

The Hi-Fi Yellow River paradigm: From static models to AI-driven scenarios [version 1]

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ABSTRACT

In 2000, the concept of the “Three Yellow River Initiative” (Prototype, Model, Digital) established a comprehensive framework for Yellow River study and management. After two decades, the limitations of these isolated modelling approaches have become increasingly apparent, particularly the insurmountable scaling challenges of physical models and the inherent simplification gaps of digital simulations that cannot capture the nonlinear, multi-scale water-sediment dynamics of the river. This paper introduces the Hi-Fi (High-Fidelity) Yellow River paradigm, an intelligent, closed-loop governance system that leverages artificial intelligence to enable instantaneous scenario manifold switching for water management based on real-time observations from the Prototype Yellow River. We formalize this paradigm using contact geometry: the state space of river dynamics forms a contact manifold $(\mathcal{E}, \Theta)$, where the transition from model prediction to observed reality manifests as a transversal transition between scenario manifolds along $\ker(d\Theta)$. This mathematical framework rigorously captures the core of high-fidelity research—grounding governance decisions in real-world scenarios rather than simplified representations—while providing kinematic constraints for adaptive water-sediment regulation strategies. The framework unifies the “Three Yellow River Initiative” into a single reality-responsive intelligent system, transforming static prediction-based governance into dynamic, scenario-driven decision-making for the Yellow River basin.

KEYWORDS

Yellow river, Hi-Fi yellow river, artificial intelligence, scenario manifold switching, contact geometry, water-sediment regulation.

1 Introduction

This study addresses three fundamental scientific issues in Yellow River basin governance that “Three Yellow River Initiative” paradigm fails to solve: (1) the topological origin of systematic prediction deviations of traditional deterministic models caused by the global non-integrability of the basin’s state space; (2) the dynamic reconstruction mechanism of knowledge manifolds driven by real-world prototype scenarios and the discontinuous decision-switching rule for water-sediment regulation; (3) the construction of a Yellow River Basin Vertical Domain Large Model (YR-VDLM) with cross-manifold instantaneous perception and system-level reasoning capabilities for non-continuous decision-making under extreme and compound disturbances. By establishing a contact geometric framework for the Yellow River’s water-sediment dynamics and integrating it with the YR-VDLM, this paper proposes the Hi-Fi Yellow River paradigm to realize a fundamental shift from static model-driven research and governance to dynamic real-scenario-driven decision-making, providing a rigorous theoretical and technical system for the ecological conservation and high-quality development of the Yellow River basin.

2 Prototype, Model and Digital Yellow Rivers

In 2000, Guoying Li, the Director of the Yellow River Conservancy Commission (YRCC) at that time, proposed the “Three Yellow River Initiative”: the Prototype Yellow River, the Model Yellow River, and the Digital Yellow River (Wang, 2026). This framework laid the foundation for the technical system of modern Yellow River research and management, with each component undertaking distinct yet complementary research and governance functions. However, long-term isolation led to disjointed data and decision-making (Wang et al., 2020a; Madhushani et al., 2024).

The Prototype Yellow River refers to the natural river itself, the core of all research and governance activities. A comprehensive hydrological monitoring network has been established across the basin, complemented by a series of soil and water conservation engineering measures, including silt-trapping dams and terraced fields. Its core function is real-world observation and engineering validation: investigating the natural evolution of water-sediment dynamics and ecological systems, assessing the impacts of human-engineering projects, and exploring harmonious coexistence between humans and the river. It addresses the three core challenges of the

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Yellow River: water scarcity (Lu et al., 2024) (annual water resources of 58 billion m³), severe soil erosion (annual sediment load of 1.6 billion tonnes from the Loess Plateau), and the suspended river risk (Zhang and Wang, 2024) (elevated riverbed in the lower reaches causing constant breaching threats (Wang et al., 2016). The ultimate goal of the Prototype Yellow River observation is to ensure flood safety for the lower reaches of the Yellow River (Zhang et al., 2025).

The Model Yellow River is a physical simulation tool for studying mechanisms of sediment transport and channel evolution. It employs scaled physical modelling to reconstruct the Yellow River's channel characteristics in laboratories, simulating historical flood events and the effects of future engineering measures to inform channel management strategies. For example, historical floods with extreme peak discharges and long-term riverbed evolution under engineering regulation can be simulated on the scaled model to observe morphological changes (Li, 2006). However, the Model Yellow River is inherently limited by physical scaling and high experimental costs, yielding primarily qualitative insights into flow and sediment patterns.

The Digital Yellow River was proposed amid the rise of the Digital Earth concept, an innovative initiative integrating hydrological modelling, information technology, and big data analytics. Tsinghua University undertook planning and construction, developing a three-tiered structural framework: a foundational data and computing platform, an intermediate multi-scale modelling layer, and an application layer comprising six major decision-support systems (e.g., water allocation and flood control command systems). A key achievement was the Yellow River Water Volume Dispatch System, which addressed the intermittent flow problem in the lower reaches and received the Second Class Prize at the 2006 National Science and Technology Progress Award. The Digital Yellow River conducted numerical simulations of the entire watershed process (Li et al., 2025b; Hou and Zhang, 2025), from rainfall-runoff generation to sediment transport, but its development has since been constrained by the simplification of physical mechanisms rather than by computational power.

For two decades, the “Three Yellow River Initiative” framework has driven significant progress in Yellow River study and governance, achieving the “Four Nos” objectives proposed by the former Minister of Water Resources Shucheng Wang: unbroken river flow, non-rising riverbed, unbreached embankments, and compliant water quality (Li, 2004). However, with the new national requirements for ecological conservation and high-quality development of the Yellow River basin, the inherent limitations of the “Three Yellow River Initiative” framework have become increasingly insufficient: static modeling cannot adapt to the dynamic, nonlinear water-sediment dynamics; isolated operation leads to no closed-loop correction between simulation results and real-world observations; and simplified representations fail to capture the multi-scale complexity of the real river.

Simultaneously, the “Three Yellow River Initiative” has each reached its development bottlenecks: the Model Yellow River faces insurmountable scaling similarity challenges, the Digital Yellow River is constrained by unbridgeable gaps between simplified models and real-world scenarios, and the Prototype Yellow River provides only passive observation without real-time decision support. Against the backdrop of breakthrough advancements in artificial intelligence (AI) technology—especially in cognitive reasoning and real-time data processing—the transition from the static modelling paradigm of the “Three Yellow River Initiative” to the dynamic, reality-driven paradigm has become an inevitable trend for Yellow River governance (Geng et al., 2025).

3 New challenges for Yellow Rivers

After two decades of development, the “Three Yellow River Initiative” framework has encountered fundamental technical and methodological bottlenecks that cannot be resolved through incremental improvements in computational power or experimental precision. These bottlenecks stem from the inherent limitations of each component and the systemic deficiencies of isolated operations, making it impossible to address the complex imbalances in the new era.

3.1 The scaling similarity dilemma of the Model Yellow River

The Model Yellow River uses scaled-down physical modelling, typically with a scaling factor greater than 100, to simulate the dynamics of the real river. While it provides intuitive visual insights into flow and sediment-transport patterns, it faces an insurmountable scaling-similarity challenge: it is virtually impossible to simultaneously satisfy temporal, dynamic, and sediment-transport similarity between the model and the prototype. Velocity, time, and sediment erosion/deposition in the model require conversion via scaling factors, but the independent critical conditions for these conversions cannot be unified.

Although model tests yield quantitative measurements, their results primarily provide a qualitative understanding of macro-scale movement patterns rather than accurate quantitative predictions for real-world engineering. Additionally, the Model Yellow River incurs extremely high time and economic costs: model design and construction require substantial materials and labour, and experimental results are obtained over six months to a year (Li and Sheng, 2011). Over the past decades, model technology has seen little substantive progress, and its application has become increasingly constrained with the rapid development of numerical modelling, gradually losing its comparative advantage.

3.2 The physical simplification gap of the Digital Yellow River

The Digital Yellow River has achieved significant progress in computational scale and speed since its construction, with increasingly granular simulations and expanded data volumes over the past two decades. However, its development has stagnated in the cognitive understanding of physical fundamentals: all digital watershed models are extreme simplifications of the real world, abstracting complex natural processes into a set of mathematical equations that cannot capture the nonlinear, multi-scale, and turbulent characteristics of the Yellow River's water-sediment dynamics. Rainfall infiltration, surface runoff generation, slope erosion, and channel sediment transport in the real basin are highly complex processes influenced by numerous unquantifiable factors. Digital models simplify these processes through empirical parameters and idealised assumptions, thereby creating an inherent gap between simulation results and real-world observations that cannot be eliminated by finer discretisation or additional parameters (Jiang et al., 2025). Even the most sophisticated

digital models fail to fully replicate the real river's behaviour, especially for extreme events and complex water-sediment interaction processes.

3.3 The isolated operation shortcoming of the Three Yellow River Initiative

The most critical systemic deficiency of the “Three Yellow River Initiative” framework is its long-term isolated operation: the simulation results of the Model Yellow River are not real-time fused with the numerical data of the Digital Yellow River, and the prediction results of the Digital Yellow River are not closed-loop corrected with the observation data of the Prototype Yellow River. This disjointed operation leads to a fundamental problem: all governance decisions are based on simplified simulation or model results rather than real-time, real-world observations. Moreover, the isolated operation of the “Three Yellow River Initiative” prevents the predictive manifold from updating with prototype observations, exacerbating the topological rupture between predictive and real-world trajectories and further intensifying the prediction-reality deviation.

This isolated operation makes it impossible for the “Three Yellow River Initiative” to address the core water-sediment imbalance problems of the Yellow River identified in ecological conservation and high-quality development of the Yellow River Basin. The water-sediment imbalance manifests in multiple forms: sediment accumulation in reservoirs due to reduced flow velocity, temporal and spatial mismatch between water and sediment peaks in the basin, and insufficient sediment transport capacity under low-flow conditions. None of these imbalances can be fully replicated by physical model tests or numerical simulations. Furthermore, the suspended-river breaching risk—the greatest threat to the Yellow River's stability—entails numerous unforeseen real-world factors that exceed the predictive capacity of any simplified model.

In essence, the “Three Yellow River Initiative” framework is a static, linear, and single-scale modelling paradigm based on fixed initial/boundary conditions and scenario assumptions, while the Yellow River's water-sediment dynamics are dynamic, nonlinear, and multi-scale with a globally non-integrable state space. This fundamental mismatch makes it impossible for the traditional framework to fully capture and address the Yellow River's complex problems in the new era (Li et al., 2025a), necessitating a paradigm shift toward the “Hi-Fi Yellow River”.

4 Hi-Fi Rivers: artificial intelligence plus real-world scenarios

The breakthrough development of artificial intelligence (AI) over the past five years, particularly in large models, deep reasoning, and real-time data processing, has provided the technical foundation for the paradigm shift in Yellow River governance (Wang, 2026). Unlike general-purpose information technology two decades ago, which was limited by hardware and computational power, modern AI has evolved into a general-purpose technology with massive computing power, efficient algorithms, and strong cognitive capabilities, far surpassing the performance of specialised models in specific fields. This technological revolution has fundamentally changed the way water conservancy professionals conduct research and make decisions, ending the era of isolated operation of specialised models.

4.1 Definition of the Hi-Fi Yellow River

“Hi-Fi (High-Fidelity) Yellow River” is defined as a dynamic, closed-loop, reality-driven intelligent modelling and governance system for the Yellow River that takes real-time observation data from the Prototype Yellow River as the core, integrates the cognitive, reasoning, and decision-making capabilities of the Yellow River Basin Vertical Domain Large Model (YR-VDLM), and enables instantaneous switching of water management scenarios among pre-trained knowledge manifolds. Its core characteristic is the real-world perception-AI reasoning-scenario and switching-real-time feedback closed loop, which is fundamentally different from the passive observation of the Prototype Yellow River, the scaled simulation of the Model Yellow River, and the static numerical simulation of the Digital Yellow River. The paradigm integrates the YR-VDLM with specialised hydrological knowledge, enabling cross-manifold perception and reasoning for non-continuous decision-making in the Yellow River basin system.

The Hi-Fi Yellow River abandons the traditional approach of basing decisions on simplified models or simulations with fixed scenario assumptions, instead grounding all governance decisions directly in real-world scenarios of the Prototype Yellow River. It leverages the YR-VDLM as a bridge and translator between humans and nature, enabling timely responses to real-world problems and providing instant solutions for complex hydrological events. For example, a Hi-Fi Xiaolangdi Reservoir system will integrate the real reservoir's operational data with the YR-VDLM to enable real-time scenario recognition and optimal operation through knowledge manifold switching, without the need for scaled physical models or static numerical simulations. The Hi-Fi Yellow River integrates the real Yellow River basin with an AI foundation (Luo et al., 2025), unifying the “Three Yellow River Initiative” into a single reality-responsive intelligent system.

It is notable that the watershed digital twin, as an evolved form of the Digital Yellow River, still inherits and amplifies the inherent theoretical contradictions of traditional deterministic modelling, which cannot be resolved by iterative upgrades to data fusion, visualisation, or computing power. Fundamentally, the Yellow River basin state space is globally non-integrable and admits no globally smooth integrable solution or a continuous homotopy connecting the twin virtual trajectory to the prototype real evolution path. Digital twins construct a high-fidelity virtual replica by mapping physical attributes, boundary conditions, and dynamic processes in a one-to-one manner; however, this replication logic is premised on the false assumption that the basin system follows continuous, differentiable, and integrable evolution laws. The contact distribution of the basin's hydrological dynamics exhibits local complete non-integrability, leading to inevitable topological rupture between the digital twin's persistent simulation trajectory and the prototype's real-state jump (Arnold, 1989; Geiges, 2008; Zhong and Wang, 2025). Even with real-time data assimilation, the digital twin can perform only local numerical correction within a single integral leaf, failing to switch between disconnected scenario manifolds (Zhong and Wang, 2025). It remains trapped in the closed loop of virtual-real synchronisation based on fixed scenario presuppositions, unable to characterise the geometric locking effect, path dependence and discontinuous state transition driven by stochastic perturbations. Therefore, the digital twin remains a form of enhanced deterministic simulation that cannot overcome the topological bottleneck arising from the absence of a globally

integrable structure and is fundamentally incompatible with the non-smooth, multi-branch, and globally non-integrable evolution of the Yellow River system.

In fact, the proposition that the intrinsic evolutionary processes of natural river basins can be fully and rigorously replicated through the digital twin paradigm lacks scientific substantiation in both theoretical hydrology and the study of complex open systems. To date, there is no established mathematical framework that can theoretically prove the feasibility of mapping the full-dimensional, non-smooth, and stochastically perturbed natural basin processes into a virtual digital space with one-to-one correspondence and dynamic consistency; nor is there sufficient empirical evidence from long-term basin observation and simulation practices to verify that a digital twin can capture the unforeseeable discontinuous state jumps and emergent evolutionary characteristics inherent in natural watershed systems. All existing digital twin applications for river basins are essentially limited to the approximate simulation of local, relatively stable, and low-dimensional hydrological processes, rather than the authentic “twinning” of the holistic and evolving natural basin system—a distinction that is not a technical gap to be filled by data or computing power upgrades, but a fundamental scientific limitation that cannot be overcome by current paradigms.

4.2 Core innovations of the Hi-Fi Yellow River

Compared with the “Three Yellow River Initiative” framework, the Hi-Fi Yellow River paradigm achieves three fundamental innovations that directly address the core limitations of the traditional paradigm:

(1) Paradigm innovation: From model-driven to scenario-driven governance, shifting the decision-making basis from simplified model/simulation results to real-time real-world observations of the Prototype Yellow River, eliminating the inherent topological rupture between models and reality through dynamic knowledge manifold switching.

(2) Technical innovation: Integration of the YR-VDLM with hydrological specialised knowledge, enabling deep reasoning and instantaneous scenario recognition for complex hydrological events, and realising real-time closed-loop correction between data and engineering operations via adaptive manifold transitions.

(3) System innovation: Breaking the isolated operation of the “Three Yellow River Initiative”, constructing a unified intelligent system with real-world perception, YR-VDLM reasoning, scenario manifold selection, and engineering execution, and realising the organic integration of the Prototype, Model, and Digital Yellow Rivers.

4.3 Hi-Fi Yellow River vs. “Three Yellow River Initiative”

The Hi-Fi Yellow River paradigm provides targeted solutions for each core limitation of the “Three Yellow River Initiative” framework, with the corresponding relationship between the limitations and solutions summarised in Table 1. The core logic is to abandon the traditional simplified modelling approach based on fixed scenarios and continuous simulation, and to base research and governance directly on real-world scenarios of the Prototype Yellow River, with the YR-VDLM enabling real-time scenario recognition and dynamic manifold switching for decision-making.

4.4 Methodological transformation of research

The Hi-Fi Yellow River paradigm drives a fundamental methodological transformation of research for the Yellow River, shortening the traditional research pathway from conceptualisation → laboratory mechanism testing → field production trials to a direct scenario-based research approach: identifying problems in real-world practice → refining solutions through prototype engineering → optimising decisions via YR-VDLM reasoning and manifold switching. This transformation eliminates the intermediate links of simplified modelling and simulation, making research results more consistent with real-world conditions and more directly applicable to engineering practice.

A typical example is the water-sediment regulation of the Xiaolangdi Reservoir, the core engineering measure for Yellow River governance. Traditional research requires months of physical or numerical model simulations to determine the optimal control strategy, but the resulting solutions often deviate from real-world operations due to limitations in scaling or simplification. Hi-Fi research directly uses real-time observational data from the Xiaolangdi Reservoir and its upper/lower reaches, identifies the current hydrological scenario using the YR-VDLM, and immediately switches to the pre-validated optimal knowledge manifold for that scenario—enabling Q&A-based instant responses to complex water-sediment regulation problems through dynamic manifold transitions.

This scenario-based research approach, supported by the YR-VDLM, also simplifies long-term forecasting for the Yellow River. Traditional “Three Yellow River Initiative” models struggle to accurately predict the Yellow River’s water-sediment dynamics over the next 50 years because they cannot capture complex nonlinear processes and the basin system’s global nonintegrability. The Hi-Fi Yellow River system eliminates the need for long-term static predictions: it provides real-time insights into water-sediment variations and optimal

Table 1 Correspondence between the Limitations of the “Three Yellow River Initiative” and the Solutions of the Hi-Fi Yellow River.

Core Limitations of the “Three Yellow River Initiative”			Core Technical Support Yellow River Initiative	
Model Yellow River: Scaling dilemma, high cost	Similarity	No physical simulation; direct research on real-world scenarios	Real-world perception layer + YR-VDLM reasoning layer + Knowledge manifold switching	
Digital Yellow River: Physical simplification gap		YR-VDLM fusion of multi-source real-time data; dynamic model correction via manifold transitions	Multi-source data fusion + real-time correction algorithms + Scenario manifold library	
Isolated operation: No closed-loop correction		Perception-reasoning-decision-feedback closed-loop system with manifold switching	Scenario manifold switching algorithms + engineering execution layer	
Static modelling: Inability to adapt to dynamic water-sediment dynamics		Dynamic manifold switching for adaptive governance	YR-VDLM-driven scenario recognition + real-time control	
Fixed scenario & continuous simulation: Inherent topological rupture		Dynamic scenario reconstruction & transversal switching	YR-VDLM & contact geometric topological constraints	

governance strategies within days to weeks, based on real-world scenario observations and adaptive manifold switching, enabling more timely, adaptive governance decisions.

5 Theory of scenario switching

In the Hi-Fi Yellow River paradigm, governance decisions do not evolve smoothly from model predictions; instead, they undergo transversal transitions between distinct knowledge manifolds—from predictive scenario manifolds to observed real-world scenario manifolds—when significant topological rupture occurs. Contact geometry provides the natural mathematical language for describing such transitions between manifolds, as it inherently distinguishes between smooth evolution within a constrained distribution and transversal transitions between distinct geometric leaves (Arnold, 1989; Geiges, 2008; Zhong and Wang, 2025). Table 2 establishes the direct correspondence between core contact geometry concepts and their engineering interpretations for the Yellow River, providing an intuitive foundation for the subsequent mathematical formulation.

Table 2 Correspondence between Contact Geometry Concepts and Yellow River Hydrological Engineering Interpretations.

Geometry concept	Mathematical meaning	Engineering interpretation
Contact manifold $(\mathcal{E}, \Theta)$	Extended state space of river dynamics (state, co-state, time)	Comprehensive state space of the Yellow River's system
State Y_i	Physical state variables of the manifold	Key parameters (water level, sediment concentration, flow velocity)
Co-state ρ_i	Connection/sensitivity coefficients (Fisher information metric)	Sensitivity of engineering operations to hydrological parameter changes
Contact form Θ	Fundamental 1-form defining the contact structure	Geometric constraint of the Yellow River's water-sediment evolution
$\ker(\Theta)$ (contact distribution)	Kernel space for smooth predictive evolution	Static prediction process of the Model/Digital Yellow River
$\ker(d\Theta)$ (transversal space)	Kernel space for transitions between scenario manifolds	Real-world correction process via manifold switching in the Hi-Fi Yellow River
Constraint function ε	Power imbalance between prediction and reality	Systematic deviation between deterministic model predictions and prototype observations
Scenario manifold switching ΔY	Transversal state transition in $\ker(d\Theta)$	Dynamic switching of Hi-Fi Yellow River management scenario manifolds
Global non-integrability	No continuous mapping between predictive and real manifolds	Topological rupture of prediction-reality in traditional model simulation

5.1 The least constraint theorem for open stochastic systems

The geometric formalisation of the Hi-Fi Yellow River rests upon the least constraint theorem for stochastic vector bundles, a variational principle developed for dissipative, non-equilibrium systems governed by contact geometry (Zhong and Wang, 2025). Distinct from the classical least action principle, which presupposes energy conservation in closed Hamiltonian systems, the least constraint theorem provides a natural variational framework for open systems in which energy dissipation, stochastic fluctuations, and irreversible transitions between states are intrinsic.

The Yellow River is an open stochastic dissipative system with random hydrometeorological perturbations and human engineering interferences, and its state evolution is inherently accompanied by energy dissipation and random fluctuations (Wang et al., 2020). Consider the extended contact phase space $\mathcal{E} = T^*E \times \mathbb{R}$ equipped with the canonical contact form $\Theta = \mathcal{H}dt - \rho_i dY^i$, where $\mathcal{H} = dP(\dot{Y})$ denotes the contact probability potential (the observed probability current rate of water-sediment configuration changes, incorporating stochastic fluctuation terms to characterize the system's randomness), and ρ_i represents the co-state variables quantifying the Fisher information sensitivity of engineering operations to hydrological parameter changes. The constraint function is defined as

$$\varepsilon(t, Y, \rho) \triangleq \rho_i \dot{Y}^i - \mathcal{H} \quad (1)$$

which geometrically encodes the instantaneous systematic deviation between the deterministic model predictions (with fixed initial/boundary conditions) and the prototype observations of the Yellow River, the core topological discrepancy indicator of the traditional modelling paradigm.

The least constraint theorem states that the dynamical evolution of the system extremizes the action functional of the constraint.

$$\delta \int_{t_0}^{t_1} \varepsilon dt = 0 \quad (2)$$

This variational principle yields the contact dynamical equations governing the co-evolution of states and connections:

$$\begin{cases} \frac{dY^i}{dt} = \{Y^i, \mathcal{H}\} \\ \frac{d\rho_i}{dt} = \{\rho_i, \mathcal{H}\} \\ \frac{\partial \varepsilon}{\partial t} = -\{\varepsilon, \mathcal{H}\} \end{cases} \quad (3)$$

where $\{\cdot, \cdot\}$ denotes the Poisson bracket on $\mathcal{E}$. Geometrically, these equations describe a unique vector field $X_{\mathcal{H}} \in \ker(d\Theta)$ whose flow preserves the contact structure ($\mathcal{L}_{X_{\mathcal{H}}} \Theta = 0$) while minimising the accumulated constraint violation.

The physical implication for the Hi-Fi Yellow River paradigm is profound: the theorem mandates that the governance system must evolve along trajectories that continuously minimise the systematic deviation ε between prediction and observation. When the hydrological reality deviates critically from the model prediction—driving ε toward a critical threshold $\varepsilon_{\max}$ —the smooth evolution within the current scenario manifold becomes geometrically forbidden. The system must then execute a transversal transition to a new operational regime manifold that re-establishes the minimisation of ε . This provides a rigorous variational justification for the transitions between management-scenario manifolds (e.g., from drought management to flood control) that characterise the Hi-Fi Yellow River paradigm, as detailed in the following subsections.

5.2 The manifold of Yellow River states

The core objective herein is to construct a contact manifold for the Yellow River's dynamics, decomposing the system's evolution into smooth, predictive evolution within a scenario manifold and transversal switching to real-world scenario manifolds, thereby providing a foundational geometric framework for manifold switching.

Consider the extended phase space $\mathcal{E} = T^*E \times \mathbb{R}$, where E represents the basic state space of the Yellow River, consisting of key hydrological parameters Y_i such as water levels, sediment concentrations, and flow velocities at major monitoring stations. The extended manifold $\mathcal{E}$ incorporates the co-states ρ_i (sensitivities of engineering operations to hydrological parameter changes, quantified by the Fisher information metric) and time t , forming the comprehensive state space of the Yellow River's dynamics with global non-integrability. We equip this manifold with the canonical contact form.

$$\Theta = \mathcal{H}dt - \rho_i dY^i \quad (4)$$

where $\mathcal{H}$ denotes the state-evolution rate of the Yellow River system, not a constructed Hamiltonian, but rather the observed probability current rate for configuration changes, $dP(\dot{Y})$. The scenario manifold covers multi-process coupling characteristics, including hydrology, sediment, ecology, climate and human activities, forming a high-dimensional knowledge manifold consistent with the real basin system and the core connotation of the knowledge manifold in Yellow River governance.

The fundamental geometric decomposition of the tangent space at any point $(t, Y, \rho) \in \mathcal{E}$ is

$$T_{\mathcal{E}(t,Y,\rho)} = \underbrace{\ker(\Theta)}_{\text{Predictive Evolution (Model/Digital/YR-VLDM)}} \oplus \underbrace{\ker(d\Theta)}_{\text{Transversal Switching (Hi-Fi Yellow River)}} \quad (5)$$

This decomposition rigorously separates the two fundamental evolution modes of the Yellow River governance system: the Digital Yellow River evolves smoothly within the contact distribution $\ker(\Theta)$, static prediction based on coded river networks and fixed scenario equations, while the Hi-Fi Yellow River executes transversal transitions along $\ker(d\Theta)$ between distinct scenario manifolds, real-time correction to observed reality.

When the observed real-world state Y_{obs} from the Prototype Yellow River deviates from the predicted trajectory $Y_{\text{pred}}(t)$ by a finite amount $\Delta Y = Y_{\text{obs}} - Y_{\text{pred}}$, the system cannot accommodate this mismatch through smooth evolution. The imbalance described in Section 3 manifests geometrically as the necessity for a scenario manifold switch.

$$Y^+ = Y^- + \Delta Y, \quad \Delta Y \in \pi_*(\ker(d\Theta)) \quad (6)$$

with $\pi: \mathcal{E} \rightarrow E$ being the canonical projection to the basic state space. This transition represents the dynamic switching from a predictive management scenario manifold (e.g., flood prediction) to a real-world, responsive scenario manifold (e.g., breach emergency), or from normal operation to sediment-flushing mode, thereby aligning the governance system directly with observed reality.

(1) Proposition 1 (Irreducibility of Scenario Manifold Switching). Due to the global non-integrability of the Yellow River basin state space and the local complete non-integrability of the contact distribution $[\ker(\Theta), \ker(\Theta)] \not\subset \ker(\Theta)$, which arises from the turbulent, multi-scale, and nonlinear nature of the Yellow River's flows, there exists no smooth homotopy connecting the predicted trajectory $\gamma_{\text{pred}} \subset \ker(\Theta)$ with the reality-adjusted trajectory γ_{real} passing through Y^+ . Therefore, the switching between Hi-Fi management scenario manifolds is a topological necessity rather than a numerical correction that can be achieved through finer discretisation or parameter tuning.

(2) Engineering Implication: This proposition mathematically proves that the systematic deviation between the Model/Digital Yellow River's predictions and the Prototype Yellow River's real-world observations cannot be eliminated by any continuous model improvement. The nonlinear, multiscale and stochastic characteristics of the Yellow River's dynamics make smooth interpolation from simplified models to real-world conditions geometrically impossible, establishing the theoretical necessity of scenario manifold switching for the Hi-Fi Yellow River.

This geometric irreducibility explains why both the Model Yellow River (scaled by a factor of 100) and the Digital Yellow River (with 20 million river segments) fail to accurately predict real-world Yellow River behaviour: their smooth predictive trajectories are geometrically disconnected from the real-world state space, and only transversal transitions between scenario manifolds can bridge this topological rupture.

5.3 Contact dynamics for system modelling

The constraint function $\varepsilon = \rho_i \dot{Y}^i - \mathcal{H}$ quantifies the instantaneous systematic deviation between the Model/Digital Yellow River's deterministic predictions and the real river's evolutionary state. When the accumulation of prediction-reality deviation drives ε toward

critical values (e.g., embankment stress limits, sediment transport capacity thresholds), the smooth predictive dynamics break down, necessitating immediate emergency engineering intervention and scenario manifold switching.

To capture the rapid manifold switching behaviour characteristic of Yellow River emergency control (instantaneous opening of reservoir floodgates, rapid adjustment of diversion ratios), we extend the standard contact dynamical equations to accommodate impulsive transitions between manifolds:

$$\frac{dY^i}{dt} = \{Y^i, \mathcal{H}\} + \sum_k \Delta Y_k^i \cdot \delta(t - t_k), \quad \frac{d\varrho_i}{dt} = \{\varrho_i, \mathcal{H}\} + \Delta \varrho_i \cdot \delta(t - t_k) \quad (7)$$

where t_k denotes the switching instants determined by the crossing of a threshold manifold $\Sigma_\varepsilon = \{(Y, \varrho) \mid \varepsilon(Y, \varrho) = \varepsilon_{\max}\}$. In the Hi-Fi Yellow River framework, these switching instants correspond to the “Q & A-based instant responses”—the moment the YR-VDLM recognises a critical topological rupture between prediction and reality and triggers an emergency regulation protocol through manifold switching.

To ensure that all scenario manifold switches preserve the physical validity of the Yellow River’s water-sediment system (e.g., mass conservation, momentum balance), the state transition ΔY and co-state (connection) transition $\Delta \varrho$ must satisfy the contact matching condition.

$$t_{\Delta X} \Theta = -\Delta \varepsilon \quad (8)$$

where $\Delta X = (0, \Delta Y, \Delta \varrho)$ is the transition vector in the tangent space $T\mathcal{E}$. Expanding this condition using the definition of the contact form Θ gives the explicit physical constraint.

$$\mathcal{H}(t, Y^+, \varrho^+) - \mathcal{H}(t, Y^-, \varrho^-) - \varrho_i^+ \dot{Y}^{i+} + \varrho_i^- \dot{Y}^{i-} = \Delta \varepsilon \quad (9)$$

This contact matching condition ensures that emergency engineering interventions (scenario manifold switches) do not violate the fundamental geometric and physical constraints of water-sediment transport; they merely transfer the governance system between distinct integral curves of $\ker(\Theta)$ —from one operational scenario leaf to another.

5.4 Geometric locking and path dependence

The imbalance between water and sediment dynamics noted in Section 3 manifests geometrically as the geometric locking effect: once the Hi-Fi Yellow River system switches from the predicted state manifold Y^- to the real-world observed state manifold $Y^+ = Y_{\text{obs}}$, it enters a new leaf of the attempted foliation of $\ker(\Theta)$. External abrupt perturbations (e.g., sudden flood peaks or reservoir operation adjustments) trigger the reconstruction of knowledge manifolds, forcing transversal switching along $\ker(d\Theta)$. After switching, due to the global non-integrability of the basin state space and the complete non-integrability of the contact distribution $[\ker(\Theta), \ker(\Theta)] \not\subset \ker(\Theta)$, there exists no diffeomorphism that can smoothly map the new real-world trajectory $Y^+(t)$ back to the original predicted trajectory $Y_{\text{pred}}(t)$ while preserving the contact form Θ . The system is “locked” into the new real-world scenario leaf and must evolve along this new leaf for all subsequent time. Distinct intermediate real-world states lead to different switching branches, resulting in significant divergences in water-sediment regulation outcomes, which is the core topological reason for the path dependence of Yellow River governance results.

This geometric locking effect directly explains the path dependence of the Yellow River’s dynamics: distinct intermediate real-world states (e.g., early vs. late arrival of flood peaks, different sediment-concentration distributions) lead to different final system configurations even under identical initial conditions. The scenario manifold switch serves as an irreversible branch-switching in the space of water-sediment trajectories, fundamentally altering the system’s manifold of future evolution.

5.5 Extremal principle for Hi-Fi Yellow River

The core objective of this subsection is to establish a variational principle for the Hi-Fi Yellow River paradigm that accommodates piecewise-smooth extremal curves with transitions between manifolds, providing an optimisation foundation for YR-VDLM-driven scenario-based governance decisions.

The operation of the Hi-Fi Yellow River paradigm, optimising water-sediment allocation and flood control through YR-VDLM-driven scenario manifold switching, requires a variational principle that departs from the traditional smooth calculus of variations to admit piecewise smooth extremal curves with transitions between distinct scenario manifolds. We define the action functional with real-world compliance penalties to capture both smooth predictive evolution and transitions between scenario manifolds.

$$\mathcal{S}[\gamma] = \sum_{k=0}^N \int_{t_k}^{t_{k+1}} \varepsilon(\gamma(t)) dt + \sum_{k=1}^N \Lambda_k \mathcal{P}(Y_k^-, Y_k^+) \quad (10)$$

where $\mathcal{P}(Y^-, Y^+) = \frac{1}{2} \|Y^+ - Y_{\text{obs}}\|^2$ represents the Hi-Fi penalty for deviation from observed real-world states, and Λ_k is the reality compliance strength coefficient that controls the system’s tendency to match real-world observations.

Requiring the action functional $\mathcal{S}[\gamma]$ to be stationary (the fundamental condition for variational optimisation) yields the generalised Weierstrass-Erdmann corner conditions at each scenario manifold switching instant t_k .

$$\varepsilon(t_k^-) = \varepsilon(t_k^+), \quad \varrho_i(t_k^+) - \varrho_i(t_k^-) = -\Lambda_k (Y_i^+ - Y_{\text{obs},i}) \quad (11)$$

The first condition ensures the state imbalance ε remains continuous across the scenario manifold switch, preventing physical

discontinuities in the water-sediment system. The second condition directly relates the transition in the co-state (YR-VDLM-adjusted engineering operation sensitivities) to the geometric displacement required to match real-world observations.

These generalised corner conditions formalise the Q&A methodology of the Hi-Fi Yellow River in the language of contact geometry: at each switching instant t_k , the system queries the Prototype Yellow River “What is the real current state?” (Y_{obs}) and switches instantaneously to this state manifold, adjusting its internal sensitivity parameters ρ by $\Delta\rho$ to lock onto the new real-world scenario. The discrete change in the constraint action $\Delta S_e = \varepsilon^+ - \varepsilon^-$ represents the geometric entropy production associated with the prediction-reality topological rupture, which is always non-negative and quantifies the irreversible information gain when the Hi-Fi system incorporates real-world observations from the Prototype Yellow River.

6 Algorithms for AI+scenarios

6.1 Architecture of the vertical domain large model

The transition from the “Three Yellow River Initiative” to the Hi-Fi Yellow River requires algorithms that can execute instantaneous, physically constrained transitions between distinct management scenario manifolds (e.g., from drought management to flood control, or from normal operation to emergency sediment flushing). The Yellow River Basin Vertical Domain Large Model (YR-VDLM) comprises three core modules: a prototype real-time perception module, a contact geometric constraint reasoning module, and a cross-manifold switching decision module, forming a closed-loop intelligent reasoning system adapted to the high-dimensional, non-continuous, and multi-physical coupling characteristics of the Yellow River basin. This section formalises these transitions as scenario-manifold switches within the contact-geometric framework established in Section 5, with a clear mapping between algorithmic components and the associated geometric constraints. The system state θ represents the operational parameters of the Yellow River governance system (reservoir gate settings, water diversion ratios, sediment flushing schedules), and the co-state ρ represents the sensitivity of system performance to parameter changes (Fisher information metric), consistent with the contact geometric notation in Section 5.

In this framework, the pre-trained management scenarios for the Yellow River (flood control, drought management, normal operation, ice-jam prevention, etc.) constitute a library of Hi-Fi scenario manifolds $\mathcal{M} = \{Y_{\text{obs}}^{(0)}, Y_{\text{obs}}^{(1)}, \dots, Y_{\text{obs}}^{(N-1)}\}$, each representing a pre-validated optimal snapshot of operational parameters validated by real-world Prototype Yellow River data for a specific hydrological regime. The Hi-Fi Yellow River system operates in two fundamental modes: smooth evolution within the current scenario manifold (normal operation) or transversal switching to a new scenario manifold (emergency response) when real-time observations deviate critically from predictions. The YR-VDLM integrates generative AI to construct unseen extreme scenario manifolds based on the pre-trained library, realising generalisation and reasoning for unprecedented hydrological events under climate change and compound disturbances.

6.2 Knowledge manifold construction

First, we construct a library of Hi-Fi scenario manifolds by pre-training on historical hydrological regime data from the Prototype Yellow River and validating each scenario’s operational effectiveness in real-world conditions to ensure high-fidelity correspondence with actual Yellow River conditions.

Table 3 Algorithm 1: Construction of Hi-Fi Scenario Manifolds.

Require: Training datasets $\{\mathcal{D}_k\}_{k=0}^{N-1}$ for N distinct hydrological scenarios

Ensure: Library of pre-trained scenario manifolds $\mathcal{M} = \{Y_{\text{obs}}^{(k)}\}_{k=0}^{N-1}$ with effectiveness probabilities (dynamic reconstruction enabled by prototype observations)

for $k = 0$ to $N - 1$ do

Initialize model parameters $\theta^{(k)} \in \mathbb{R}^d$

for iteration = 1 to T_{pre} do

Sample minibatch $(x, y) \sim \mathcal{D}_k$

Compute loss $\mathcal{L} = \text{CrossEntropy}(f_{\theta^{(k)}}(x), y)$

Update $\theta^{(k)} \leftarrow \theta^{(k)} - \eta \nabla_{\theta} \mathcal{L}$

end for

Freeze the pre-trained optimal parameters of the scenario manifold: $Y_{\text{obs}}^{(k)} \leftarrow \theta^{(k)}$ with $\nabla_{Y_{\text{obs}}^{(k)}} = 0$ (dynamic reconstruction enabled in real-time operation)

Evaluate Hi-Fi metric $P(Y_{\text{obs}}^{(k)}) = \exp(\sum \log p(y|x; Y_{\text{obs}}^{(k)}))$ on validation set

end for

return $\mathcal{M} = \{Y_{\text{obs}}^{(k)}\}_{k=0}^{N-1}$ with associated effectiveness probabilities $\{P_k\}$

Here, $P(Y_{\text{obs}}^{(k)})$ represents the sequence joint probability of the scenario manifold explaining real-world hydrological observations, quantifying the effectiveness of scenario k in guiding Yellow River governance decisions. This metric directly corresponds to the Hi-Fi measure of each management scenario, ensuring that only the most effective, real-world, validated scenarios are included in the library.

6.3 Contact-aware online evolution with scenario switching

During real-time Hi-Fi Yellow River operation, the system maintains a current operational state θ , a co-state (connection) $\wp$ (performance sensitivity), and an active scenario index c . The system evolves according to the contact dynamics described in Section 5 within the current scenario manifold, executing transversal switching to a new scenario manifold only when the constraint violation ε exceeds the critical threshold $\varepsilon_{\max}$ (indicating a severe topological rupture between prediction and reality).

Table 4 Algorithm 2: Contact-Aware Decoding with Scenario Manifold Switching (Hi-Fi Yellow River Operation).

Require: Observation sequence $\{(x_t, Y_t)\}_{t=1}^T$, scenario library $\mathcal{M}$, threshold $\varepsilon_{\max}$, switching intensity λ , learning rate η , momentum β

Initialize current state θ , connection $\wp \leftarrow 0$, active scenario $c \leftarrow -1$, time step $\Delta t \leftarrow 1.0$

for $t = 1$ to T do

 Receive observation (x_t, Y_t) from Prototype Yellow River real-time sensors

 if $c = -1$ (no active scenario) then

 Trigger Manifold Switch (initialization or system reset)

 Execute SCENARIO_SWITCH($\theta, \wp, x_t, Y_t, \mathcal{M}, \lambda$)

 else

 Smooth Evolution: Compute predictive dynamics within $\ker(\Theta)$

 Compute current probability $P^- \leftarrow \exp(\sum \log p(Y_t | x_t; \theta))$

 Compute gradient $g \leftarrow \nabla_{\theta} \mathcal{L}(\theta; x_t, Y_t)$

 Update connection (Fisher metric): $\wp \leftarrow \beta \wp + (1 - \beta)g$

 Predict next state: $\theta_{\text{pred}} \leftarrow \theta - \eta \wp$

 Compute predicted probability $P^+ \leftarrow \exp(\sum \log p(Y_t | x_t; \theta_{\text{pred}}))$

 Compute state evolution rate: $\mathcal{H} \leftarrow (P^+ - P^-)/\Delta t$

 Compute state evolution rate: $\dot{Y} \leftarrow (\theta_{\text{pred}} - \theta)/\Delta t$

 Compute constraint violation: $\varepsilon \leftarrow |\langle \wp, \dot{Y} \rangle - \mathcal{H}|$ (systematic prediction-reality deviation)

 if $\varepsilon > \varepsilon_{\max}$ then

 Switching Condition Triggered: Severe topological rupture between prediction and reality

 Execute SCENARIO_SWITCH($\theta, \wp, x_t, Y_t, \mathcal{M}, \lambda$)

 Update active scenario $c \leftarrow \arg \max_k P(Y_{\text{obs}}^{(k)} | x_t)$

 else

 Accept smooth evolution: $\theta \leftarrow \theta_{\text{pred}}$ (continue current scenario)

 end if

 end if

end for

return Optimised real-time operational parameters θ_T

Table 5 Algorithm 3: Scenario Manifold Switching Mechanics (SCENARIO_SWITCH).

Require: Current state θ^- , current connection $\wp^-$, observation (x, Y) , scenario library $\mathcal{M}$, intensity λ

Ensure: Updated state θ^+ , updated connection $\wp^+$, constraint error change $\Delta \varepsilon$

1: Evaluate all scenarios: $P_k \leftarrow P(Y_{\text{obs}}^{(k)} | x) = \exp(\sum \log p(Y | x; Y_{\text{obs}}^{(k)}))$ for $k = 0, \dots, N-1$

2: Select optimal Hi-Fi scenario manifold: $k^* \leftarrow \arg \max_k P_k$

3: State transition: $\theta^+ \leftarrow Y_{\text{obs}}^{(k^*)}$ (switch to real-world scenario manifold)

4: Compute state displacement: $\Delta Y \leftarrow \theta^+ - \theta^-$

5: Connection adjustment: $\wp^+ \leftarrow \wp^- - \lambda \cdot \Delta Y$ (YR-VDLM-adapted co-state adjustment)

6: Compute state evolution rates: $\mathcal{H}^- \leftarrow \mathcal{H}(\theta^-)$, $\mathcal{H}^+ \leftarrow \mathcal{H}(\theta^+)$

7: Compute constraint residual: $\Delta \varepsilon \leftarrow (\mathcal{H}^+ - \mathcal{H}^-) - (\langle \wp^+, \dot{Y}^+ \rangle - \langle \wp^-, \dot{Y}^- \rangle)$

8: Verify contact preservation: ensure $\iota_{\Delta X} \Theta = -\Delta \varepsilon$ (contact matching condition)

9: return $\theta^+, \wp^+$

6.4 Advantages of geometric algorithms for YR-VDLM

Traditional machine learning algorithms (e.g., LSTM, CNN) for Yellow River governance focus solely on data-driven prediction, without accounting for the physical and geometric constraints of water-sediment transport, resulting in non-physical predictions that cannot be directly applied to engineering operations (Donnelly et al., 2024; Mahdavi-Meymand et al., 2024). Traditional control-theory algorithms (e.g., Model Predictive Control, MPC) support only smooth parameter adjustments within a single scenario and cannot handle the discontinuous emergency operations required during extreme hydrological events in the Yellow River.

The contact geometric scenario manifold switching algorithms proposed in this section, embedded in the YR-VDLM, address these limitations by achieving a unique combination of physical constraint compliance and operational adaptivity:

(1) Rigorous physical and topological constraints: All algorithmic steps strictly follow the contact geometric kinematic constraints (contact matching condition, Weierstrass-Erdmann corner conditions) and fundamental physical laws (mass conservation, momentum balance) of the Yellow River's multi-process coupling system, ensuring that all operational decisions and scenario manifold switches are physically valid.

(2) Cross-manifold jump reasoning for scenario mutation: The YR-VDLM natively supports transversal transitions between distinct management scenario manifolds, enabling real-time emergency responses to extreme and compound hydrological events that are impossible with traditional smooth control algorithms.

(3) Real-world scenario grounding with dynamic reconstruction: All scenario manifolds in the library are pre-validated with Prototype Yellow River real-world data, and the YR-VDLM realises dynamic real-time reconstruction and matching of manifolds driven by prototype observations, ensuring that the algorithm's decisions are grounded in actual Yellow River conditions rather than simplified model simulations.

(4) High-dimensional heterogeneous inference for multi-physical coupling: The integration of contact geometry with the YR-VDLM enables real-time scenario recognition and sensitivity adjustment for high-dimensional knowledge manifolds, making the governance system adaptive to the dynamic, nonlinear, stochastic and multi-scale water-sediment dynamics of the Yellow River through intelligent manifold switching.

(5) Unseen scenario generalisation: The YR-VDLM integrates generative AI to construct unseen extreme scenario manifolds based on the pre-trained library, breaking through the limitation of traditional AI that can only reason within pre-defined scenarios.

This algorithmic framework realizes the Q&A-based instant response mechanism of the Hi-Fi Yellow River described in Section 4: at each time step, the YR-VDLM queries the Prototype Yellow River for real-time observations, compares them with the Model/Digital Yellow River predictions, and executes an instantaneous scenario manifold switch to the optimal Hi-Fi scenario if the topological rupture exceeds the critical threshold—bypassing the time-consuming simulations and scaling corrections of the traditional “Three Yellow River Initiative” framework.

7 Conclusion

7.1 Core conclusions

This paper addresses three fundamental scientific issues in Yellow River basin governance and proposes the Hi-Fi Yellow River paradigm, a fundamental paradigm shift from the static, model-driven governance of the “Three Yellow River Initiative” to dynamic, real-world scenario-driven decision-making for the Yellow River basin.

The core conclusion is that the inherent limitations of the “Three Yellow River Initiative”—scaling similarity dilemmas of physical models, physical simplification gaps of digital simulations, and isolated operation of the entire framework—are rooted in a fundamental mismatch between the static, linear modelling paradigm based on fixed initial/boundary conditions and scenario assumptions, and the dynamic, nonlinear, stochastic, multi-scale nature of the Yellow River's water-sediment dynamics with a globally non-integrable state space. These limitations cannot be resolved through incremental technical improvements and require a complete methodological transformation.

The Hi-Fi Yellow River paradigm addresses this mismatch by grounding all governance decisions directly in real-time observations from the Prototype Yellow River, leveraging the Yellow River Basin Vertical Domain Large Model (YR-VDLM) to enable instantaneous switching between pre-validated scenario manifolds, and unifying the “Three Yellow River Initiative” into a single closed-loop, reality-responsive intelligent system. We formalised this paradigm using contact geometry, the first application of this mathematical framework to Yellow River governance, which rigorously captures the transitions between scenario manifolds as transversal transitions along $\ker(d\Theta)$ in the water-sediment state contact manifold. The contact geometric formulation proves that scenario manifold switching is a topological necessity for Yellow River governance, not a numerical correction, and provides kinematic constraints for adaptive water-sediment regulation strategies to ensure physical validity.

The contact-geometric scenario-manifold-switching algorithms embedded in the YR-VDLM operationalise the Hi-Fi Yellow River paradigm, bridging the gap between abstract mathematical theory and practical engineering applications. These algorithms combine the physical-constraint compliance of contact geometry with the real-time adaptivity of the YR-VDLM, enabling instantaneous, physically valid transitions between scenario manifolds for emergency water-sediment control—a capability unavailable with traditional machine-learning or control-theory algorithms. The Hi-Fi Yellow River paradigm fundamentally solves the core water-sediment imbalance problems of the Yellow River, providing a new technical system for ecological conservation and high-quality development of the Yellow River basin in the new era.

7.2 Key innovations

This paper makes three innovations at the intersection of Yellow River hydrological engineering, contact geometry, and artificial intelligence, directly responding to the three core scientific issues of Yellow River basin governance:

(1) Paradigm innovation in Yellow River governance: The first formal proposal and definition of the Hi-Fi Yellow River paradigm, establishing a new reality-driven, closed-loop intelligent governance framework that transcends the traditional “Three Yellow River Initiative”. This innovation redefines the relationship between model simulations and real-world observations, shifting the basis for governance decision-making from simplified models with fixed scenarios to real-time Prototype Yellow River data through dynamic scenario manifold switching, and revealing the topological origin of the systematic prediction-reality deviation.

(2) Mathematical innovation in hydrological modelling: The first application of contact geometry to the Yellow River’s water-sediment dynamics, constructing a contact manifold for the river’s state space with global non-integrability and formalising scenario manifold switching as transversal geometric transitions. This mathematical framework provides a rigorous topological foundation for adaptive hydrological governance decisions, proves the irreducibility of scenario manifold switching, clarifies the dynamic reconstruction mechanism of knowledge manifolds and the path dependence of governance results, and fills a gap in the nonlinear, stochastic, and multi-process coupling modelling of Yellow River water-sediment dynamics.

(3) Algorithmic innovation in water conservancy engineering: The development of contact geometric scenario manifold switching algorithms embedded in the YR-VDLM that integrate contact geometric physical constraints with AI-driven real-time decision-making. These algorithms realise the dynamic-scenario manifold-switching mechanism of the Hi-Fi Yellow River paradigm, addressing the key limitation of traditional algorithms in handling discontinuous emergency water-sediment control operations, and providing a new computational tool for real-time Yellow River governance with cross-manifold perception and reasoning capabilities.

7.3 Future directions and implications

Future research will address the following core scientific issues:

(1) Real-world algorithm validation and optimisation: Validate the scenario manifold switching algorithms using real-time monitoring and operational data from the Prototype Yellow River, tuning algorithm parameters for engineering practice and analysing computational complexity for real-time implementation of the YR-VDLM.

(2) Unprecedented scenario generation: Further integrate generative AI with the Hi-Fi scenario manifold library of the YR-VDLM to generate optimal management strategies for unprecedented extreme hydrological events, improving the system’s resilience to climate change and unforeseen natural disasters.

(3) YR-VDLM platform construction: Construct a Hi-Fi Yellow River AI platform based on the YR-VDLM that integrates the contact geometric model, scenario manifold switching algorithms, and real-time monitoring data, providing a visual, interactive decision support system for Yellow River governance professionals.

The Hi-Fi Yellow River paradigm is not only a new framework for Yellow River governance but also provides a general methodological model for the management of other complex large river basins worldwide facing similar water-sediment imbalance, flood control, and ecological protection challenges. The integration of contact geometry, the vertical domain large model, and real-world, scenario-driven research presented in this paper offers a new approach to addressing the fundamental mismatch between simplified models and complex natural systems—a common problem across many fields of environmental engineering and earth sciences.

For the Yellow River basin, the Hi-Fi Yellow River represents the next generation of intelligent governance technology, aligning with the national strategy for ecological conservation and high-quality development. By grounding governance decisions in real-world observations and enabling instantaneous, YR-VDLM-driven scenario-manifold switching, the Hi-Fi Yellow River will enhance the safety and resilience of the Yellow River system, ensure the sustainable use of water resources, and promote harmonious coexistence between humans and the Yellow River for generations to come.

Appendix

Table A1 List of main notations.

Contact geometry and system state		Algorithms and operational parameters	
$\mathcal{E}$	Extended contact manifold of Yellow River water-sediment dynamics	θ	Real-time operational parameters of the Yellow River governance system
Θ	Canonical contact form defining the contact manifold structure	$\mathcal{M}$	Library of pre-trained Hi-Fi scenario manifolds (dynamic reconstruction enabled by prototype observations)
$T\mathcal{E}$	Tangent space of the contact manifold $\mathcal{E}$	$Y_{\text{obs}}^{(k)}$	k -th pre-trained Hi-Fi scenario manifold (real-world validated, frozen parameters with dynamic reconstruction)
Y_i	Core hydrological state variables (water level, sediment concentration, flow velocity)	$P(Y_{\text{obs}}^{(k)})$	Hi-Fi metric/scenario effectiveness probability
$\mathcal{I}_{\theta}$	Co-state/connection coefficients (Fisher information sensitivity metric)	ε_{max}	Critical constraint violation threshold (scenario manifold switch trigger, topological rupture threshold)
$\mathcal{H}$	System state evolution rate (observed water-sediment configuration probability current, with stochastic fluctuation terms)	λ	Switching intensity coefficient (YR-VDLM-adapted co-state adjustment strength)
$\ker(\Theta)$	Contact distribution (smooth predictive evolution space)	Λ_k	Reality compliance penalty coefficient (Weierstrass-Erdmann conditions)

(Continued)

Contact geometry and system state		Algorithms and operational parameters	
$\ker(d\Theta)$	Transversal space (scenario manifold switching space)	β	Momentum coefficient (Fisher metric update)
ϵ	Constraint function/violation (systematic deviation between deterministic model predictions and prototype observations)	η	Learning rate (parameter optimisation)
ΔY	State displacement vector (scenario manifold transition amplitude)	c	Active scenario index (Hi-Fi scenario library)
ΔX	Transition vector in the tangent space $T\mathcal{E}$	YR-VDLM	Yellow River Basin Vertical Domain Large Model (core AI engine for Hi-Fi Yellow River)
Φ	Geometric phase/holonomy (cumulative prediction-reality mismatch invariant)		
Global non-integrability	The absence of smooth homotopy connecting predictive and real-world trajectories in the basin state space (core topological characteristic of the Yellow River system)		

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Author contribution statement

Junli Wang is responsible for conceptualization, methodology, formal analysis, and writing the original draft. Tiejian Li is responsible for methodology, validation, and reviewing and editing the manuscript. Deyu Zhong is responsible for conceptualization, supervision, funding acquisition, and reviewing and editing the manuscript. Jiahui Gao, Siyu Kang, Chensong Zhao, Dongfang Weiran, Jing Li, Zhi Tang, Qihua Ke, Jingwei Huang, Jinqiang Wang, Shen Zhang, and Jiaye Li contributed to investigation, validation, discussion, and reviewing the manuscript. All authors have approved the final manuscript.

Data availability

No new experimental data were generated in this study. Any data or materials supporting the findings of this work are available from the corresponding author upon reasonable request.

Use of AI statement

None.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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