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A Novel Numerical Approach to the Study of Riverbed Morphometric and Hydrological Characteristics

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ABSTRACT

The lack of reliable bathymetric data for large alluvial rivers with intensely deformable channels significantly limits the application of process-based hydrodynamic models and reduces the accuracy of assessing channel processes, sediment transport, and the ecological state of aquatic ecosystems. The objective of this study is to develop an integrated methodology for reconstructing channel morphometric characteristics by combining diverse hydrological, topographic, and remote sensing data in the face of limited in-situ measurements. The study was conducted for a 5-km stretch of the lower reaches of the Amu Darya River in the area of the damless water intake of the Tashsaka Channel. The methodology is based on the combined use of long-term hydrological observations, multi-temporal satellite images, topographic maps, and two-dimensional numerical flow modeling, taking into account sediment transport, erosion, and accumulation of channel sediments. Consistent model calibration resulted in a discrepancy between calculated and observed water levels of no more than ± 5 cm, confirming the internal consistency of the reconstructed channel geometry and hydrodynamic calculations.

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The obtained results showed that the proposed approach ensures a reliable reconstruction of the channel morphometry in conditions of a deficit of bathymetric information, allows one to assess the spatiotemporal variability of channel processes, predict the redistribution of sediments, and analyze the impact of channel deformations on the functioning of water intake structures. The developed methodology is of practical value for hydraulic engineering design, river system management, and environmental assessment of alluvial rivers, contributing to increased sustainability of water management facilities and the preservation of the hydromorphological state of aquatic ecosystems.

Keywords: Riverbed Morphology; Numerical Modelling; Sediment Transport; Data Integration; Amu Darya River; Hydrodynamics

1. Introduction

The main difficulty in modeling alluvial rivers with easily erodible channels lies not in the hydrodynamic equations themselves, which are well known^[1], but in the fact that reliable process-based modeling of channel change requires detailed knowledge of the river channel geometry, which is rarely available at the required resolution and frequency, especially where the channel is unstable and calibration data are scarce^[2,3]. This contradiction—between what is required for physically based models and what is actually provided by data-poor rivers—is the issue addressed in this study.

In response to this, two main modeling traditions developed. Physically based numerical models solve flow and sediment transport equations directly and remain the primary tool for describing river hydrodynamics, but they depend on precisely specified channel geometry and boundary conditions, and their calibration is easily distorted if these input data are poorly known. Data-driven statistical approaches, in contrast, infer hydrological behavior directly from observed records without requiring a full description of channel geometry^[4], but they typically rely on assumptions about the order of nonlinearity between input and output variables that are difficult to justify in river systems characterized by pronounced nonlinearity and heterogeneity. Neither tradition is inherently suitable for a river reach for which neither detailed bathymetry nor a long-term homogeneous statistical record is available.

Within the physically based tradition, most existing numerical reconstructions and morphodynamic studies assume that channel bathymetry is already known or can be measured directly. Radu and Comănescu^[5] and Hauer et al.^[6] analyzed how channel and bank deformation affects modeling results after the geometry became available; Yang et al.^[7] and Zhang et al.^[8] showed that the same governing equations can give

completely different forecasts depending on hydrological, geological, and anthropogenic conditions; and Jia and Wang^[9], Farsirotou et al.^[10], and Costabile et al.^[11] linked flow, sediment transport, and channel morphology evolution within a two-dimensional CCHE2D model, again assuming a measured source channel^[12]. Further showed, based on physical models of gravel-bed rivers, how sensitive bed sorting and channel morphology are to lateral constraint—highlighting how much detailed channel geometry is used in these models, and how little of it is available for a river like the Amu Darya.

A second, largely separate line of research uses remote sensing and morphometric indices precisely because direct bathymetric surveys are not possible. Mahala^[13], Akhtar et al.^[14], and Vasil'eva et al.^[15] derived morphometric and hydrological characteristics of river basins from indices and images rather than from in-channel data, and Li et al.^[16] used numerical modeling to investigate river channel evolution after disturbances under comparable data constraints. More recently, Schwedhelm et al.^[17] proposed a remote sensing framework specifically designed to characterize the planned state of rivers in data-poor regions, including rivers in Central Asia, but as in the studies mentioned above, stopped short of describing the morphological state rather than developing a calibrated hydrodynamic and sediment transport model from it. This leaves a gap in the workflow that simultaneously reconstructs river channel geometry from such indirect remote sensing and hydrological data and then uses this reconstruction to run and calibrate a true 2D hydrodynamic sediment transport model in data-poor and morphologically active environments such as the lower Amu Darya.

Addressing this gap, this study aims to develop an integrated methodology that combines diverse datasets—field measurements, satellite imagery, and hydrological observations—to reconstruct the missing morphometric information required for process-based hydrodynamic model-

ing. Application of this approach to a representative section in the lower reaches of the Amu Darya River allows for the assessment of channel behavior under variable sediment loads and the quantification of the impact of hydraulic structures. The methodology aims to provide sufficiently accurate morphometric data for subsequent numerical modeling of river channel evolution and to advance scientific understanding of the dynamics of deformable channels in regions where direct bathymetric surveys are unavailable.

The main reason for choosing this particular section of the Amu Darya is that the depth and width of the riverbed in this part of the river fluctuate rapidly throughout the year. This is due to the high turbidity of the Amu Darya's waters, which flow through easily eroded soils. In addition, changes in the riverbed are influenced by the fact that the Tuyamuyun reservoir, located upstream from the Tashsaka water intake, is cleared of silt at certain times of the year, and the silt is discharged directly into the river.

It should be emphasized that the individual components of this workflow—GIS-based terrain processing, satellite shoreline extraction, water stage and discharge interpolation, and 2D morphodynamic modeling—are established methods, and none of them, in and of themselves, claim to be new. The contribution of this study lies in adapting and integrating these components into a single, internally consistent procedure for a highly data-poor, highly mobile stretch of a large, regulated river, and in clearly defining what the resulting model can and cannot support: it is best described as an engineering integration of existing methods under extremely data-poor conditions, rather than as a fundamentally new numerical method. Since river channel morphology, sediment transport and bottom hydraulics jointly control habitat availability, substrate conditions and ecological functioning of alluvial reaches, reconstruction of this morphology is also relevant to the assessment of the aquatic ecosystem and the sustainable operation of the Tashsaka water intake, and we return to these ecological aspects in the Discussion section.

2. Materials and Methods

2.1. Study Area

The study was conducted along a selected section of the Amu Darya River, one of the largest transboundary rivers in Central Asia. The Amu Darya River originates at the confluence

of the Panj and Vakhsh rivers and is characterized by diverse hydrological and geomorphological features throughout its length. Based on these characteristics, the basin is conventionally divided into three distinct sections: the upper reaches, located above Kelifa along the border of Turkmenistan and Uzbekistan; the middle reaches, between Tuyamuyun and Kelifa; and the lower reaches, extending downstream from the Tuyamuyun hydroelectric power station.

The selected study site is located 22 km downstream of the Tuyamuyun hydroelectric power station and encompasses a 5-km stretch of the river—3 km upstream and 2 km downstream of the Tashsaka Channel intake point (**Figure 1**). This location is in the lower reaches of the Amu Darya River in northwestern Uzbekistan. This site was chosen because both the channel depth and width fluctuate significantly throughout the year, indicating active morphodynamic behavior in a highly sediment-laden flow.

The annual hydrological regime of rivers within the Amu Darya Basin is characterized by two main phases: a spring-summer period of high-water levels (flood) and a period of low water levels in autumn and winter. From November to March, most tributaries and main channels experience low water levels with minor fluctuations, and baseflow is maintained primarily by groundwater and limited precipitation. The transition to the high-water phase typically occurs between February and May, when the combined effects of snowmelt and seasonal rains sharply increase water discharge, causing the prevailing spring-summer flood^[18].

This hydrological pattern is further influenced by anthropogenic regulation and sediment management in the upstream Tuyamuyun Reservoir. During certain periods of operation, accumulated silt is washed from the reservoir into the river, leading to a sharp increase in turbidity and a shift in the sediment balance downstream. As a result of a combination of natural and anthropogenic factors, there is a continuous change in the shape of the riverbed, retreat of the banks and intra-annual variability in depth and width.

The geomorphology of this section consists predominantly of fine-grained alluvial sediments—sands, loams, and silts—that are subject to severe erosion at variable flow rates. Suspended solids concentrations in this section of the river typically range from 1 to 5 kg m⁻³. The selected section reflects the transition between the relatively stable upper zone below the dam and the mobile lower zone, susceptible to

lateral migration and island formation.

These conditions make the Tashsaka intake area particularly suitable for testing the proposed numerical approach. Rapid morphometric changes, the presence of easily eroded soils, and the availability of hydrological observations at the Tuyamuyun and Tashsaka stations provide a unique opportunity

to test a data-fusion-based hydrodynamic model under realistic morphological variability.

Figure 1 presents typical field photographs of the Amu Darya River in the study area. Together, these panels reflect the spatial context of the study area and the distribution of the main morphological units.



(a) The area above the Tashsaka Channel intake.



(b) The area below the intake.



(c) The entrance to the Tashsaka intake structure itself.

Figure 1. Field photographs of the Amu Darya River channel along a 5 km stretch located 22 km downstream of the Tuyamuyun hydroelectric power station, from 3 km upstream to 2 km downstream of the Tashsaka Channel water intake.

2.2. Initial Data

The initial input datasets describing the hydrological regime of the Amu Darya River were obtained as detailed Excel tables containing daily water-level and discharge records from the Tuyamuyun and Tashsaka hydroposts for 2020 and 2021. In addition, water turbidity observations at the Tashsaka station were available for 2021 ^[19].

For the year 2024, cross-sectional channel-profile measurements were collected on 19 individual survey dates, each accompanied by simultaneous water-surface-elevation and discharge readings. These observations provided an essential foundation for reconstructing the three-dimensional morphol-

ogy of the study reach and for calibrating the hydrodynamic model.

Composite datasets for water level, discharge, and bed profiles are illustrated in **Figures 2–4**. **Figure 2** represents pointwise distributions of river levels at the Tuyamuyun gauging station for 2020, 2021 and 2024 based on measured profile data. **Figure 3** displays the corresponding discharge variations for the same years. **Figure 4** shows combined cross-sectional bottom profiles of the Amu Darya channel recorded in 2024. These datasets collectively describe the temporal evolution of hydraulic conditions and bed morphology at the upstream boundary and provide calibration constraints for the numerical model.

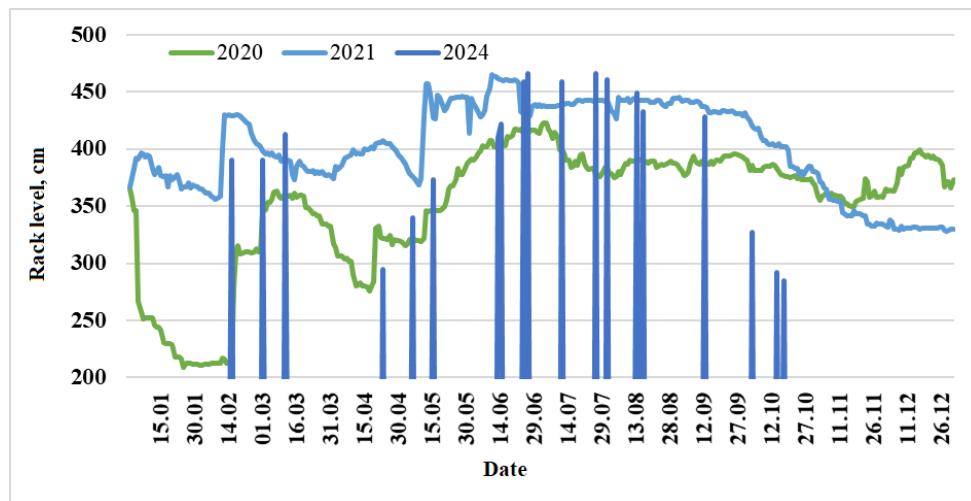


Figure 2. Combined data on the level of the Amu Darya River (according to the Tuyamuyun hydropost) for 2020, 2021, and 2024 is presented pointwise based on data from channel profile measurements.

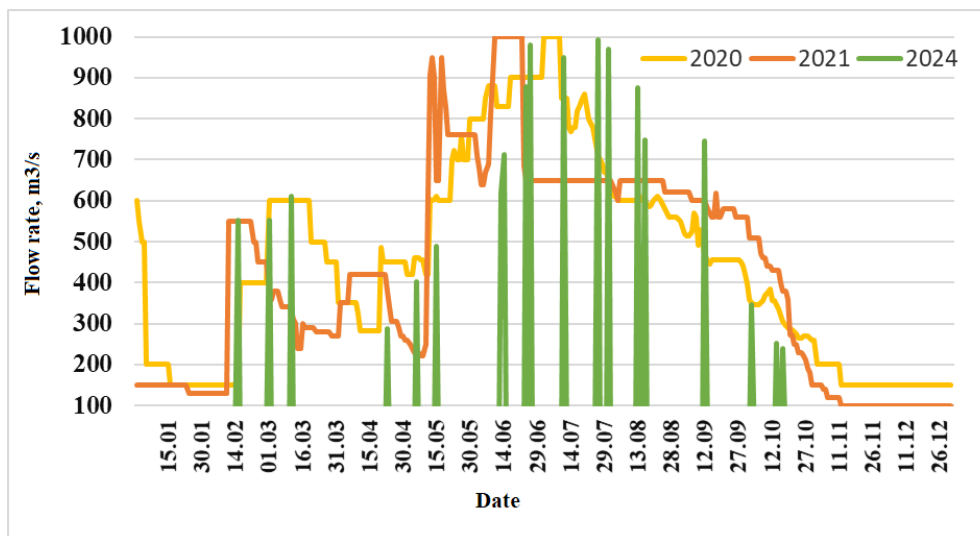


Figure 3. Combined data on the flow of the Amu Darya River (according to the Tuyamuyun hydropost) for 2020, 2021, and 2024 is presented pointwise based on data from channel profile measurements.

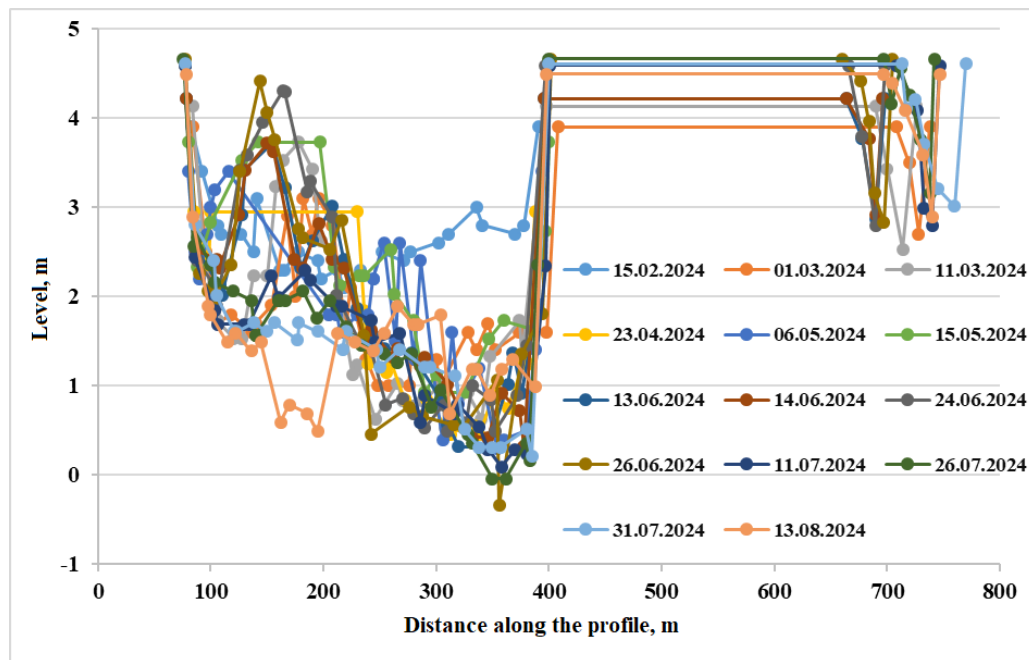


Figure 4. Combined data on the bottom profiles of the Amu Darya River channel (according to the Tuyamuyun hydropost) for 2024.

2.3. Developed Methodology and Preparation of Initial Data

To conduct hydrodynamic modeling, detailed information on the riverbed topography of the simulated reach is required. In the present case, such data were limited to measurements from two hydrometric stations (**Figures 2–4**): The Tashsaka hydropost located within the study area and the Tuyamuyun hydropost situated approximately 22 km upstream, outside the modeled reach; no additional bathymetric information was available.

The proposed approach includes 21 detailed operations, which are divided into six broader methodological steps: (i) defining the modeling domain and searching for auxiliary topographic and satellite data (steps 1–2); (ii) preparation and digitization of coastlines based on georeferenced images (steps 3–8); (iii) constructing a computational grid and aligning the digitized features to it (steps 9–11); (iv) determination of the water surface and bottom heights at reference flow rates based on the hydrometric post data (steps 12–16); and (v) preparing files, running calibration runs, and iteratively adjusting the reconstructed layer until the modeled and observed levels match within the calibration tolerance (steps 17–21). The complete sequence of actions is given below to ensure reproducibility:

1. Define the modeling boundaries and search for auxil-

iary information (3 km upstream of the Tashsaka water intake along the Amu Darya River and 2 km downstream).

2. Search for topographic data for the modeling area.
3. Analyze, select, and digitize topographic data.
4. Search for satellite images for the modeling area with survey dates for which hydrographs are available at hydroposts.
5. Select at least two multi-temporal series of images for the selected (calibration) river discharges.
6. Georeference and orthorectify the satellite images with high accuracy (approximately 5 m on the ground) for the image series.
7. Recognize the water-shore boundaries using georeferenced images and digitize the river and island shorelines.
8. Assembling digitalized information into a single space.
9. Creating a rectangular grid for the hydrodynamic model, condensing it in the area of the water intake, railway bridge, and river bends with the smallest possible grid spacing.
10. Aligning digitalized objects with each other and transferring them to the grid cells.
11. Creating bed break lines between shorelines to create a riverbed trough.
12. Determining the relationships between discharges and

water levels at the Tuyamuyun and Tashsaka hydroposts. Calculating water surface slopes in the Amu Darya River at reference discharges and determining reference level values at the model boundaries at these discharges.

13. Interpolating shoreline elevations (taking into account the water surface slope) at reference discharges into the model cells.
14. Determination of the average depth of the river; calculation of the levels of the bottom break lines for calibration flow rates.
15. Interpolate the heights of the channel break lines, taking into account the depth and slope of the water surface, into the model cells to calibrate the discharge.
16. Interpolate heights into cells with uncertain values based on the heights in adjacent cells.
17. Configure files for the calculation program, create calibration and actual hydrograph files.
18. Run calculations with calibration discharges, taking into account bed erosion and sediment deposition in the channel until the channel stabilizes.
19. Compare the specified calibration and calculated water levels.
20. Adjust the depths of bed break lines and discharges at the model output to achieve minimal discrepancies between the calculated levels and the calibration values.

21. Repeat the calibration calculations (item 18) until acceptable deviations from the calibration values are obtained.

2.4. Collection of Initial Data

The following materials were used to restore the riverbed relief:

- Topographic map (**Figure 4**). Topographic maps at a scale of 1:100,000 provide an accuracy of position of point objects of the order of 5 m, and linear and area objects of the order of 10–30 m. The map was used only to assess the general relief of the area and the position of the stability of areas that are not flooded during floods.
- Satellite imagery (**Figure 5**). To assess the terrain in the modeling area and determine the boundaries of possible river spreading, a height map obtained from SRTM-3 satellite imagery in 2012 was used. The map was taken with a resolution of 90 m on the ground and an accuracy in height from 3 to 20 m.
- Data from the measurement of the Amu Darya River cross-section (**Figure 4**).

The largest available topographic map, M 1:100,000, K-41-099 (Terrain status 1980), was found for the modeling area (**Figure 6**).

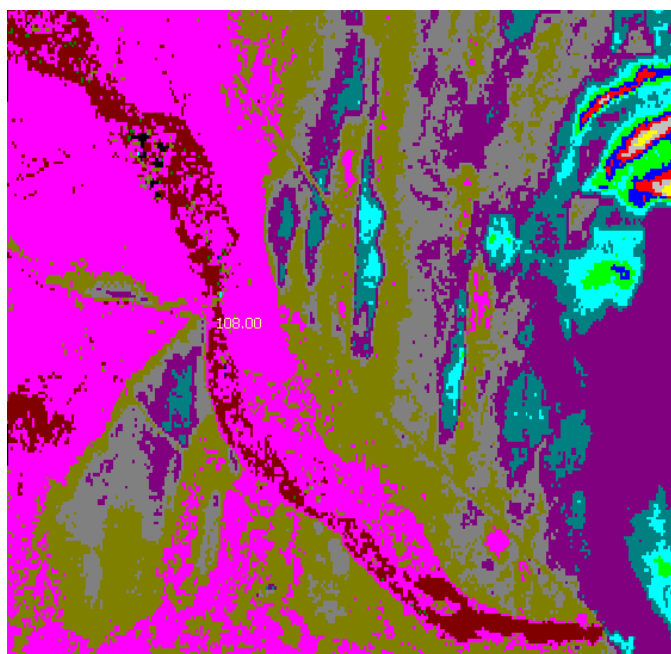


Figure 5. Fragment of satellite data (elevation maps) SRTM-3 for the calculated area of the Amu Darya River (the number 108 in the water intake area shows the approximate absolute level of the water surface in the water intake area).

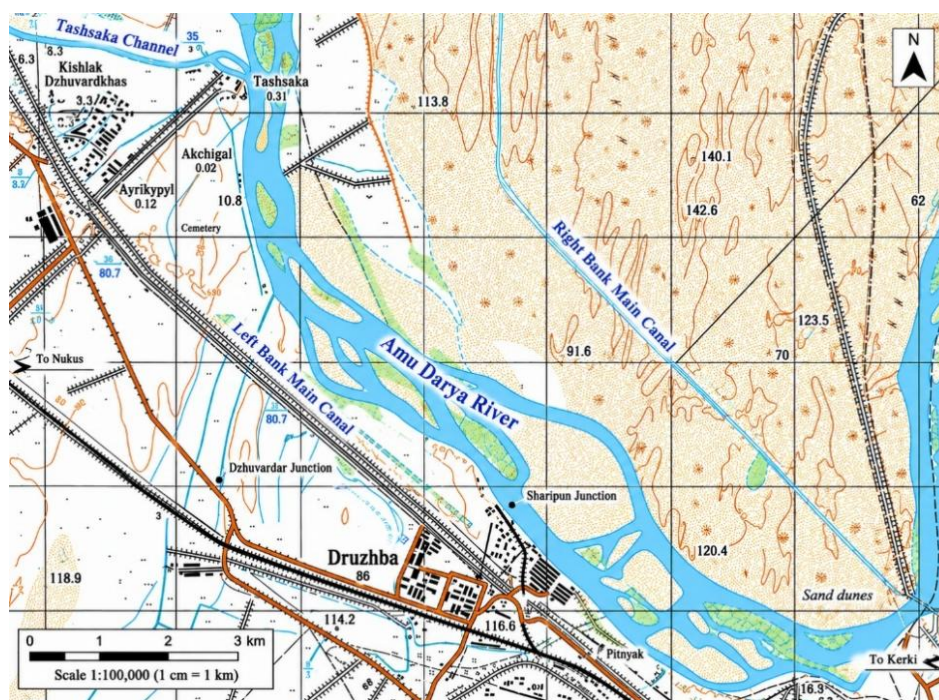


Figure 6. Fragment of topographic map K-41-099 at a scale of 1:100,000 for the modeling area.

The SAS-Planet program produces orthorectified (in the metric, not degree, system) stitched satellite images of varying detail from different periods (**Figure 7**). However,

the program does not allow for georeferencing by date, and the stitched images are used as a basis for georeferencing and orthorectifying other images.



Figure 7. Stitching of satellite, orthorectified images onto the modeling area from the SAS Planet program.

Google Earth. It allows you to view historical images of an area, take linear measurements, and plot and display routes. The program doesn't allow you to download images; you can only take screenshots and stitch them together into a single photo, but the information may become blurred where

the fragments join.

The modeling area contains images from 1985 to 2023.

We were able to find three complete terrain fragments for the modeling area from different survey years, which depict river floods at calibrated discharges (**Table 1**).

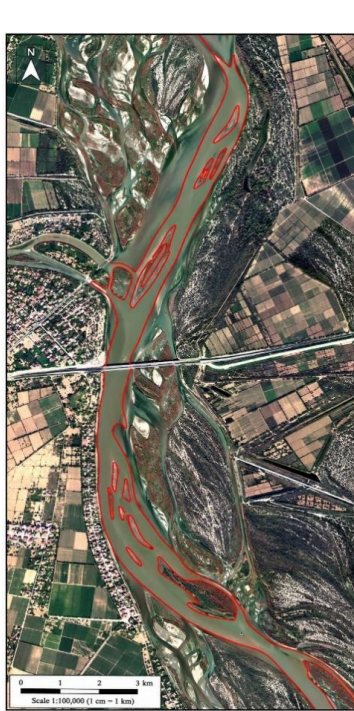
Table 1. Calibration flow rate of the river and Tashsaka channel.

Year of Survey	Month of Survey	The Nature of the River Flood	Average (Calibration) River Flow, m ³ /s	Average Flow Rate in the Tashsaka Channel, m ³ /s	Average Turbidity, kg/m ³
2021	11	Minimum	100	5	1
2021	09	Average	615	6	3.3
2019	08	Maximum	1,200*	13*	5.1*

Note: * presumably similar to 06.2021 (1,000 m³/s), but the flooding is even greater.

The photographs (**Figure 8**) show that the river has a variable riverbed and systematically flooded islands and

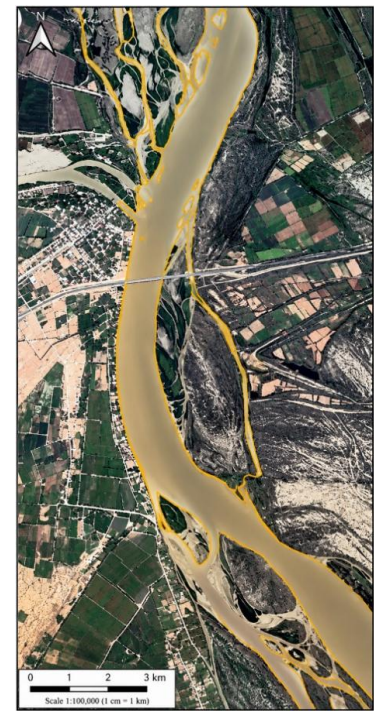
shoals, which makes it possible to identify stable areas of elevation in the riverbed.



(a) 100 m³/c.



(b) 615 m³/c.



(c) 1,200 m³/c.

Figure 8. Digitized coastlines of the river and islands on orthorectified satellite images, at calibration rates.

2.5. Equations Describing the Process and a Numerical Solution Scheme

For numerical calculations of flows with a deformable bottom, it is proposed to use the system of two-dimensional Saint-Venant partial differential equations as a mathematical model, as described in detail by Militeev^[20] and Vol'tsinger and Pyaskovskii^[21] (Equations (1)–(3)):

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad (1)$$

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x} (hu^2 + gh^2/2) + \frac{\partial(huv)}{\partial y} = gh(S_{0x} - S_{fx}) \quad (2)$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(huv)}{\partial x} + \frac{\partial}{\partial y} (hv^2 + gh^2/2) = gh(S_{0y} - S_{fy}) \quad (3)$$

Where: h is the water depth, u and v are the depth-averaged velocity components, and g is the acceleration due to gravity. The bottom friction terms S_{fx} and S_{fy} account for the effect of bottom friction. The corresponding bottom friction stress vector τ_D is collinear with the water flow velocity vector, directed in the opposite direction, and is determined by Darcy's formula:

$$\tau_D = \frac{\rho\lambda}{8}|V|V \quad (4)$$

where λ is the Darcy-Weisbach coefficient of hydraulic friction, determined by the Manning empirical formula:

$$\lambda = \frac{2gn^2}{H^{\frac{1}{3}}} \quad (5)$$

where n is the dimensional roughness coefficient. The system of equations does not include terms accounting for inter-jet friction in the planform (turbulent viscosity). However, as hydraulic numerical modeling experience has shown, incorporating convective terms in the mathematical model enables direct numerical simulation of large-scale turbulence and allows for the calculation of separated flows in channels with abrupt changes in planform shape with sufficient accuracy for practical use in solving hydraulic engineering problems. The system of differential equations is hyperbolic. The propagation velocity of small-amplitude waves for this system is:

$$c = |V| + \sqrt{gh} \quad (6)$$

To close the problem of describing a non-stationary flow in a fragment of a river channel, it is necessary to specify initial and boundary conditions. As noted by Montgomery and Buffington^[1], Krutov et al.^[2], Zhang et al.^[8], and Farisrotou et al.^[10], when calculating planned deformations, it is necessary to take into account the probability of erosion of the soil banks, including concentrated erosion, especially in cases where the channel is composed of easily eroded soils. In such situations, it is proposed to separately determine in calculations the deformations of the bottom surface associated with the difference between the actual sediment content in the water flow and the transport capacity of the flow, as well as the influence of sediments formed as a result of the deformation of the banks and slopes. The calculation of the parameters of the hydrodynamic model using the explicit calculation method occurs step by step: (1) determining the maximum possible step in the simulation time to maintain the

stability of the calculation; (2) calculation in each calculation cell of changes in the values of the initial value fields (depth, speed and turbidity of the water flow) per time step; (3) adjustment of the bottom level of the calculation cell taking into account changes in turbidity due to the influx and outflow of sediments, bottom erosion and sedimentation, slope creep; (4) when slopes slide, the bottom level of the cells adjacent to the calculated one is adjusted; (5) introduction of changes to the initial values; (6) cyclic repetition, starting from step 1, until the calculation time limit is reached. Change in the bottom level of the calculation cell:

$$\frac{\Delta z_{d,x,y}}{\Delta t} = \frac{M_{act} - M_{max} - M_{slid}}{\rho_s dx dy (1-P)} \quad (7)$$

where M_{act} is the mass of the actual sediment content in the water flow; M_{max} is the mass corresponding to the maximum transport capacity of the water flow; M_{slid} is the mass of sliding into adjacent cells during slope deformation in the calculation cell; ρ_s is the bulk density of the soil; dx and dy are the linear dimensions of the cell; P is the soil porosity coefficient. The mass of the actual sediment content in the calculation cell changes when part of the sediment enters or leaves the cell with water into adjacent cells and increases or decreases during slope sliding:

$$\frac{\Delta M_{act}}{\Delta t} = \sum_{i=1}^4 S_i W_i + M_{trans} \quad (8)$$

where S_i and W_i are the sediment concentration and the flow of water volume from cells adjacent to the calculated one, for one calculation step, respectively; M_{trans} is part of the soil mass that turns into transported sediment due to slope sliding. Maximum transported mass of sediment by water flow in a calculation cell:

$$M_{max} = S_{max} \rho_s dx dy H \quad (9)$$

where S_{max} is the maximum flow saturation concentration of sediments; dx , dy are the linear dimensions of the cell, and H is the water depth in the calculation cell. To calculate the flow saturation concentration (the maximum volume concentration that the flow can transport) in the calculation cell, the Bagnold formula is used^[22]:

$$\alpha \frac{\rho}{(\rho_s - \rho_w)} \frac{\lambda V^2}{2g} \left(\frac{0.13}{tg(\varphi) - I_{max,x,y}} + \frac{0.01V}{w} \right) \quad (10)$$

Here α is the empirical coefficient of intensity of sediment exchange between the bottom and the flow; ρ_s and ρ_w are the bulk density of soil and water, respectively; g is the

acceleration due to gravity; λ is the coefficient of hydraulic friction from Equation (5); V is the velocity modulus:

$$V = \sqrt{V_x^2 + V_y^2} \quad (11)$$

Here V_x and V_y are the water velocities in the cell along the X and Y axes, respectively; H is the flow depth; $tg(\varphi)$ is the tangent of the internal friction angle of the soil; w is the weighted average hydraulic size of the soil; n is the roughness coefficient; $I_{max,x,y}$ is the maximum slope of the bottom of the computational cell relative to the neighboring ones:

$$I_{max,x,y} = \max(I_{x-1,y}; I_{x+1,y}; I_{x,y-1}; I_{x,y+1}); \quad (12)$$

here the slopes to adjacent cells of the computational grid are determined by the formulas:

$$I_{x\pm 1,y} \left\{ \begin{array}{l} \frac{(Z_{d,x,y} - Z_{d,x\pm 1,y})}{(d_x + d_{x\pm 1})/2}, \text{ as } Z_{d,x,y} > Z_{d,x\pm 1,y} \\ \text{otherwise, it is not used (the bottom} \\ \text{of the adjacent cell is higher)} \end{array} \right\} \quad (13a)$$

$$I_{x,y\pm 1} \left\{ \begin{array}{l} \frac{(Z_{d,x,y} - Z_{d,x,y\pm 1})}{(d_y + d_{y\pm 1})/2}, \text{ as } Z_{d,x,y} > Z_{d,x,y\pm 1} \\ \text{otherwise, it is not used (the bottom} \\ \text{of the adjacent cell is higher)} \end{array} \right\} \quad (13b)$$

where Z_d is the cell bottom elevation. A similar proposal to use the bottom slope in the calculation cell instead of the flow bottom slope was formulated by Bailard^[23]. The introduction of local slopes allows calculations to be performed for both flooded and coastal (partially dry) cells and, thus, to take into account the action of rolling forces on particles located on underwater slopes. When calculating the mass sliding, the hypothesis of a limiting stable slope is used; the calculation is performed in coastal, dry cells that have one or more (up to 4) adjacent cells with a non-zero depth. If there is a difference between the bottom elevation in the calculation cell and the bottom of the adjacent (wet) cell and this difference exceeds the height of the stable slope, then the soil pyramid slides towards the adjacent cell. The excess of the bottom of the calculation cell over the bottom of each of the four adjacent cells:

$$\sum_{i=1}^4 \Delta Z^*_{x,y,i} = Z_{d,x,y} - Z_{d,x\pm 1,y\pm 1} \quad (14)$$

If this value is ≤ 0 , then the creep calculation for that side is not performed. If the slope height is greater than the

maximum stable slope height on that side, the slope creeps to the stable slope height. The volume of soil subject to creep is calculated using the formula:

$$W_i = d_x d_y (\Delta Z^*_{x,y,i} - H_{max,i} (1 - \frac{d_x}{3(d_x + d_{x+1})})) \quad (15)$$

where ΔZ^* is the height of the bottom of the calculation cell above the adjacent cell; $H_{max,i}$ is the maximum height of the stable slope toward the same adjacent cell. The mass of the sliding pyramid (from the center of the calculation cell) along each of the adjacent sides of the calculation cell is determined as:

$$M_{pyr,i} = \beta t \rho_s W_i \quad (16)$$

Here β is an empirical coefficient; t is the simulation step time. The maximum height of a stable slope:

$$H_{max,i} = a \varepsilon_i + R_i tg(\varphi) \quad (17)$$

here R_i is the distance between the centers of the calculated and the corresponding neighboring cell; a is the auxiliary coefficient:

$$a = \frac{2c(1 + \sin(\varphi))}{\gamma(1 - \sin(\varphi))} \quad (18)$$

where c is the cohesion of water-saturated soil, t/m²; γ is the bulk density of water-saturated soil, t/m³; φ is the angle of internal friction of the soil, deg.; ε_i is the relative coordinate of the center of the adjacent cell:

$$\varepsilon_i = \left(\frac{\pi}{2} - 1\right) \cdot e^{C_i}; \quad (19)$$

$$C_i = \frac{R_i}{a} \quad (20)$$

Here, i is the serial number of the adjacent cell (from 1 to 4). In the proposed scheme, calculations are based on the weighted average soil size, so we assume that the portion of sediment larger than the weighted average will slide into adjacent cells, while the remainder will remain in the cell as transported sediment.

Initial and boundary conditions. The initial conditions include the initial bed elevation, $(Z_d(x, y, 0))$, the corresponding instantaneous velocity fields $V(x, y, 0)$, water depth, $(H(x, y, 0))$, and sediment concentration, $S(x, y, 0)$. At solid boundaries, a no-flow (impermeable) boundary condition is imposed. At open boundaries, either the flow rate or the water level is specified. At inflow boundaries, the concentration of sediment is specified.

2.6. Uncertainty and Validation Strategy

The agreement of ± 5 cm between the simulated and observed water levels, discussed in section 3.3 for the calibration discharges is an internal and self-consistency check. In addition, similar 2021 stage–discharge connections were used for reconstructing the terrain and judging conformity of the model with it. Therefore, it is expected to obtain a close equivalent by construction, demonstrating predicative skill for discharges outside the calibration set.

First, an extra indication of the agreement between the observed and calculated stage–discharge relationships is obtained through the logarithmic regression curves. The determination coefficients of these regressions fluctuate from $R^2 = 0.90$ to $R^2 = 0.92$ for the Tuyamuyun and Tashsaka hydroposts in 2021, while an $R^2 = 0.90$ was acquired for the 2020 channel rating curve. The values discussed prove that the logarithmic functions satisfactorily describe the observed stage–discharge relationships for each individual year. Yet, the determination coefficient should not be considered a replacement for performance indicators such as the Nash–Sutcliffe efficiency (NSE) or the root-mean-square error (RMSE), which are usually evaluated by an independent validation dataset. For this reason, the reported R^2 values are presented only as additional evidence, together with the ± 5 cm accuracy, in accordance with the general recommendations for model performance assessment given by Nash and Sutcliffe^[24], Moriasi et al.^[25], and Melsen et al.^[26].

In addition, the 2020 dataset was not suitable as a reference period, since the stage–discharge relationship at the Tuyamuyun hydropost demonstrate two distinct branches under low-flow conditions. This behavior is attributed to channel bed aggradation caused by the August 2019 flood (**Table 1**; **Figure 8c**). As a result, using the 2020 rating curve as a calibration reference might have introduced additional uncertainty caused by seasonal changes in the stage–discharge relationship. Consequently, the 2021 dataset was selected as the reference period, representing more stable hydraulic conditions. The cross-sectional survey of 2024 was used only for qualitative verification and demonstrated reasonable agreement with the 2021 rating curve at high discharges (Section 3.2). This limitation is due to the availability of long-term monitoring data for the Amu Darya River, which are not relevant to the proposed methodology, and it is explicitly stated to clarify the rationale for the approach adopted.

For the $100 \text{ m}^3/\text{s}$ discharge case, the simulation time of 333 h (Section 3.3.1) was selected due to the fact it corresponded to the midpoint of the period with the minimum water-level deviation. was selected due to the fact it corresponded to the midpoint of the period with the minimum water-level deviation. However, the water levels were used for assessing convergence, while the stabilization of sediment transport and bed deformation was not evaluated separately. Consequently, stable water levels do not indicate that erosion and deposition processes had reached equilibrium. In future studies, the convergence criterion could be improved by including an additional indicator based on bed-level changes, such as a specified maximum scour or deposition depth maintained below a predefined threshold over a defined number of successive simulation hours. Such an approach would provide a more reliable assessment of model convergence and is compatible with the recommendations of previous studies on the calibration and uncertainty analysis of two-dimensional sediment-transport models^[27,28].

Fourth, an additional source of ambiguity is associated with the remote-sensing data used in the study. The shoreline was digitized from SAS-Planet image mosaics, which was compiled from historical satellite imagery of different and unspecified sensors, with an estimated georeferencing accuracy of approximately 5 m (Section 2.3, Step 6). The surrounding floodplain topography was obtained using SRTM-3 elevation data, which have a reported vertical accuracy of approximately 3–20 m (Section 2.4). Based on the estimated horizontal accuracy of the satellite imagery, the uncertainty in the extracted shoreline position at the calibration discharges (**Table 1**) is expected to be of a similar magnitude. Considering the computational grid used in the study (195×141 cells over a 5 km river section), this uncertainty is only a small fraction of the grid cell size. It should be noted, however, that this estimate is intended to indicate an order of magnitude of uncertainty and does not represent a rigorous analysis of error propagation. A more detailed assessment of remote-sensing uncertainty, including pixel-level error analysis as reported in recent studies of data-scarce river systems^[29], should be considered in future investigations. In addition, the satellite image acquired during the August 2019 flood (**Table 1**) was not clear enough due to high water turbidity, which may have reduced the accuracy of shoreline determination under flood conditions.

Overall, the obtained ± 5 cm agreement indicates that the reconstructed river-bed geometry together with the calibrated hydraulic roughness and sediment-transport parameters provide a consistent representation of the 2021 hydro-metric observations. Nonetheless, this result should not be interpreted as confirmation that the model is equally applicable under conditions outside the available observation period. A more rigorous validation, such as a leave-one-out approach in which the bed geometry is reconstructed using part of the available discharge records and verified against the remaining observations, should be carried out when additional simultaneous measurements of water level, discharge, and channel cross-sections become available. This remains an important direction for future research.

3. Results and Discussions

3.1. Building a Model

The digitized data were combined, the boundaries of the model were determined, and a rectangular non-uniform computational grid with dimensions of 195×141 cells was constructed (**Figure 9**).

The coastlines are coordinated with each other and tied to the centers of the calculation cells, and the bottom break lines are drawn (**Figure 10**).

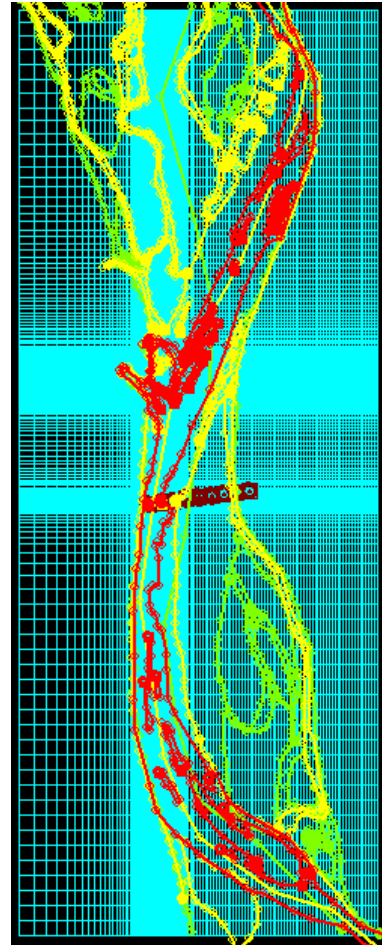


Figure 9. Combined coastlines at selected flow rates against the background of the calculated grid.

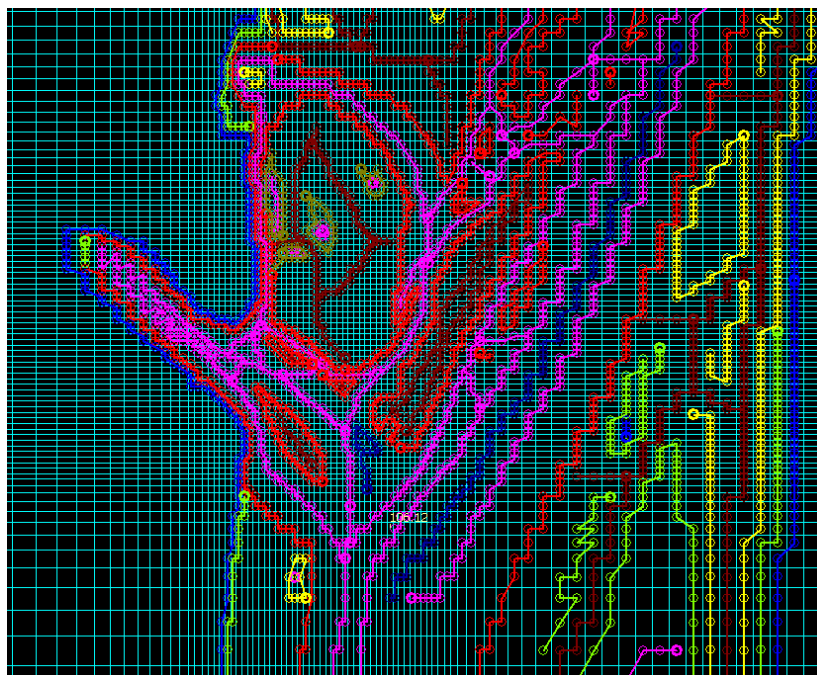


Figure 10. Agreed coastal and bottom fracture lines on the computational grid.

3.2. Calculation of Levels at the Boundaries of the Model

Based on water level and discharge data collected in 2021, a statistical analysis was performed to establish a mathematical relationship (trend) between the water levels observed at the Tuyamuyun and Tash-Saka hydrometric stations

and the discharge of the Amu Darya River (Figure 11).

Based on the data for 2020 and 2024, as well as the trends of the 2021 dependencies (Figure 11), graphs of the dependence of the water level at the Tuyamuyun (river) and Tashsaka (channel) hydroposts on the flow rates were constructed (Figures 12 and 13).

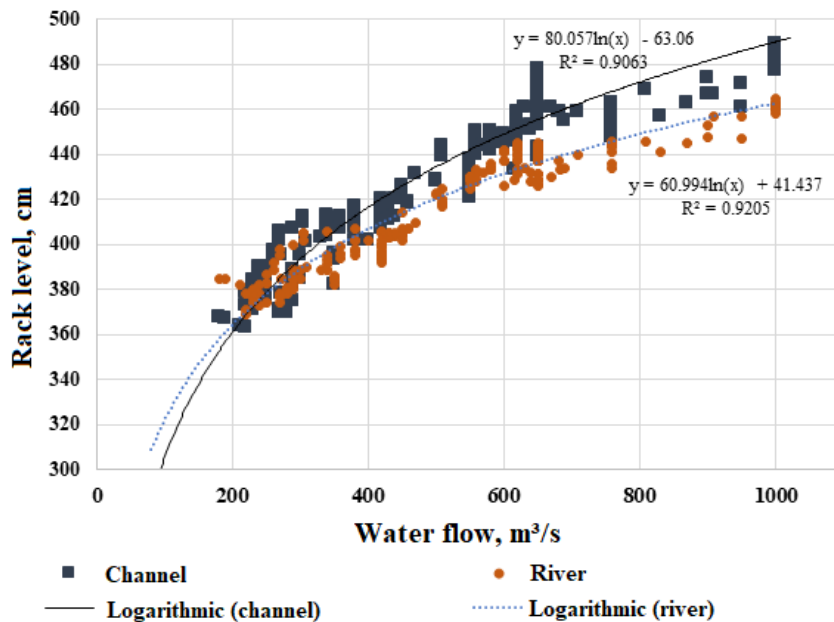


Figure 11. Trends in the dependence of water levels at the Tuyamuyun (river) and Tashsaka (channel) hydroposts on flow rates in 2021.

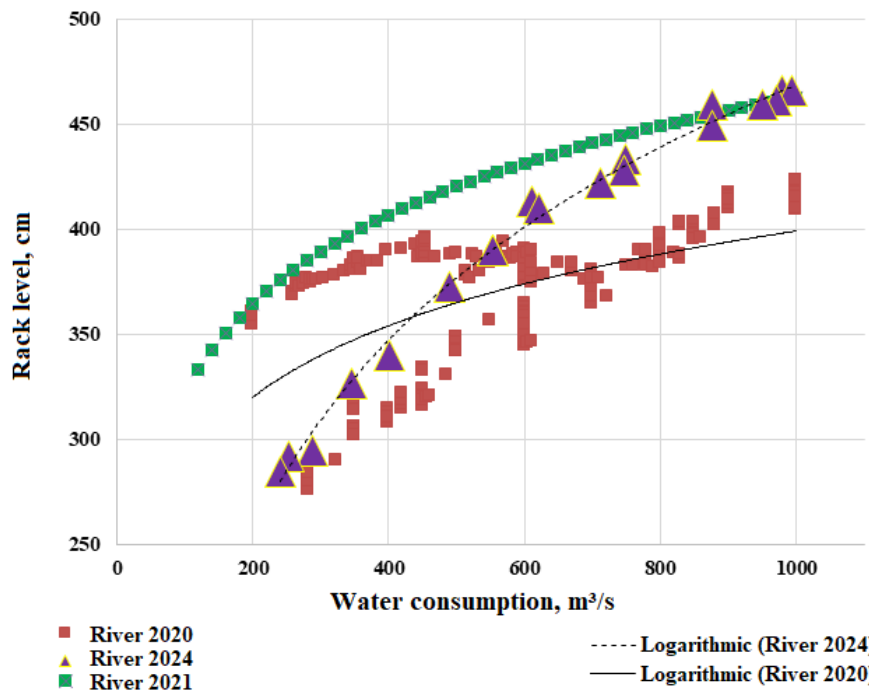


Figure 12. Trends in the dependence of the water level at the Tuyamuyun (River) hydropost on discharges in 2020, 2021 and 2024. The year 2021 is shown by the trend (Figure 11).

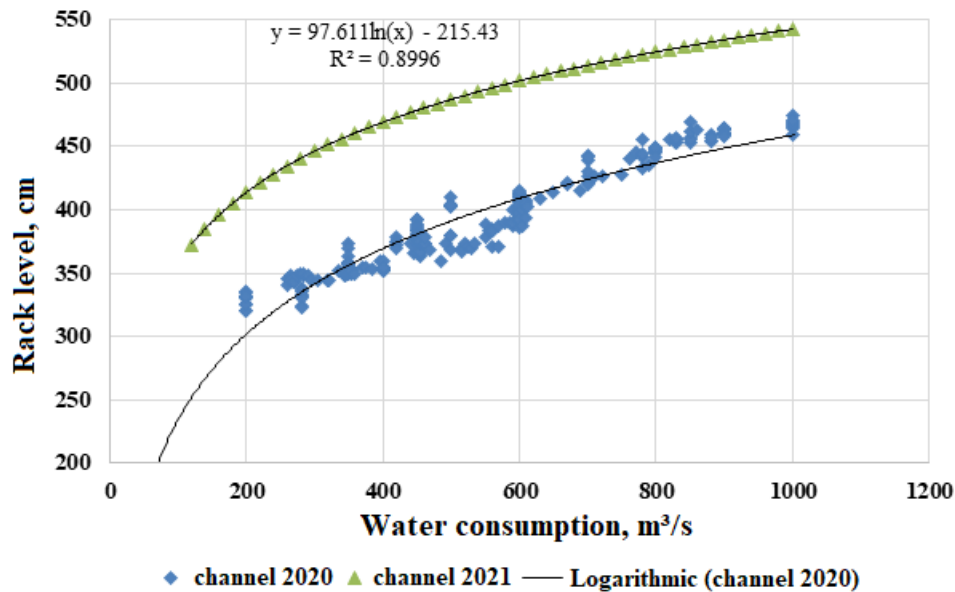


Figure 13. Trend of water level dependence at the Tashsaka hydropost (channel) on flow rates in 2020 and 2021. 2021 is shown by the trend (Figure 11).

An analysis of the trends in the relationship between water levels at the Tuyamuyun water station and discharge (Figure 12) shows that in 2020, this relationship had two distinct branches: a spring (lower) branch and a fall-winter (upper) branch. The branch in the low-discharge region (at the end of 2020) intersects with similar discharges at the beginning of 2021, indicating sufficient accuracy of the initial data.

The splitting of the data grouping into two branches at low discharges in 2020 suggests a high discharge with high turbidity in the previous year (2019) (confirmed by the major flood of the Amu Darya River in Figure 8c), which led to a rise in the water level and bed surface by 0.3–1.2 m (according to data at the Tuyamuyun and Tashsaka hydroposts). This instability makes it impossible to use the 2020 data for calculations.

The selection of 2021 data as the basis for modeling is supported by partial 2024 observations, which show good agreement with the 2021 data in the high-discharge range.

Water level measurements at the gauging stations are recorded in centimeters relative to the gauge zero. To obtain absolute elevations, as required for the modeling software, the gauge zero reference must be added to these values (Table 2)^[1].

Based on the recalculated dependencies (Figure 14), the height values for shorelines (Figure 8) at the calibration discharges (Table 1) were entered into the cell centers, taking into account the slopes.

Based on the measured channel bottom profiles (Figure 4), the average depths for the calibration discharges (Table 3) were calculated. These values for the bed break line (Figure 10) were also entered into the calculation cells.

The remaining unfilled cells of the calculation model were filled with values using planned interpolation based on the elevations of adjacent cells. After this, the bottom elevation field for the modeled area took the form (Figure 15).

Table 2. River sections Amu Darya.

Location, Hydropost Title	Distance from the Mouth, km	Hydropost Zero-Mark, Height in m	Validity Period: Day, Month, Year
Tuyamuyun Gorge	475	107.08	16.07.1924 (05.10.1979)
Tashsaka channel	467	105.23	10.06.1912 (17.04.1993)

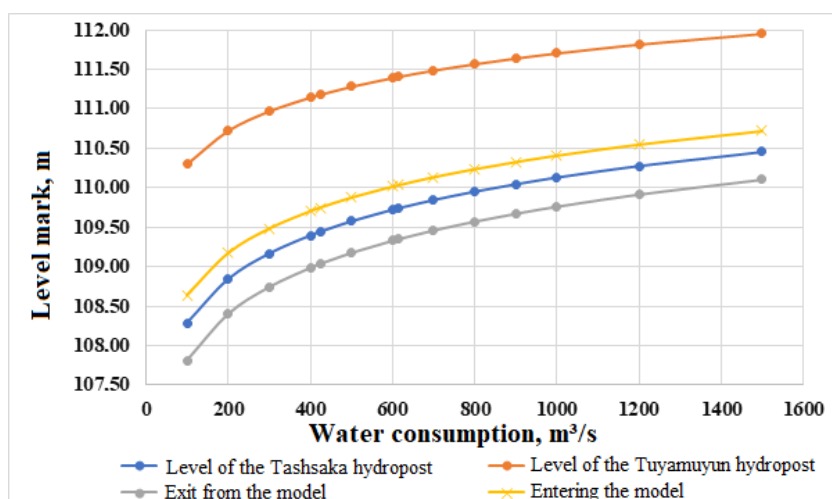


Figure 14. Dependence of water level on flow rate, recalculated based on trend dependencies of the Amu Darya flow in 2021 into absolute elevation marks.

Table 3. Data for calibrating the relief of the Amu Darya River.

Calibration Flow Rate, m ³ /s	Average Current Depth, m	Level at the Entrance to the Model, m	The Water Level at the Tashsaka Channel Water Intake
100	2.5	108.64	108.29
615	3.73	110.01	109.72
1,200	4.22	110.56	110.28

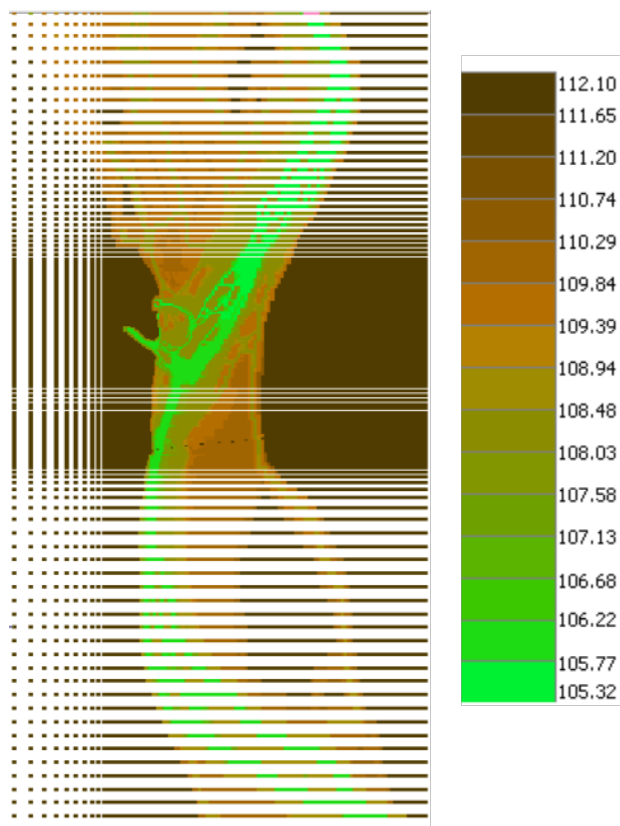


Figure 15. Reconstructed relief of the Amu Darya river bed with a height scale.

3.3. Calibration Calculations

Calibration at a Flow Rate of 100 m³/s

A hydrodynamic river flow simulation program was run on the constructed relief with a constant calibrated flow rate of 100 m³/s (Tables 1 and 3) and a regime of erosion and

sediment transport. This resulted in self-correction (“flushing”) of the relief during flow stabilization. The water level trend is shown in Figure 16. The calculation was restarted several times, adjusting the water level at the outlet section of the model until the Channel intake level was as close as possible to the calibrated value (Table 3).

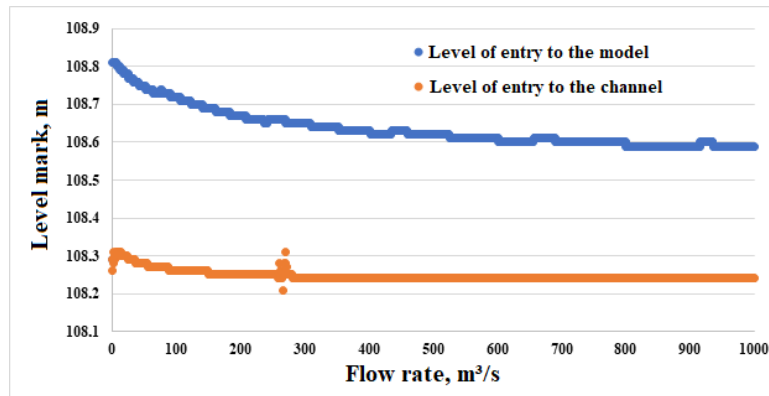


Figure 16. The course of water levels at the entrance to the model and the entrance to the channel at a calibrated water flow rate of 100 m³/s.

The graphs (Figure 16) show that, starting at 300 h of calculations (approximately 12 days of water flow), the channel level stabilizes while the level at the model inlet continues to fall. This indicates insufficient turbidity at the model inlet to stabilize the flow and continued erosion of the inlet section.

Therefore, to determine the moment of flow stabiliza-

tion, a graph of absolute deviations from the calibrated water level values was plotted (Table 3, Figure 17).

From Figure 17, the midpoint of the long-term minimum (5 cm) of deviations is taken at 333 h of modeling.

Figure 18 shows the similarity between the depth map based on the modeling results for this time and the original satellite image (Figure 18a) at the same water flow rate.

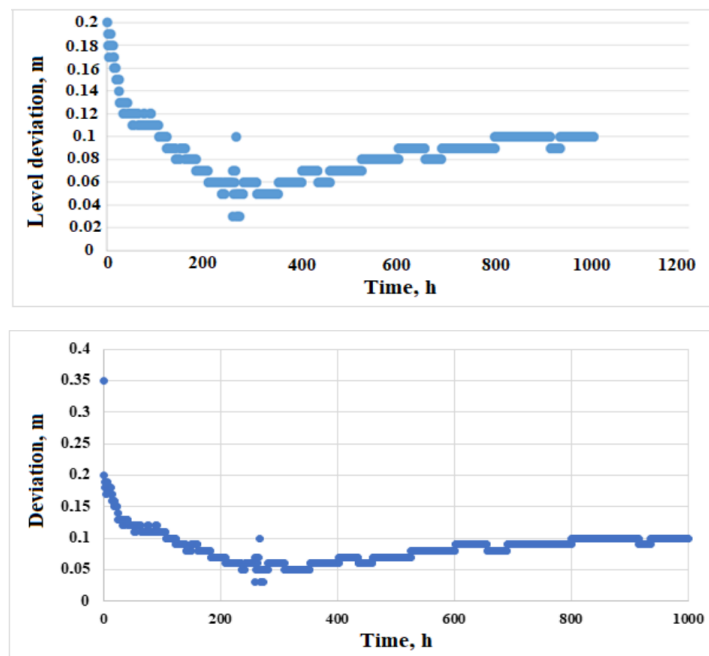


Figure 17. Dependence of the total deviation on the calibration values for the level at a flow rate of 100 m³/s.

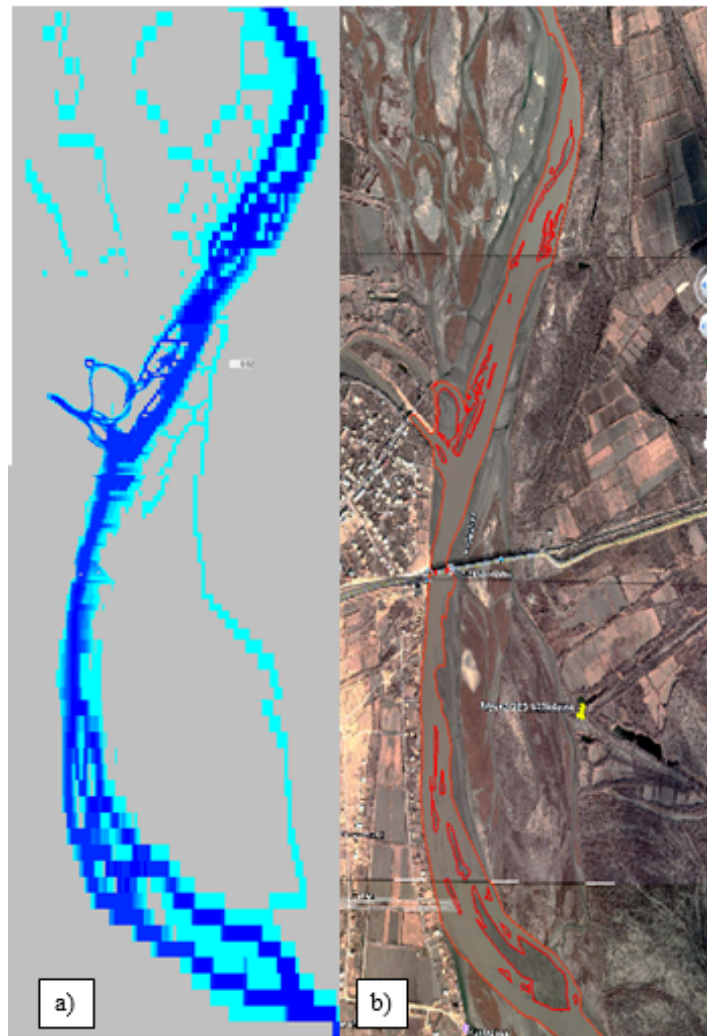


Figure 18. Comparison of flood boundaries at a calibration flow rate of $100 \text{ m}^3/\text{s}$: (a) depth map for 333 h from the hydrodynamic model; (b) coastlines in a satellite image from 11.2021.

This bottom condition is recorded as the basis for starting the calculation at the next calibration flow rate. All the steps described above are used until the calibration is completed at all selected flow rates.

3.4. Why the Approach Works, Where It Is Likely to Fail, and How It Compares with Other Methods

The proposed workflow yielded satisfactory results under the conditions of this study for several reasons. First, the presence of two gauging stations located upstream and downstream of the study area provided continuous water level and discharge observations, which could be used to determine hydraulic conditions in the computational domain. Second, satellite images obtained under various discharge conditions

(Table 1) allowed us to determine the shoreline position over a range of flow levels, enabling a more reliable reconstruction of channel geometry than would have been possible from a single image. Third, the erosion-deposition module (Section 2.5) allowed the initially interpolated channel topography to evolve to a hydraulically and morphologically consistent state under specified flow conditions and calibrated sediment transport parameters.

The applicability of the approach may be limited if the specified conditions are not met. For example, reduced reliability is expected in river reaches where only a single hydrological measuring station operates, satellite observations are limited, or sediment transport is negligible. As a result, channel evolution modeling cannot effectively compensate for uncertainties in the initial channel geometry. Other limitations may arise in rivers with coarse-grained or highly

heterogeneous channel material, where the sediment transport equation^[22] and the assumption of a single representative grain size may not fully capture transport processes. Similarly, for gravel-bedded rivers, rock-controlled channels, or reaches strongly influenced by channel stabilization or vegetation, alternative formulas for sediment transport and hydraulic resistance may be required.

Compared with fully three-dimensional or multi-fraction sediment-transport models such as CCHE2D^[9,10] or the shallow-water modeling approach presented by Costabile et al.^[11], the proposed methodology adopts several assumptions. It is based on a depth-averaged formulation, uses a single representative grain size, and does not account for in-plane turbulent viscosity. These simplifications reduce both the data requirements and the computational effort, which is important for river reaches such as the present study area, where systematic bathymetric surveys are not available. Under these conditions, the approach provides a practical solution for reconstructing channel-bed geometry and simulating hydraulic and sediment-transport processes with the available information. In this respect, the main contribution of the present study is closer to recent data-fusion and remote-sensing-based river reconstruction methods, which were developed for data-scarce or difficult-to-survey environments^[29] than to the development of a new hydrodynamic solver, as already stated in Section 1.

The proposed methodology is expected to be applicable to other regulated alluvial rivers with significant sediment transport, provided certain conditions are met. These include the presence of at least two hydrological stations located upstream and downstream of the study area, multi-temporal satellite imagery obtained under varying discharge conditions, and channel material that can be accurately represented by a single characteristic grain size. However, the applicability of the method may be limited in braided or rapidly changing channels, tidal reaches of rivers, or rivers with highly heterogeneous sediment composition. In such cases, modification of one or more of the sediment transport equations and hydraulic parameters described in Section 2.5 will be necessary.

3.5. Ecological Implications

Despite the fact that this study mainly focuses on hydraulic engineering and riverbed processes, the obtained

morphometric and hydrodynamic results are of great importance for the environmental conditions of the study area. Topography of the area, current velocity, sediment concentration and transport patterns can influence the distribution of aquatic habitats, including pools, riffles, sandbars, and channel banks, as well as the composition of bottom material that supports benthic organisms and fish spawning. These factors also influence the exchange of water and fine sediments between the different parts of main channel and its surroundings (Section 2.1; **Figures 1 and 8**). In addition, increased amount of sediments and water turbidity in the Tuyamuyun Reservoir (Section 1) is recognized as one of the environmental impacts in regulated alluvial rivers. The reconstructed channel topography and the calibrated numerical model developed in this study can be utilized to assess the impact of the timing and scale of such sediment discharges on channel morphology and hydraulic conditions near the Tashsaka intake. Previous studies have indicated that changes in flow and sediment regimes affect riverine habitats and ecological processes^[8,30]. A comprehensive ecological assessment would require hydraulic modeling combined with biological observations or habitat data, which were not available for the present study. Therefore, this aspect is considered as a subject for future scientific research in the sphere of environment. If engineering measures such as dredging, bank protection, or intake structure modification are planned and implemented the future, their design should be assessed not only from a hydraulic perspective but also in terms of habitat conservation and sediment continuity, in line with current river restoration practice^[30].

4. Conclusions

1. The riverbed relief reconstructed using the proposed method can serve as a reliable basis for hydrodynamic calculations with real hydrographs and for assessing the impact of riverbed engineering or adjustment works.
2. In cases where observational data are limited or of low reliability, the method provides satisfactory estimates of the riverbed's morphometric characteristics.
3. A key requirement for applying this method is the availability of contemporaneous satellite imagery, along with water level and discharge data collected during the same survey period.

4. The calibration agreement within ± 5 cm indicates that the reconstructed riverbed corresponds to the 2021 hydrometric measurements. However, this reflects internal consistency rather than independent validation of the model. Future studies are recommended to validate the model using independent datasets, including data from a different observation year, or by applying the leave-one-out validation method for different flow conditions when such data become available.
5. Clearly, riverbed morphology and sediment transport have a strong influence on aquatic habitats. The reconstructed riverbed geometry and calibrated model obtained in this study can also be used for a preliminary assessment of environmental conditions in the Tashsaka catchment area. It is recommended that future studies integrate these results with biological and habitat data to conduct a comprehensive environmental assessment.
6. Future research should also evaluate the uncertainty connected with shoreline extraction from remote sensing, SRTM elevation data, and the stage–discharge relationship used in the riverbed reconstruction. When independent validation data are available, the model performance is recommended to be assessed using standard statistical indicators such as RMSE, NSE, and R^2 .

Author Contributions

Conceptualization, O.V. and D.B.; methodology, O.V., D.B. and A.K.; software, O.V. and V.K.; validation, A.K., I.S. and A.B.; formal analysis, O.V., V.K. and I.S.; investigation, O.V., A.M. and S.S.; data curation, A.M. and S.S.; writing—original draft preparation, O.V.; writing—review and editing, D.B., A.K., V.K., I.S., A.M., S.S. and A.B.; visualization, O.V., A.M. and S.S.; supervision, D.B. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable. This study did not involve human participants.

Data Availability Statement

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

In preparing this manuscript, the authors used a large-scale language model (Claude, Anthropic) solely for English language improvement and text editing. No artificial intelligence tools were used for data analysis, numerical modeling, results interpretation, or preparation of the scientific content and conclusions. All figures, tables, equations, and numerical results are the result of the authors' fieldwork, project reports, and calculations. The AI-edited text was carefully reviewed and revised by the authors. The authors bear full responsibility for the accuracy, originality, and integrity of the manuscript.

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