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Research on Key Technologies for Simulating Dynamic Geomorphic Evolution of Estuaries and Coasts

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Abstract. The dynamic processes in estuarine and coastal regions are relatively complex in themselves, and the shoreline morphology has also always been in a state of change. Accurately predicting the dynamic geomorphic evolution of this region is of great significance for coastal engineering construction, disaster prevention and mitigation, and ecological protection. With the continuous development of computer technology, numerical simulation has already been able to effectively break through the spatial and temporal limitations of field observations and physical models, and has gradually become a core method for carrying out research on medium- and long-term geomorphic evolution. This paper systematically reviews the research progress in the field of numerical simulation of dynamic geomorphic evolution in estuarine and coastal regions, and focuses on discussing the frontier methods adopted to solve the two major technical bottlenecks of model "spatial span" and "temporal span". From the spatial dimension, it expounds multidimensional nested models and multi-type-grid cross-scale coupling technologies, and at the same time analyzes their advantages in taking into account both the large-scale background dynamic field and local high-resolution topographic feedback. From the temporal dimension, it provides a detailed analysis of the medium- and long-term simulation acceleration mechanisms represented by the morphological acceleration factor method (MAF), as well as the corresponding parameter constraint conditions. Finally, combined with application cases of typical estuaries at home and abroad, this paper summarizes the achievements made by multiscale coupling models in empirical research on geomorphic evolution, and also looks ahead to future trends in intelligent simulation involving multiphysical-process coupling, dynamic optimization of parameters, and the integration of digital twins and machine learning.

Keywords: estuaries and coasts, dynamic geomorphic evolution, numerical simulation, cross-scale coupling, morphological acceleration factor (MAF)

1. Introduction

Estuaries and coasts are sensitive regions where terrestrial runoff intersects with ocean tides and waves. Under the combined effects of climate change, such as sea-level rise and the frequent occurrence of extreme storm surges [1], and high-intensity human activities, such as dam construction and sediment trapping in river basins, dredging of deep-water channels, and land reclamation from the sea [2], the geomorphic evolution of this region has been undergoing profound adjustments. The intense erosion and deposition changes occurring within the region not only directly threaten the navigation safety of ports and waterways and the stability of coastal protection structures, but also cause changes in the habitats of surrounding ecological communities [3]. Therefore, deeply analyzing the coupling mechanism among dynamic action, sediment transport, and topographic feedback, and accurately predicting the medium- and long-term geomorphic evolution trends on the scale of several decades or even one hundred years, have become a major strategic demand that urgently needs to be solved in the current international fields of coastal dynamics and ocean engineering.

Traditional research on geomorphic evolution has mainly relied on field observations and physical model experiments. However, field observations are often relatively costly and also make it difficult to capture complete data under extreme weather conditions. Physical models are also constrained by the "scale effect", making it impossible to realize panoramic reproduction over large spaces and long periods. In recent years, with the rapid development of computational fluid dynamics and high-performance computers, numerical simulation, by virtue of its advantages such as low cost, high efficiency, flexible scale, and support for multi-scenario prediction, has gradually developed into the most widely used core method in research on dynamic geomorphic evolution of estuaries and coasts [4].

Although numerical simulation has made considerable progress, in the process of practical application, it still faces two major technical challenges. The first is the problem at the spatial-scale level, namely how, in a single model, to accurately simulate large-scale low-frequency dynamics in the open sea while also finely depicting the high-frequency nonlinear topographic responses brought about by complex nearshore shorelines. The second is the problem at the temporal-scale level, namely the huge difference between the computational time step of hydrodynamics, which is at the second level, and the scale of geomorphic evolution, which is at the decadal level. In order to break through these bottlenecks, in recent years, academia has made relatively important progress in two key technologies: multiscale spatial coupling and medium- and long-term simulation acceleration. This paper will systematically review the development context and theoretical mechanisms of cross-scale downscaling grid-coupled models and geomorphic acceleration calculation technologies, sort out their current application status in the geomorphic evolution of typical complex estuaries at home and abroad, and also look ahead to the challenges faced by this field and its intelligent development trends, hoping to provide corresponding support for the research and development of a new generation of mathematical models for estuarine and coastal geomorphic dynamics and for engineering practice [4].

2. Main research methods for dynamic geomorphic evolution of estuaries and coasts

The core of research on dynamic geomorphic evolution of estuaries and coasts is to analyze the internal mechanism of the mutual association and dynamic coupling among dynamic action, sediment transport, and topographic response. At present, academia mainly adopts three types of research methods: field observation, physical model experiments, and numerical simulation.

Field observation is the basic method for obtaining prototype data of estuaries and coasts. Through direct or indirect monitoring, it records the actual processes of the dynamic field, sediment movement, and geomorphic evolution under natural conditions, and can also provide necessary data support for constructing physical and mathematical models. Its core applications mainly include the collection of three types of key information: using technologies such as multibeam bathymetry and satellite remote sensing to obtain the topography and sediment grain-size distribution of tidal flats and subaqueous deltas; monitoring runoff discharge, tidal water level, tidal-current velocity and direction, and wave parameters through equipment such as water-level stations and wave buoys; measuring sediment concentration by means of water-sample collection and optical turbidimeters, then estimating the transport rate in combination with the velocity profile, and determining the sediment settling velocity through field settling tubes or laboratory settling experiments [5].

Physical model experiments [6] follow gravity similarity and geometric scale reduction laws, can reproduce the dynamic geomorphic processes of estuaries and coasts in a laboratory environment, and are also an important bridge connecting field observation and numerical simulation. Such experiments are mainly divided into two categories: wave-driven models can simulate phenomena such as beach erosion and deposition and sandbar migration under the action of irregular waves, and are used to analyze the evolution laws of wave-dominated coasts; runoff–tide coupled models reproduce macroscopic geomorphic processes, such as the evolution of branching channels and the advance and retreat of mouth bars under the combined action of runoff and tides, by scaling estuarine morphology and river-network structure.

Numerical simulation quantitatively describes the dynamic processes and geomorphic evolution laws of estuaries and coasts through mathematical equations, relies on computers to solve the relevant equations, and realizes the reproduction of actual processes and prediction under different scenarios. It is the most widely used method in current related research [7]. Its computational process generally takes the field topography as the initial condition, first solves the flow-field governing equations to obtain the dynamic field, then combines sediment transport equations to calculate sediment flux, and finally updates the bed morphology through the topographic-change formula and outputs erosion and deposition data. The application scenarios of numerical simulation cover multiple spatial and temporal scales. It can not only simulate local erosion and deposition of tidal flats caused by a single storm surge or flood and ebb tides within a short period, but also predict the evolution trends of estuarine deltas and mouth bars over long time scales, as well as the impacts of human activities such as engineering construction on geomorphology.

The advantages and disadvantages of the three types of research methods are all very obvious. Field observation can directly reflect natural processes, can capture the sudden impacts brought by extreme events such as typhoons and floods, and is also an important standard for verifying the authenticity of simulation results, but it has relatively high cost, a long cycle, and relatively poor controllability. Physical model experiments have strong intuitiveness and high controllability, and can be used to verify nonlinear processes, but they are costly, have obvious "scale effects", and lack flexibility. Numerical simulation has low cost, fast computational speed, flexible applicable scales, and strong scenario expansibility, but it also depends greatly on the quality of initial data and has certain simplification errors.

The three types of methods constitute a collaborative system: field observation provides prototype data, physical models verify nonlinear processes, and numerical simulation expands the long-period and large-scale research scenarios that are difficult for the first two types of methods to cover. With the continuous development of computer technology, the advantages of numerical simulation, namely "low cost, high speed, and large scale", have become increasingly prominent, and it has also become the most widely used core method. The following sections will focus on two key technologies of numerical simulation—multiscale spatial coupling and nesting technology [7] and medium- and long-term simulation acceleration technology [8]—and discuss their technical principles and practical application scenarios.

3. Multiscale spatial coupling simulation technology

3.1 Multidimensional nested models

In order to take into account the multiscale coupling requirements between large-scale driving fields and local fine processes in the process of estuarine and coastal dynamic simulation, multidimensional nested model technology has been widely applied. This technology realizes the two-way transmission of boundary conditions and cross-scale information feedback through the nesting of submodels with different resolutions and different dimensions.

The independently developed CHINACOAST system in China is a typical representative of the triple two-way nested three-dimensional storm surge, ocean current, temperature, and salinity forecasting model [4]. The whole system includes three layers of models: a two-dimensional barotropic large model, with a horizontal resolution of approximately 7 km, covering the Chinese sea area from the Bohai Sea to the northern South China Sea and responsible for providing boundary conditions for the medium model; a three-dimensional baroclinic medium model, with a horizontal resolution of approximately 3 km and a range covering the continental shelf region of the northern South China Sea, used to simulate local sea-area dynamic processes; and a three-dimensional baroclinic small model, with a horizontal resolution of approximately 1.2 km, covering the Pearl River Estuary and nearby waters and carrying out refined simulation [4]. The nesting technology enables the computational domain of the internal small model to be positioned arbitrarily within the coastal area of China. Through the transmission of boundary conditions, two-way coupling between models of different scales is realized: the large model provides offshore boundary conditions for the small model, and the small model then feeds the refined simulation results back to the large model. This technology has been successfully applied in the storm-surge forecasting system of the Pearl River Estuary, realizing automatic daily operation, and can provide the hindcast results of the previous day and the real-time forecasts for the following two days, thereby providing important technical support for disaster prevention and mitigation work.

In view of the complex structural characteristics of delta river-network water systems, relevant researchers have proposed a coupled model of a one-dimensional river network and a two-dimensional estuary. First, a three-level joint solution method is adopted to solve the whole one-dimensional river-network model, and then the computational results of the one-dimensional model are substituted into the two-dimensional model as boundary conditions for calculation, effectively solving the contradiction between large-range simulation and local refined simulation. The practical application of this model in the Pearl River network area and estuarine bay shows that the coupling method can relatively accurately reflect the impacts caused by engineering construction on local waters, while also meeting the precision requirements needed for engineering [9]. The one-dimensional river-network model is mainly used to simulate the water and sediment transport processes of main streams and tributaries, and it transmits key parameters such as discharge and sediment transport volume in the river network to the two-dimensional estuarine model, realizing the transition from the macroscopic basin to the microscopic estuary. The two-dimensional estuarine model focuses on simulating the interaction between tide and runoff in the estuarine region, residual sediment transport, and bed evolution processes [9]. It can effectively handle the problem of water and sediment exchange between the river network and the estuary, and provides a powerful tool for studying the evolution laws of large estuarine and coastal systems.

3.2 Multi-type grid coupling models

Estuarine and coastal regions have complex shoreline morphology, irregular underwater topography, and coexisting multiscale dynamic processes. In numerical simulation work, the grid generation strategy directly determines the model's ability to characterize physical processes and its overall computational efficiency.

Structured grids, such as quadrilateral grids, have simple topological relationships, high numerical discretization accuracy, and small computational storage requirements. However, their ability to fit complex geometric boundaries is limited, and during local refinement, they often cause a large number of redundant grids to be generated throughout the entire computational domain. Unstructured grids, such as triangular grids, can flexibly adapt to complex boundaries and support local refinement at arbitrary positions, but their computational efficiency is relatively low, and the implementation of high-order numerical schemes is also more difficult [10].

In order to take into account both the computational efficiency of structured grids and the geometric flexibility of unstructured grids, relevant researchers have proposed a modeling idea that couples structured and unstructured grids. Structured grids are used in areas with regular shorelines and gentle topography, so as to improve overall computational efficiency. Unstructured grids are used near areas with tortuous shorelines, abrupt topographic changes, or engineering structures, so as to accurately characterize the corresponding geometric details [11]. Between the two types of grids, information transmission of the dynamic field and material flux is realized through specialized interface interpolation algorithms, thereby optimizing the overall allocation of computational resources on the premise of ensuring numerical accuracy.

Among the frontier applications of cross-scale coupling, the CURAE project supported by the European Union Copernicus Marine Environment Monitoring Service (CMEMS) is highly representative. It takes large-scale structured ocean data as open boundaries and drives nearshore unstructured models through downscaling. Typical applications carried out under different dynamic environments have fully verified the effectiveness of this technology [12]. For the microtidal weak-dynamic environment, Fangar Bay in Spain is taken as an example. In this region, water flow is slow and aquaculture activities are intensive. Through downscaling coupling between large-scale structured physical fields and nearshore unstructured grids, the model can accurately characterize freshwater discharge from agricultural irrigation channels and the dynamic shoreline evolution process, providing high-resolution decision support for improving local water quality and the aquaculture environment. For the strong-tide high-energy environment, the German Bight is taken as an example. In this macrotidal region where morphodynamic changes are very intense, relevant researchers, through deep coupling of structured and unstructured grids, combined a high-resolution wave–current coupled model with a sediment bed-evolution module, and successfully reproduced complex morphodynamic processes such as tidal asymmetry and density-field-driven processes [12].

4.medium- And long-term numerical simulation acceleration technologies

4.1 Morphological acceleration factor method

In research on the dynamic geomorphic evolution of estuaries and coasts, it is often necessary to simulate and predict medium- and long-term evolution processes over several decades to more than one hundred years, so as to grasp the relevant laws and trends and provide support for engineering parameter design, basin management, and ecological protection work [7]. However, in order to ensure that the model can converge, the simulation time steps of hydrodynamics and sediment transport usually need to be set at the second level or minute level. When medium- and long-term geomorphic evolution simulation is carried out, the computational amount becomes exceptionally huge. Traditional methods can hardly meet practical needs, and acceleration processing of the model is required.

The Morphological Acceleration Factor (MAF) method is one of the most widely used acceleration technologies. It was first proposed by Lesser and Roelvink et al [13]. when developing a three-dimensional morphodynamic model, while Roelvink [14] systematically expounded the application of this technology under different coastal dynamic environments. Its core idea is to introduce an acceleration factor, linearly extend the sediment transport amount within a short period into the long-term topographic change amount, and shorten the overall simulation time by amplifying the bed-change rate. The basic principle can be expressed by Formula (1), that is, shortening the simulation time by changing the rate.

$$\boldsymbol{\Delta}\mathrm{t}_{\mathrm{morph}} = f_{mor} \cdot \boldsymbol{\Delta}\mathrm{t}_{\mathrm{hydro}} \tag{1}$$

where: f_{mor} is the morphological acceleration factor; $\boldsymbol{\Delta}\mathrm{t}_{\mathrm{hydro}}$ is the hydrodynamic time step; $\boldsymbol{\Delta}\mathrm{t}_{\mathrm{morph}}$ is the accelerated time step. By multiplying by a constant factor to increase the topographic change rate, after the calculation of one tidal cycle, the model has in fact simulated the geomorphic changes of (n) cycles, where n(n=f_{mor}). Figure 1 shows the comparison between the original discharge process and the compressed discharge process when the acceleration factor is 5 [7].

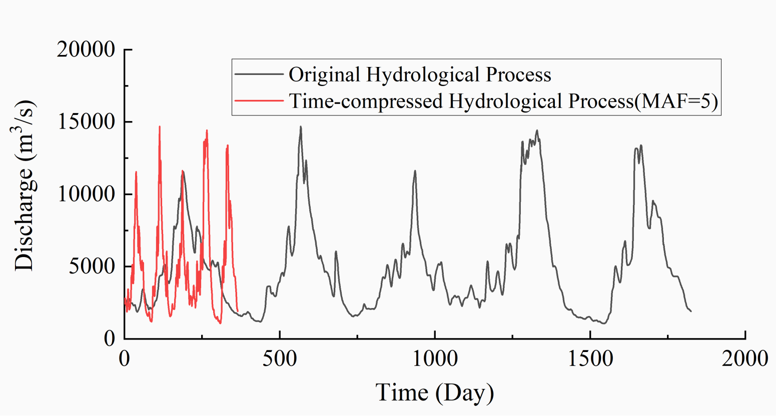

Figure 1. Schematic diagram of discharge process compression

The value of MAF needs to be determined through sensitivity tests. The conventional constraint condition is that the bed change in a single tidal cycle should not exceed 10% of the water depth. In their study on decadal erosion and deposition evolution in the Yangtze Estuary, Luan Hualong et al., through a series of sensitivity tests and in combination with the above constraint condition and the analysis of the consistency between the simulation results and the measured erosion and deposition distribution, determined that the value range of the acceleration factor was 20–30, and established a hydrodynamic–sediment–geomorphic evolution mathematical model covering the entire Yangtze Estuary and adjacent sea areas [15]. The model considers seasonal water and sediment input. According to the intra-annual distribution of multi-year monthly average runoff and sediment discharge at Datong Hydrological Station, one year is generalized into six periods, ensuring that the total runoff and sediment amount during the simulation period are consistent with the measured values, avoiding the accumulation of long-term simulation errors caused by a single acceleration factor, and significantly improving the accuracy of medium- and long-term prediction.

4.2 Other geomorphic simulation acceleration strategies

In addition to MAF, researchers have also developed simplified strategies such as the tidal-cycle averaging method [16], which drives geomorphic change after averaging the hydrodynamic results of multiple tidal cycles, and the quasi-steady-state assumption [17], further reducing computational cost and making them applicable to specific slowly varying topographic scenarios.

4.3 General computational efficiency improvement technologies

The implementation of the above acceleration methods depends on an efficient numerical solution environment and is often supplemented by general high-performance computing technologies: parallel computing based on MPI/OpenMP, GPU acceleration, adaptive mesh refinement, and efficient algorithms such as ADI. Although these technologies are not unique to geomorphic simulation, they can significantly improve the computational efficiency of complex models and provide computational support for medium- and long-term prediction.

5. Typical application cases

5.1 Numerical simulation research on major estuaries in China

Based on the PRD-LTMM model [18], Wei Xing et al. successfully simulated the evolution process of the Pearl River Delta from 6000 to 2500 years ago, revealed the key controlling role of the "gate" system and the bidirectional tidal-jet system in delta evolution, and confirmed the promoting effect of bedrock islands as depositional nuclei on the formation of delta morphology. Based on measured data from 1958 to 2022, Qu Geng’s team systematically revealed the differentiated evolution laws of the northern and southern branch reaches of the Yangtze Estuary: the inlet section of the North Branch shows a significant silting trend, and the river channel has been shrinking year by year; the South Branch reach presents an erosional state, and the -20 m deep channel further extends downward and expands [19]. The pattern of "silting in the north and erosion in the south" originates from differences in water–sediment–tidal dynamic conditions: the diversion ratio of the North Branch decreased from 21.6% in the late 1970s to around 10%, gradually evolving into a flood-dominated flood channel; the South Branch is dominated by ebb flow and is the main channel for the discharge of upstream runoff.

5.2 Numerical simulation research on typical international estuaries

In international research, cross-scale coupling technology has been widely used to capture the medium- and long-term geomorphic evolution characteristics of complex estuaries. In terms of the evolution of estuarine channels and tidal flats, Van der Wegen et al. coupled the Delft3D hydrodynamic model with a geomorphic evolution module, adopted MORFAC acceleration technology, and successfully simulated the century-scale evolution process of the Western Scheldt Estuary in the Netherlands [20]. The study locally refined the channel area through an unstructured grid, accurately reproduced channel siltation and tidal-flat erosion caused by changes in the dynamic environment, and improved prediction accuracy by 30% compared with traditional models, providing a decision-making basis for channel maintenance for the Dutch Delta Works Management

Authority. In the field of geomorphic response of the basin–estuary continuum, Tu et al. constructed a one- and two-dimensional coupled model based on the Delft3D series models, focusing on evaluating the dynamic impact of upstream sluice and dam groups on the topography of the Mekong Delta [21]. The model uses the sediment transport amount of the one-dimensional river network as boundary conditions and downscales it into the two-dimensional geomorphic evolution module. The simulation found that dam operation caused the erosion rate of the delta front to accelerate to 15–20 m per year, and the results were adopted by the United Nations Mekong River Commission for transboundary water-resource and coastline management.

6. Challenges and prospects

Although significant progress has currently been made in research on the dynamic geomorphic evolution of estuaries and coasts, it still faces many challenges.

First, in terms of multiprocess coupling mechanisms, the coupling mechanisms among multiple processes such as hydrodynamics, sediment, and ecology are still not completely clear. For example, the feedback mechanism of coastal vegetation on sediment transport, the interaction between biogeochemical processes and geomorphic evolution, and other issues still need further research.

Second, in terms of parameter uncertainty, there is still considerable uncertainty in model parameter determination and calibration. Key parameters such as sediment settling velocity and bed resistance coefficient are greatly affected by experimental conditions and environmental factors, and are difficult to obtain accurately.

Third, in terms of computational efficiency, the computational efficiency of medium- and long-term high-resolution simulation still needs to be improved. Although the MAF method and parallel computing technology have significantly improved computational efficiency, in the face of increasingly complex multiphysical-field coupled simulations, more efficient algorithms and computational frameworks still need to be developed.

Fourth, in terms of data acquisition, the acquisition of high-quality field observation data is costly and difficult. Especially under harsh environmental conditions, such as during extreme events including typhoons and floods, data acquisition faces enormous challenges.

In the future, with the continuous progress of computer and measurement technologies and the interdisciplinary integration of multiple disciplines, simulation of the dynamic geomorphic evolution of estuaries and coasts will develop toward directions such as efficient multiscale coupling and integration with machine learning, further improving the reliability and accuracy of medium- and long-term prediction. By combining the FVCOM sediment module, including the bed evolution equation, with the tidal–wave coupling capability of ADCIRC, a three-dimensional hydrodynamic–sediment transport coupled model for estuaries and coasts can be constructed to realize refined simulation of key regions. Based on reinforcement learning, the dynamic adjustment of MAF can be optimized, and the acceleration factor can be automatically adjusted through a "trial-and-error–feedback–iteration" mechanism, thereby reducing computational errors. Field observation and model integration should be strengthened. High-precision topographic data can be obtained by using multibeam bathymetry and satellite remote sensing, and dynamic parameters can be monitored in combination with water-level stations and wave buoys, providing more accurate initial conditions and validation data for the model. In combination with future climate-change models, multi-scenario simulation and uncertainty analysis should be carried out to quantify the evolution trends of estuaries and coasts under different climate-change and human-activity scenarios, and to provide a scientific basis for planning and management.

7. Conclusion

Research on the dynamic geomorphic evolution of estuaries and coasts often adopts methods such as field observation, physical model experiments, and numerical simulation: field observation provides prototype data, physical model experiments verify nonlinear processes, and numerical simulation expands the long-period and large-scale research scenarios that are difficult for the first two types of methods to cover. With the development of computer technology, the advantages of numerical simulation, namely "low cost, high speed, and large scale", have become increasingly prominent, and it has also become the most widely used core method.

The development of multiscale spatial coupling models and simulation acceleration technologies has greatly improved the medium- and long-term simulation capability for complex estuarine and coastal systems. Nested model technology realizes the transition from the macroscopic scale to the microscopic scale and solves the contradiction between large-range simulation and local refined simulation. Medium- and long-term simulation acceleration technologies represented by the MAF method and parallel computing technology have significantly improved the efficiency of numerical simulation, making century-scale evolution prediction possible. The above technologies provide powerful tools for estuarine and coastal planning and management, and help formulate strategies to cope with the impacts of future climate change and human activities.

Future research needs to further strengthen interdisciplinary integration and develop more accurate and efficient simulation technologies, so as to provide stronger scientific and technological support for the sustainable development of estuaries and coasts. Against the background of intensified global climate change and human activities, estuaries and coasts are facing unprecedented challenges. It is urgent to carry out more in-depth research and make more accurate predictions, so as to guide scientific planning and management decisions.

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