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Sensitivity Analysis of Hydrodynamic and Sediment Parameters Affecting Bed Morphology in Tidal Environments, and Potential Application on Soil

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ABSTRACT

Comprehending sediment transport dynamics is crucial for forecasting morphological changes in aquatic and terrestrial ecosystems, especially where hydrodynamic factors like tides or surface runoff markedly affect sediment redistribution. This research employs a one-dimensional (1D) numerical model that integrates the Saint-Venant shallow water equations with sediment transport equations, using the Exner equation for bed evolution and the advection-diffusion equation for suspended load. Bedload transport is characterized by the Grass equation, which models sediment flux as a function of depth-averaged velocity and an empirical coefficient (A_g) that incorporates a combined effects of many physical properties on sediment transport. Simulations were performed over diverse tidal ranges, durations, Grass coefficient, and bed friction coefficients (C_f) to evaluate their singular impacts on sediment dynamics. Results indicated that prolonged simulation durations and heightened tidal amplitudes exacerbated sediment redistribution and bedform flattening, signifying cumulative morphological changes over time. Elevated Grass coefficient and friction coefficient values substantially impacted bed stability, with high A_g values promoting sediment mobility and high C_f acting as a regulator of shear stress and reduce erosion intensity. Sensitivity analysis indicated that A_g is the most significant parameter influencing morphological change. These findings hold significant significance for agricultural soil erosion research, as analogous mechanisms of sediment displacement regulate both natural and managed systems. The coefficients for Grass and friction can be modified to reflect surface conditions, including vegetation cover and tillage methods on agricultural lands. This underscores the potential for interdisciplinary application of hydrodynamic sediment models to guide erosion control measures and sustainable land use planning. The study recommends extending the model to study and facilitating its practical application in erosion monitoring and agricultural management systems.

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1. Introduction

Soil erosion and sediment movement are dynamic natural processes that profoundly affect the shape of terrestrial and aquatic ecosystems. These activities are especially vital in agricultural settings, where the movement of surface materials can diminish soil fertility, hinder crop output, and result in environmental deterioration in downstream ecosystems. Comprehending the mechanisms that regulate sediment transport is crucial for sustainable management of land and water resources, particularly in places vulnerable to erosion influenced by hydrodynamic forces like rainfall runoff or tidal currents.

In recent years, numerical simulations have emerged as potent instruments for examining sediment transport by controlling parameter fluctuations [1]. These models provide a comprehensive examination of the impact of environmental and surface conditions on bedform alterations. Factors including vegetation cover, surface roughness, water flow intensity, and exposure time can now be methodically examined to enhance comprehension of their impacts on sediment stability and transport of sediment. Models facilitate sensitivity analysis, aiding in the identification of the most significant variables in intricate erosion systems [2].

Key parameters in sediment transport modelling include the Grass coefficient (A_g) [3], indicating the combined impacts of vegetation density and soil cohesion, and the bed friction coefficient (C_f) [4], representing the surface roughness of the sediment bed. These parameters are particularly essential in modelling soil erosion situations, as they reflect actual factors such as land cover type, conservation strategies, and soil texture. Moreover, extrinsic factors such as tidal range [5], precipitation intensity, and the duration of water exposure substantially influence sediment displacement rates. Long-term simulations might thus include cumulative impacts that short-term field observations might overlook.

While sediment transport modelling has been extensively utilized in coastal and riverine systems [6], its application in agricultural erosion research is yet little investigated. Considering the analogous mechanisms between coastal sediment displacement and soil erosion in agricultural lands—both influenced by hydrodynamic energy and surface characteristics—there exists significant potential to adapt sediment transport simulations for agricultural research. This methodology would facilitate the creation of predictive instruments and management techniques designed to mitigate soil deterioration and promote land sustainability.

This study aims to examine the sensitivity of sediment transport parameters and discuss the parameters analogy in modelling soil erosion processes. The two specific objectives are: (1) to assess the sensitivity of parameters as in the simulation duration, tidal range, bed friction coefficient, and Grass coefficient on sediment transport and morphological alterations via numerical modelling; and (2) to discuss the potential adaptation of these parameters for use in soil erosion research within agricultural settings.

2. Methodology

2.1 Governing Equation for Hydrodynamic and Sediment Transport

In this study, a one-dimensional (1D) coupled hydrodynamic and sediment transport model is implemented to simulate shallow water flow and the associated sediment dynamics. The governing equations consist of the Saint-Venant shallow water equations (SWEs), which include the water continuity and momentum equations, coupled with the Exner equation for bed evolution and a transport equation for suspended sediment concentration.

The conservation of mass for the water column is described by the continuity equation [7],

$$\frac{dh}{dt}+\frac{d(hu)}{dx}=0 \tag{1}$$

where h is the water depth (m), u is the depth-averaged velocity (m/s), t is time (s), and x is spatial coordinate (m).

The momentum balance in the flow is governed by Simpson and Castelltort [8],

$$\frac{d(hu)}{dt}+\frac{d}{dx}(hu^2+\frac{1}{2}gh^2)=-gh\frac{dz_b}{dx}-C_f u\,|\,u\,| \tag{2}$$

where g is gravitational acceleration (m/s^2), z_b is the bed elevation (m), and C_f is the friction coefficient (s^2/m). The friction term accounts for the resistance exerted by the channel bed on the flow.

Sediment transport is modelled using two primary equations. First, the bed evolution due to sediment transport is governed by the Exner equation [9],

$$\frac{dz_b}{dt}+\frac{1}{1-\lambda}\frac{dQ_s}{dx}=0 \tag{3}$$

where λ is the bed porosity (dimensionless), and Q_s is the volumetric sediment transport rate per unit width (m^2/s). This equation ensures mass conservation of the sediment and describes the dynamic feedback between the bed and the flow.

The suspended sediment concentration, C (kg/m^3), is calculated using an advection-diffusion equation [10],

$$\frac{d(hC)}{dt}+\frac{d(hCu)}{dx}=\frac{d}{dx}(D_s\frac{dC}{dx})+S \tag{4}$$

where D_s is sediment diffusivity (m^2/s), and S is source/sink term (kg/m^2/s) accounting for processes such as entrainment and deposition.

The volumetric sediment transport rate per unit width Q_s (m^2/s) is also known as the bedload sediment transport rate per unit width, and it is given by Grass [11],

$$Q_s = A_g\,|\,u\,|^m\,u \tag{5}$$

where A_g is Grass coefficient (s^2/m), m is empirical exponent that typically varied between 3 and 5, and $|\,u\,|\,u$ maintain direction and nonlinearity.

2.2 Numerical Method

The coupled set of equations is discretized and solved numerically using a finite volume method to ensure mass conservation and numerical stability. The implementation allows for dynamic interaction between flow hydraulics and sediment transport processes, which is critical for accurately simulating morphological changes in riverine and coastal environments.

2.3 Initial Values for Parameters in Simulation

The numerical simulation of sediment transport was performed utilizing a standard set of parameters to assure consistency and replicability. The coefficient Ag, indicative of Grass coefficient, was taken at 0.001 s^2/m. The tidal range affecting water level variation was established at 2 m, with gravity acceleration presumed to be 9.81 m/s^2. A cumulative simulation duration of 15,552,000 seconds (equal to 180 days, also represent 6 months) was employed to analyze long-term transport dynamics. A dimensionless friction coefficient (C_f) of 0.002 was utilized to simulate bed resistance. The average length of the simulation domain was established at 10,000 m, with an initial water height of 20 m. A 20 m depth is comparable to 7.4 km away from shoreline near Kuala Terengganu area [12]. The parameter values, as detailed in Table 1, were selected to reflect standard environmental and hydrodynamic conditions pertinent to the study condition.

Table 1
Default parameters, values, and unit used in the simulation for sediment transport

Parameters	Value	Unit
Grass coefficient (A_g)	0.001	s^2/m
Tidal range	2	m
Gravity	9.81	m/s^2
Simulation time	15552000	s
Friction (C_f)	0.002	dimensionless
Medium length	10000	m
Water height	20	m

The simulation region was initialized with a specified bed profile to accurately represent topographic conditions for sediment transport analysis. Figure 1 demonstrates that the starting bed height was established according to a side view of the domain, reflecting the elevation gradient crucial for facilitating sediment transport. This starting state established the baseline for monitoring morphological alterations during the simulation and was essential in assessing the sediment deposition patterns over time.

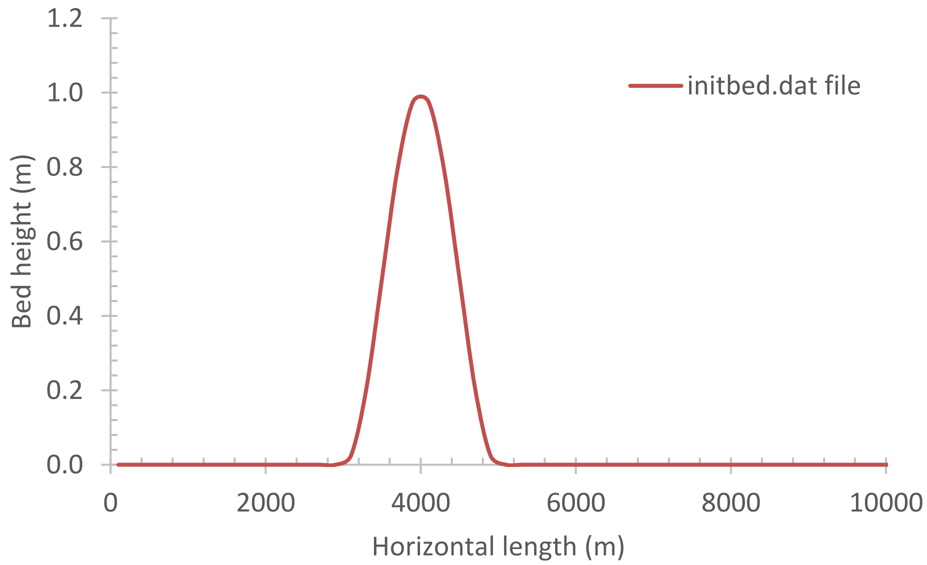

Fig. 1. Initial bed height on the side view of simulation domain. Incoming tidal wave from left to right

2.4 Uncertainty in Input Parameters' Values

To examine the sensitivity of sediment transport to several environmental and hydraulic conditions, a spectrum of values was methodically implemented in the simulation. The grass coefficient (A_g), indicative of combined effects of many physical properties, ranged from 0.0005 to 0.07 s^2/m to accommodate varying vegetation densities. The tidal range was modified to between 1.8 and 2.7 meters to replicate various tidal circumstances [13]. The friction coefficient (C_f), indicative of bed resistance, was examined across a broad spectrum from 0.000001 to 1.0 to represent various bed roughness conditions [14]. The simulation duration ranged from 7,776,000 seconds (roughly 3 months) to 93,312,000 seconds (about 3 years), facilitating both short-term and long-term sediment movement investigation. The parameter ranges (delineated in Table 2) were chosen to assess the model's reaction to diverse settings in the study of uncertainty impact on the simulation results.

Table 2
Range in the values for each parameter investigated in the simulation

Parameters	Value	Unit
Grass coefficient (A_g)	0.0005 - 0.07	s^2/m
Tidal range	1.8 - 2.7	m
Simulation time	7,776,000 - 93,312,000	s
Friction (C_f)	0.000001 - 1.0	dimensionless

Note: 7,776,000 - 93,312,000 is corresponding to 3 months – 3 years

3. Results and Discussion

3.1 Input Parameters Affecting Sediment Transport

Figure 2 illustrates the temporal progression of the bed profile inside the simulation domain, spanning from the baseline condition to 3 years, with intermediate assessments at 3, 6, and 9 months, as well as at 1 and 2 years. The bed was originally designed with a central elevated element, creating a symmetrical prominence between around 3000 m and 5000 m. Over time, the summit experienced gradual erosion, while sediment was redistributed to the sides, showing both depositional and erosional processes along the profile. After three months, some alterations were noted; nevertheless, by six and nine months, the crest continue to decline, and neighbouring regions exhibited initial indications of sediment deposition. The tendency persisted over one year, with a more significant stabilization of the core elevation and the formation of wider deposition zones extending outward. At 2 and particularly at 3 years, the profile exhibited a progressively flattened appearance, indicative of a mature phase of sediment redistribution influenced by extended hydrodynamic forces. The results indicate the cumulative impact of sediment transport processes and stress the necessity for long-term simulations to comprehensively represent the bed's morphological modification over time.

The effect of tidal range variation on alterations in bed profile was shown in Figure 3, with values spanning from 1.8 to 2.7 m, in comparison to the original bed state. The original profile exhibited a central elevation that was gradually altered as the tidal range expanded. At reduced tidal amplitudes (e.g., 1.8 m and 2.0 m), alterations in bed elevation were negligible, signifying restricted sediment mobility under diminished tidal forces. As the tidal range exceeded 2.3 m, a distinct pattern of erosion at the crest and depositing at the peripheries became apparent. Significant morphological alterations were noted at 2.5 and 2.7 m, where the central peak exhibited considerable erosion and sediment was dispersed across an expanded area. This tendency underscores the significance of tidal energy in augmenting shear stress and sediment distribution, hence facilitating more dynamic and extensive bedform evolution. The results indicate that areas with elevated tidal ranges are more susceptible to morphological changes and necessitate greater focus in coastal and estuarine sediment management approaches [15].

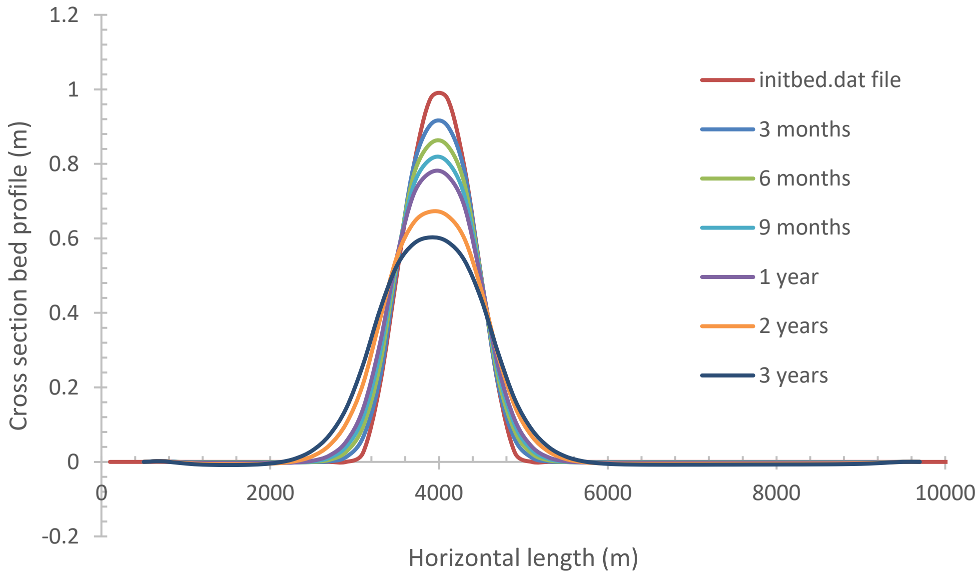

Fig. 2. Simulation time effect on bed changes after 3, 6, 9 months, and 1,2, and 3 years of simulation. The base input values used in the simulation is based on Table 1 and the simulation time is referred to Table 2

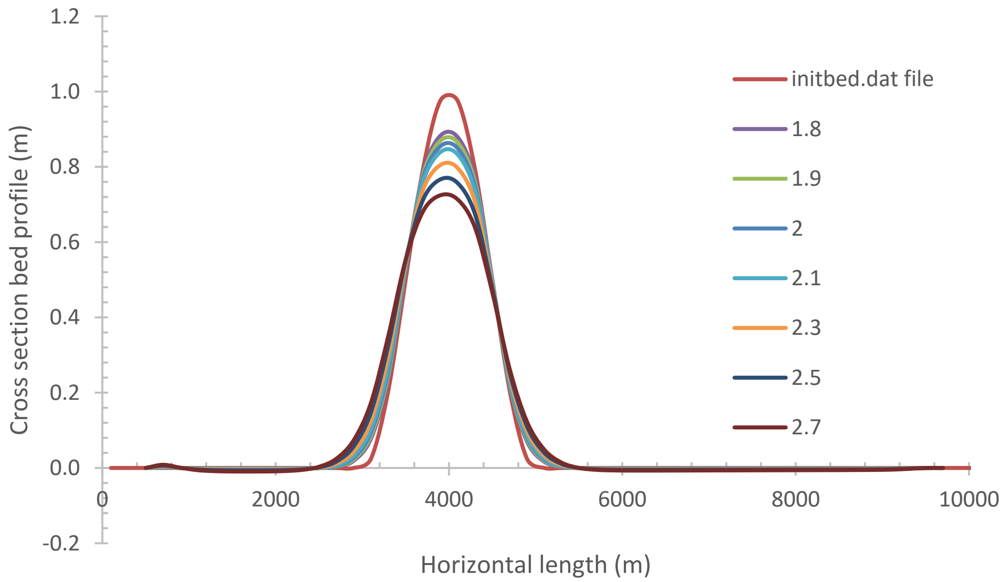

Fig. 3. Tidal range effect on bed changes after varied from 1.8 to 2.7 m in tidal range values. The base input values used in the simulation is based on Table 1 and the tidal range value is referred to Table 2

Moreover, Figure 4 illustrates the effect of different bed friction coefficients, from 0.000001 to 1.0, on the cross-sectional bed profile in relation to the beginning condition. The original bed exhibited a central elevation that experienced morphological alterations based on the frictional resistance imposed during the simulation. At extremely low friction values (e.g., between 0.000001 and 0.00001), the bed displayed unsubstantial changes, characterized by limited erosion at the crest and sediment redistribution towards the sides, signifying limited sediment mobility due to negligible energy dissipation. As the friction coefficient rose, especially beyond 0.01, the alterations in bed profile became progressively increasing its crest height. At a maximum coefficient of 1.0, the profile recovers its original crest that it exhibited minimal alteration from its original condition, indicating that increased bed roughness significantly inhibits sediment movement by diminishing flow velocity and shear stress at the bed interface. These findings underscore the essential function of bed friction in governing sediment movements and morphological development, particularly in systems characterized by heterogeneous substrate roughness or artificial roughness features.

Furthermore, Figure 5 depicts the effect of the grass coefficient (A_g), ranging from 0.0005 to 0.07 s^2/m, on alterations in the bed profile compared to the starting condition. The Grass coefficient denotes a combined effects of many physical properties on sediment transport, with elevated values signifying less resilient sediment surfaces [16]. At low A_g values (e.g., between 0.0005 and 0.001 s^2/m), the bed profile exhibited significantly less deformation, characterized by limited erosion at the crest and sediment deposition upstream and trough formation at the downstream, signifying active sediment transport. As the Grass coefficient rose, the magnitude of bed alteration increased progressively. At A_g = 0.04 and 0.07 s^2/m, the bed profile essentially varied the most, indicating that the submerged land surface becoming susceptible to sediment movement. The results underscore the critical function of a combined effects of many physical properties given by Grass coefficient in stabilizing bed morphology and regulating sediment dynamics, indicating that the integration of a combined effects of many physical properties alteration may be helpful for erosion control and sediment management in both natural and restored ecosystems.

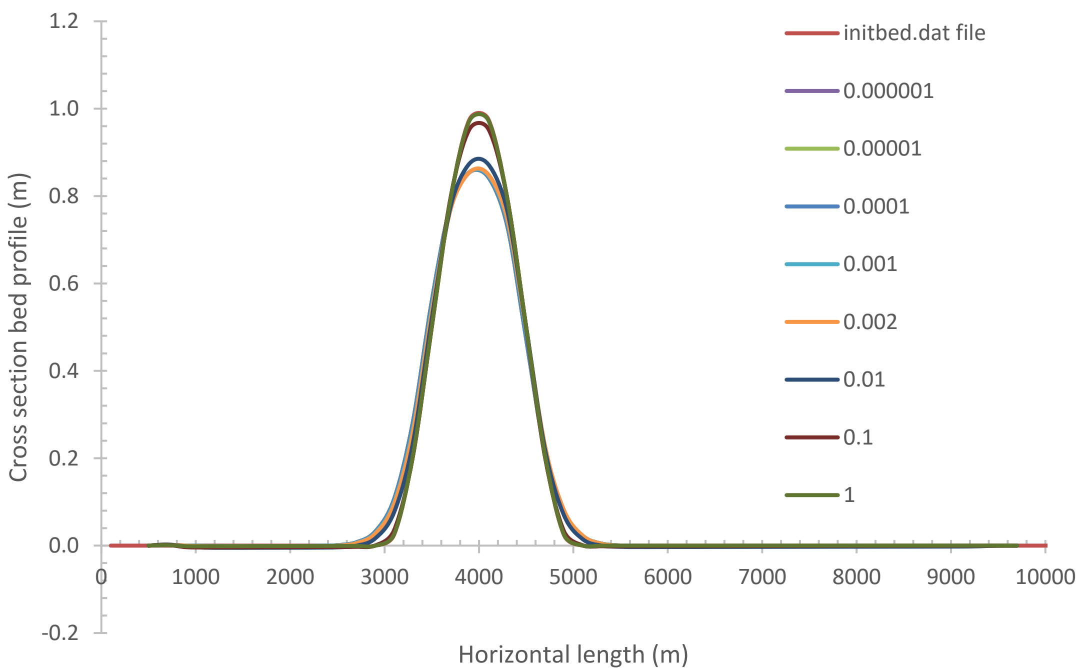

Fig. 4. Bed friction coefficient effect on bed changes after varied from 0.000001 to 1 in friction coefficient values. The base input values used in the simulation is based on Table 1 and the bed friction coefficient value is referred to Table 2

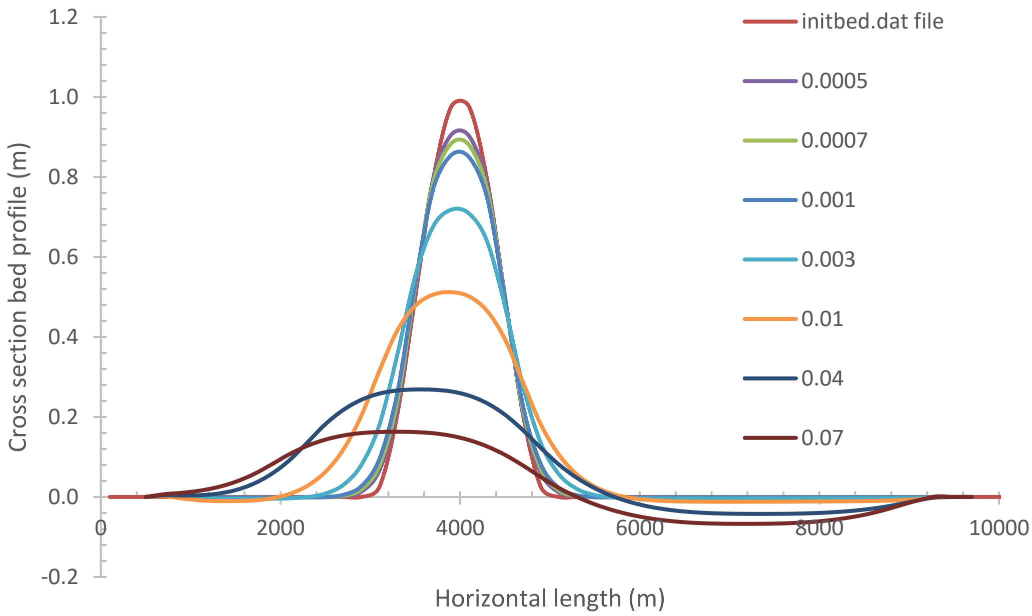

Fig. 5. Grass coefficient effect on bed changes after varied from 0.0005 to 0.04 in Grass coefficient values. The base input values used in the simulation is based on Table 1 and the Grass coefficient value is referred to Table 2

The findings from Figures 2 to 5 collectively underscore the intricate relationships between hydrodynamic factors and sediment transport processes that influence bed morphology over time. Simulation duration was crucial in demonstrating the gradual nature of sediment redistribution, with extended periods leading to progressively flattened bedforms. The tidal range was identified as an important factor influencing morphological change, with greater tidal amplitudes increasing sediment mobility and sediment redistribution. The bed friction coefficient influenced sediment flow by regulating shear stress, with elevated values mitigating erosion and maintaining the original bedform. Likewise, the Grass coefficient, which signifies the cumulative impact of surface resistance, demonstrated efficacy in mitigating sediment movement, especially at its lowest values. These findings underscore the necessity of considering various interconnected physical parameters in the evaluation of sediment dynamics, indicating that environmental conditions such as substrate roughness can be pivotal in managing erosion and enhancing sediment stability in both natural and engineered aquatic systems.

3.2 Sensitivity Analysis on Input Parameters, and Its Influence on Sediment Transport

The overall sensitivity analysis is illustrated in Figure 6, and the findings are depicting the correlation between the ratio of bed height variation and four critical parameters—simulation duration, Grass coefficient (A_g), tidal range, and bed friction coefficient (C_f)—on a logarithmic x-axis. The application of a logarithmic scale emphasizes the varying magnitudes and nonlinear patterns among the parameters. The Grass coefficient exhibited the greatest sensitivity, with the ratio decreasing significantly as A_g increased, demonstrating a robust stabilizing (lower changing bed height rate) influence on bed morphology. The bed friction coefficient (C_f) demonstrated a nonlinear response; at low values, sediment mobility was elevated (more negative ratio), however higher C_f values resulted in a reversal of this trend, ultimately producing positive ratio values, profile leading recovery of its original crest. Conversely, tidal range and simulation time had more mild and consistent impacts. The ratio diminished progressively with extended time and heightened tidal amplitude, indicating cumulative sediment redistribution over prolonged periods and under intensified hydrodynamic stresses. Hence, in terms of ratio of bed height variation and four critical parameters, this research highlights that a combined effects of many physical properties (A_g) and bed roughness (C_f) are primary factors affecting the rate of sediment stability and morphological evolution, whereas time and tidal force exert a consistent but less pronounced influence. The log-scale perspective accurately reflects the varied sensitivities, underscoring the significance of strategic parameter selection in model calibration and erosion management planning.

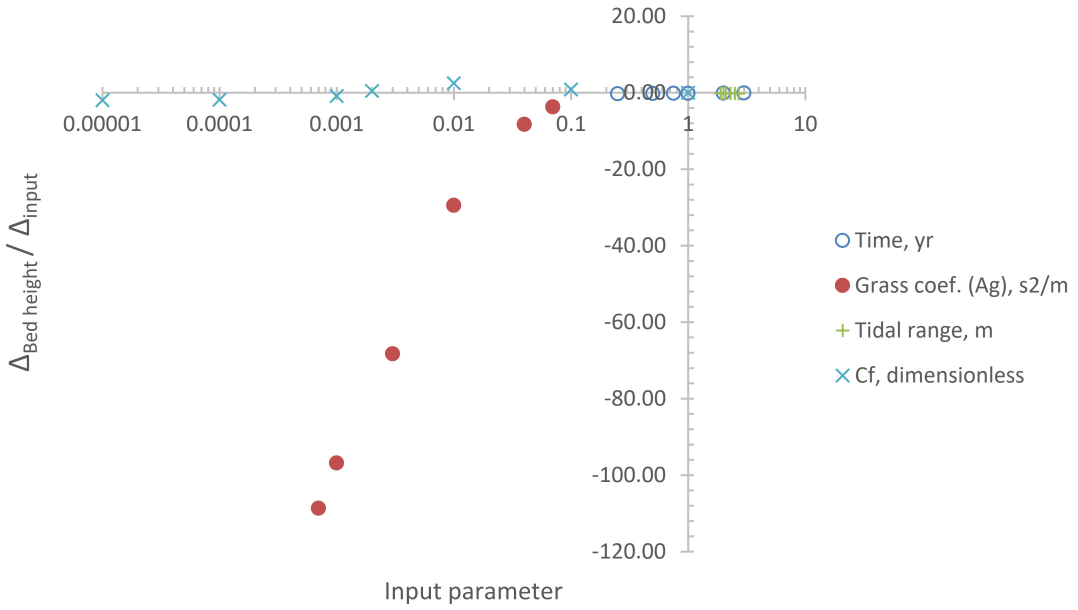

Fig. 6. The sensitivity of bed height change over a unit change in input parameters value.
Note: Cf refers to bed friction coefficient, and time refers to simulation time

3.3 Possible Adaptation of Sediment Transport into Soil Erosion Study in Agricultural Field

This simulation-based sediment transport study provides essential insights into the influence of environmental parameters—such as simulation duration, tidal range, bed friction, and Grass coefficient—on bed morphology over time. These findings can be readily applied to the examination of soil erosion in agricultural fields, as the fundamental mechanisms of sediment displacement, redistribution, and stabilization are comparable. Extended simulation durations of up to three years demonstrated a slow attenuation of raised bedforms resulting from cumulative sediment transport, reflecting the long-term effects of precipitation and surface runoff on agricultural soil profiles. The impact of tidal range on sediment mobility parallels the effect of differing rainfall intensities or irrigation flows in exacerbating soil erosion and deposition in agricultural lands. The model results emphasize the significance of hydrodynamic forces in altering land surfaces, rendering this sediment transport framework particularly relevant for predicting erosion scenarios in agricultural settings where water-induced soil displacement is a primary issue.

Furthermore, the Grass coefficient (A_g), which represents the aggregate effects of several surface physical features including vegetation and soil texture, reflects the impact of surface cover and land management strategies on erosion control in agricultural settings. High A_g levels in the simulation signified increased sediment mobility, equivalent to bare or inadequately covered agricultural soils, whereas low A_g values exhibited a stabilizing influence reminiscent of vegetation cover or mulch.

Similarly, the bed friction coefficient (C_f) demonstrated that heightened surface resistance diminishes sediment transport, akin to the role of soil roughness elements such as crop residues or conservation tillage in lessening erosion potential. The studies highlight the efficacy of sediment transport modelling as a predictive and diagnostic instrument in agricultural erosion research, facilitating enhanced soil conservation strategies by adjusting field-specific parameters that affect hydrodynamics and sediment dynamics.

4. Conclusions

This study illustrated the efficacy of sediment transport models in understanding processes across diverse environmental and hydrodynamic conditions. The numerical simulations indicated that factors including the Grass coefficient (A_g), bed friction coefficient (C_f), tidal range, and simulation time significantly influence sediment redistribution and bedform evolution. The Grass coefficient proved to be the most sensitive variable, demonstrating its significant impact on surface stability and sediment transport. Bed friction was also essential in managing the degree of erosion and deposition by the shear stress at the sediment-water interface. These findings are relevant to the investigation of soil erosion in agricultural fields, where analogous physical factors facilitate sediment movement. The Grass coefficient quantifies surface characteristics, including vegetation cover, crop residue, and soil texture, elements that considerably influence erosion potential in agricultural land. Likewise, bed friction plays a role analogous to that of soil surface roughness and conservation tillage methods in reducing soil erosion. The observed impact of tidal range and simulation duration mirrors the impacts of varying rainfall intensities and extended water exposure on soil deterioration. By modifying sediment transport models with parameters specific to agricultural landscapes, researchers and land managers can more accurately forecast erosion risks and devise targeted mitigation solutions. This method facilitates strategies development for soil preservation, endorses sustainable land management methods, and aids in safeguarding the enduring productivity of agricultural ecosystems. Future investigation may involve integrating the model with rainfall-runoff simulations and corroborating forecasts with field data to examine its practical utility in erosion monitoring and management.

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