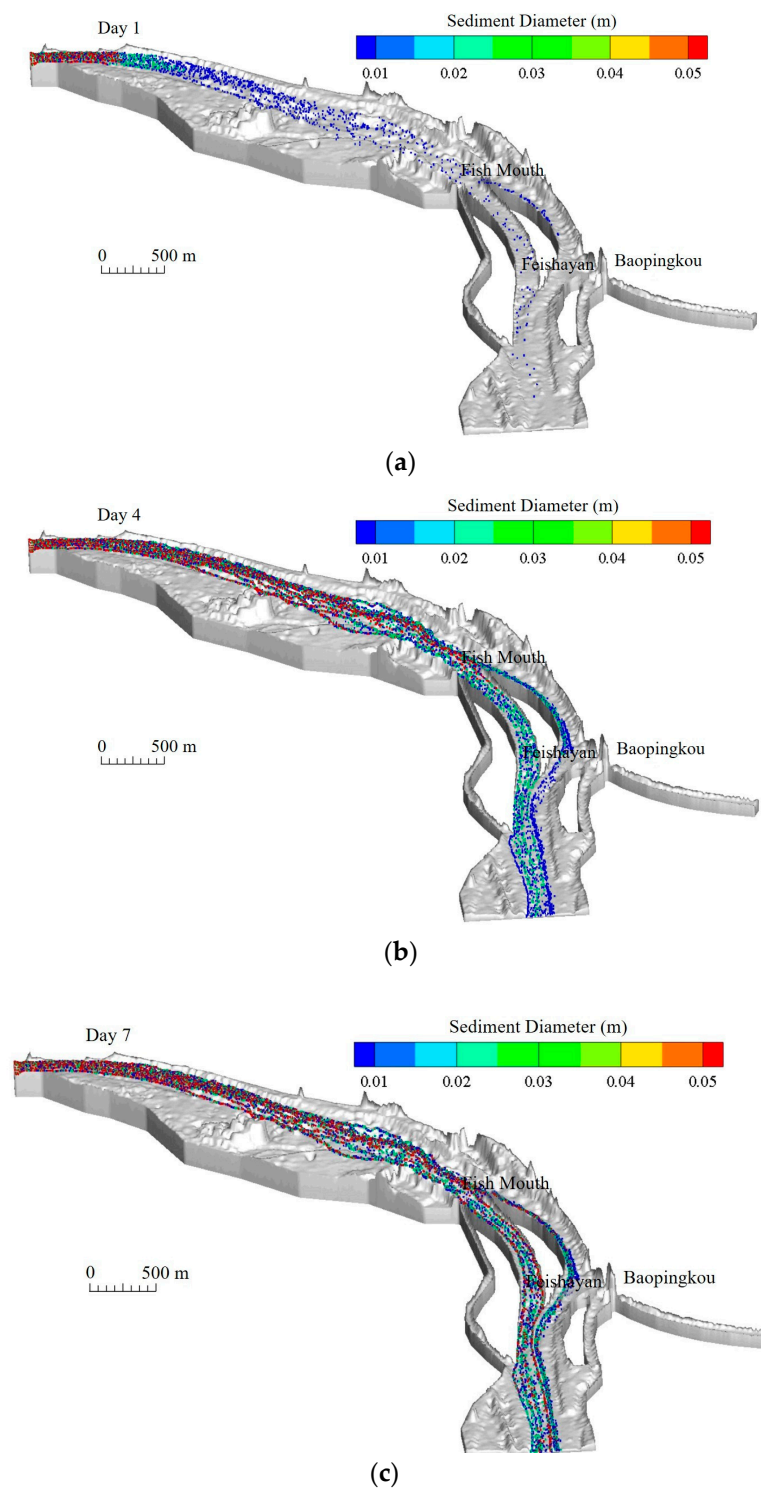


Figure 9. Bed load movement process under the discharge of $1800 \text{ m}^3/\text{s}$ on: (a) Day 1; (b) Day 4; and (c) Day 7.

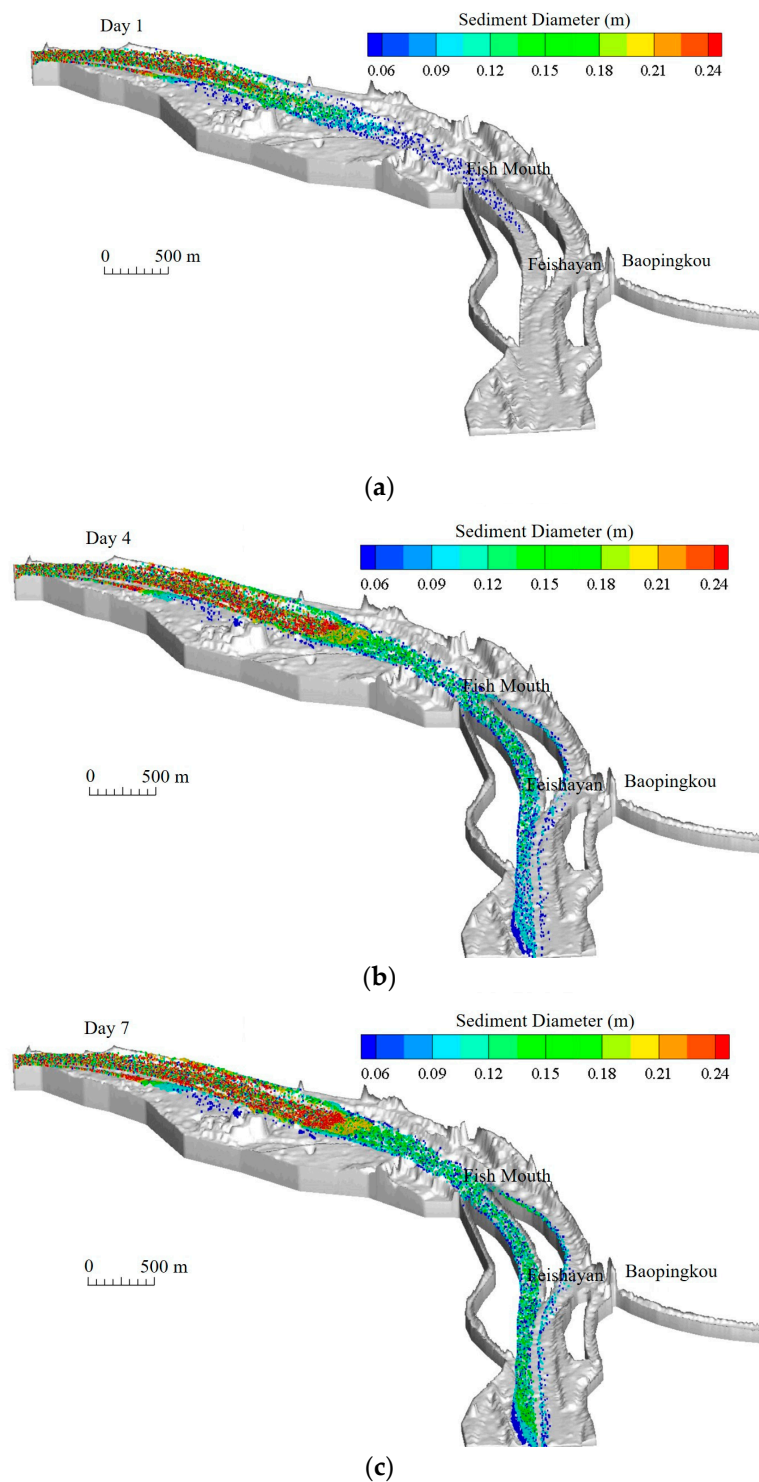


Figure 10. Bed load movement process under the discharge of $10,120 \text{ m}^3/\text{s}$ on: (a) Day 1; (b) Day 4; and (c) Day 7.

There is a small amount of sediment which is not discharged through the Feishayan, but deposits in the Fengqiwo Section. This is because the narrow Baopingkou is not located at the middle of the width of the Inner River. The flood flows to the Lidui and then a backwater is formed in front of it. The effect of the backwater propagates upstream with the increase of the Inner River discharge. Once the backwater effect reaches the Feishayan, some amount of the sediment deposits at the Fengqiwo Section

due to a large reduction in the bottom flow velocity. The deposited sediment is removed in the annual dredging project. Under a high discharge condition, the upstream central shoal is submerged, thus the main flood current carrying most of the moving bed load diverts directly toward the Outer River. At the same time, due to the fact that the Inner River is located on the concave bank of the curved river section, the bed load is transported into the Outer River along the convex bank under the function of the bend flow. In summary, the major amounts of the flood and the bed load are diverted into the Outer River at the Fish Mouth (Figure 6; Figure 10).

The rest of the sediment and water which flow into the Inner River is diverted once again at the Feishayan. After this diversion, if the flood discharge is still high, then the excess amount is automatically discharged through the V-Shaped Dike Spillway. The V-Shaped Dike is an auxiliary project located downstream of the Feishayan and is a low spillway dam with 60 m width and 729 m average weir crest elevation which is slightly higher than that of the Feishayan. Under low and medium flood conditions, the influence of the backwater is not substantial in front of the Baopingkou, meaning that the water level of the Inner River only reaches the crest of the Feishayan and is below that of the V-Shaped Dike (i.e., the V-Shaped Dike Spillway is effectively dry at low and medium discharges). Thus, the flood entering the Inner River is mainly discharged via the Feishayan (see Figures 4 and 5). However, during the high flood discharge period, the upstream backwater of the Baopingkou is considerable and the water level is higher than the V-Shaped Dike, enabling part of the flood to discharge into the Outer River via the V-Shaped Dike Spillway (Figure 6). The flood diversion through the V-Shaped Dike Spillway causes a reduction in the upstream water level and therefore is beneficial for the reasonable water intake of the Baopingkou. The larger the discharge in the Inner River is, the more effective is the function of the V-Shaped Dike Spillway.

In summary, the results showed that most of the flood in the Inner River is discharged to the Outer River via the Feishayan; and under the high flood discharge condition, a part of it can also be discharged through the V-Shaped Dike Spillway to the Outer River. In addition, as shown in Figure 7, a larger flood discharge in the Minjiang River results in smaller water diversion ratios at the Baopingkou, a function that protects the Chengdu Plain from disastrous floods.

5. Discussion

Three key components of the DIS (i.e., the Fish Mouth, the Feishayan, and the Baopingkou) combining with ancillary embankments and watercourses ensure there is efficient sediment diversion and regular water supply for the Chengdu Plain. The reason behind that the DIS is still performing designated functions today is that the sediment is automatically transported in an orderly manner without causing adverse effects on the system. A summary of the operation of the DIS is the 6-character maxim “deeply clearing channel (specially meaning the channel at the Fengqiwo Section), building low dike” [1].

The purpose of a “deeply clearing channel” is to keep the sediment transport in an equilibrium state during a year, namely, the equilibrium of erosion and deposition in the Inner River. This requires the longitudinal profile of the riverbed to reach the balanced section. Therefore, annual dredging is necessary. Also, the dredging level needs to reach the iron bar markers (the position of the riverbed balanced section) buried in the Fengqiwo Section. If the dredging depth is shallower than the iron bar markers, the sediment will further deposit, which is an adverse effect to the sediment diversion and the water intake of irrigation areas. If the dredging depth exceeds the iron bar markers (equivalent to the reduction of the erosional basis), then the erosion will strengthen and cause the non-equilibrium of the sediment supply and transport. The DIS is a successful case where the theory of riverbed balanced section can be applied to the water conservancy project [30].

“Building low dike” means that the height of the Feishayan should be low, which is conducive to discharge water and sediment in the flood period. It shows that floods have been a key factor in designing the DIS. If a hydraulic system is designed without taking floods into consideration, it is unlikely that it can remain in working condition. There are numerous examples of hydraulic works

built in which usage for irrigation and the hydraulic profile for the flood period have been combined. A few examples are the spate irrigation system in Africa [31–34] and the ancient irrigation system in the Central Negev desert [35].

Principles of the DIS are still valuable references in modern diversion project design, including: making full use of the natural bend flow to discharge water and sediment; annual well-organized maintenance to dredge a specific river section; and coexistence of water intake and flood control. This is a good example of comprehensively utilizing natural water resources and realizing harmonious coordination between humans and the nature.

6. Conclusions

The DIS, both naturally and with the aid of man-made structures, has been functioning for 2300 years, excluding sediment, preventing flood, and diverting water for irrigation in the Chengdu plain. To better understand the hydrodynamics and sediment transport processes in the system, numerical modeling approaches were used in this study. A coupled explicit-implicit numerical scheme was applied to simulate the fluid flow, coupled with an SM model for the sediment transport. The simulations were carried out for three different flow regimes: low, medium, and high (based on the 1000-year flood event) discharges; and the water and sediment diversions at the Fish Mouth, Feishayan, and V-shaped Dike Spillway were investigated in detail.

According to the model results, (1) under the low discharge condition, the system mainly diverts the water flow at the Fish Mouth for irrigation; (2) under the medium discharge condition, the current carries more bed load flowing into the Inner River, which is then discharged through the Feishayan to the Outer River; and (3) under the high discharge condition, the main current flows straight into the Outer River, thus the bed load is discharged directly through that channel. The model was able to demonstrate these processes numerically and complement the findings of the previous studies. The processes are mainly attributed to the central shoal located upstream of the Fish Mouth and the bending channel, i.e., at low discharges, the shoal is unsubmerged, thus it diverts more water into the Inner River; and when coming to the high discharge conditions, the shoal is submerged and the water flows straight into the Outer River.

In summary, the water flow and sediment diversion project (Fish Mouth), the discharge projects (Feishayan and V-shaped Dike Spillway) and the intake project (Baopingkou) make full use of the flow dynamics and topographical characteristics (e.g., the bending channel and the elevation differences between these components) to effectively discharge excess floodwater and provide a reliable water supply to the irrigation areas. The results and discussions in this study clearly explain why the DIS has operated for thousands of years, and provide useful references for the engineering design of such systems. The proposed numerical models, however, still need rigorous and comprehensive validations based on benchmark tests of flow and sediment transport, different channel geometries, and various flow conditions. These are considered as future study areas.

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