



GLOBAL GEOPHYSICAL HAZARDS: INTEGRATING
MECHANICAL EROSION MODELING WITH REGIONAL MUDFLOW
AND COASTAL GROUNDWATER VULNERABILITY ASSESSMENTS

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Annotation: *This article analyzes the critical intersection of mechanical erosion modeling in multi-phase mass flows and the subsurface impacts of sea-level rise (SLR) on coastal groundwater dynamics. By employing the Unified Mechanical Erosion Model (UMEM), the study evaluates geophysical hazards in volatile mountainous corridors—specifically utilizing Uzbekistan's Fergana Valley as a primary case study—while concurrently addressing the "hidden" convergence of impacts in global coastal megalopolises. The research details how subsurface hydrological shifts compromise urban infrastructure, mobilize contaminants, and threaten public health. Ultimately, this unified framework provides a corrective roadmap for international policymakers, advocating for a transition from reactive, single-phase catastrophe management to proactive, data-driven adaptive strategies.*

Keywords: *Geophysical Hazards, Unified Mechanical Erosion Model (UMEM), Multi-phase Flow, Mudflow Dynamics, Coastal Groundwater, Sea-Level Rise (SLR), Infrastructure Vulnerability, Adaptive Management.*

1. Executive Introduction: The Convergent Crisis of Geophysical Instability

Modern risk management is confronting a convergent crisis where traditional, empirical assessments fail to account for the non-linear mechanics of

multi-phase flows and subsurface hydrological shifts [1]. As global development penetrates volatile mountainous corridors and low-lying coastal megalopolises, the strategic imperative shifts toward a unified quantification of mass flow energy budgets and groundwater-induced structural decay.

Resilience mandates a rigorous quantification of the stress jumps across the erosion interface to prevent the historical trend of "maladaptation"—specifically the deployment of rigid defensive infrastructure that neglects the surreptitious subsurface mechanics of water-table rise and soil saturation [1], [2]. This document codifies a unified framework bridging the gap between theoretical fluid dynamics and strategic hazard mitigation.



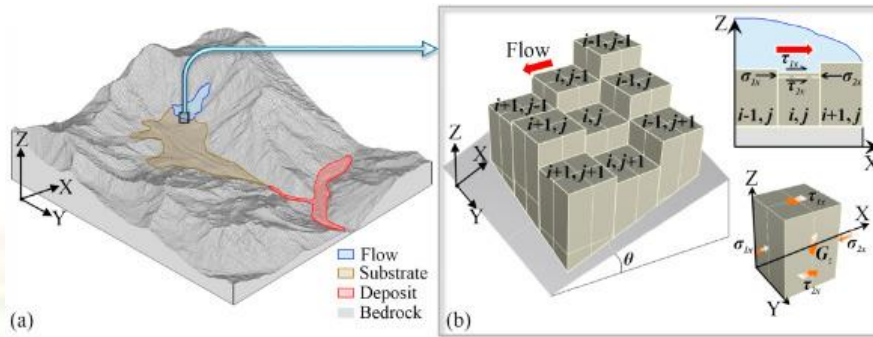
1st Image

2. Theoretical Framework: The Unified Mechanical Erosion Model for Multi-phase Mass Flows

2.1 Limitations of Single-Phase Models and the "Bulking" Effect

Predicting the destructive potential of landslides, debris flows, and avalanches requires a strategic shift from effectively single-phase empirical models to the Unified Mechanical Erosion Model (UMEM) [1], [3]. Single-phase models routinely underestimate the "bulking" effects of flows where entrained material can increase destructive volume by several orders of magnitude.

The UMEM establishes the "jump" in shear stresses and momentum fluxes across the erosion-matrix—the interface where stationary bed material is mobilized. This process is governed by erosive product viscosity (P-viscosity) and the mechanical interactions between solid and fluid phases, which determine the net energy budget of the hazard [3].



2nd image

2.2 Fundamental Phase-Interactions

The UMEM identifies four fundamental phase-interactions that define the mechanical shear structures between the flow and the erodible substrate [1]:

Interaction Type	Stress Mechanism	Impact on Landslide Mobility
Solid-Solid (SS)	Coulomb-type (Frictional) & Bagnold-type (Collisional)	Determines the primary resistive force and internal energy dissipation within granular flows.
Solid-Fluid (SF)	Chezy-type (Frictional)	Represents the resistance of basal fluid against the solid phase's downward shear.



Interaction Type	Stress Mechanism	Impact on Landslide Mobility
Fluid-Solid (FS)	Chezy-type (Modified)	Captures the fluid phase’s capacity to mobilize and entrain solid particles from the bed.
Fluid-Fluid (FF)	Beavers-Joseph-type (Viscous/Slip)	Models the viscous shear and P-viscosity between the flow's fluid and the porous bed fluid.

2.3 "Erosion-Thrust" and Net Momentum Production

The strategic value of this framework lies in the calculation of Net Momentum Production. This accounts for the erosion-induced change in inertia—the energetic cost of accelerating stationary bed material into the flow [1], [7]. By calculating the "erosion-thrust," scientists can quantify whether erosion will enhance or reduce flow mobility, determining the final impact force and travel distance.

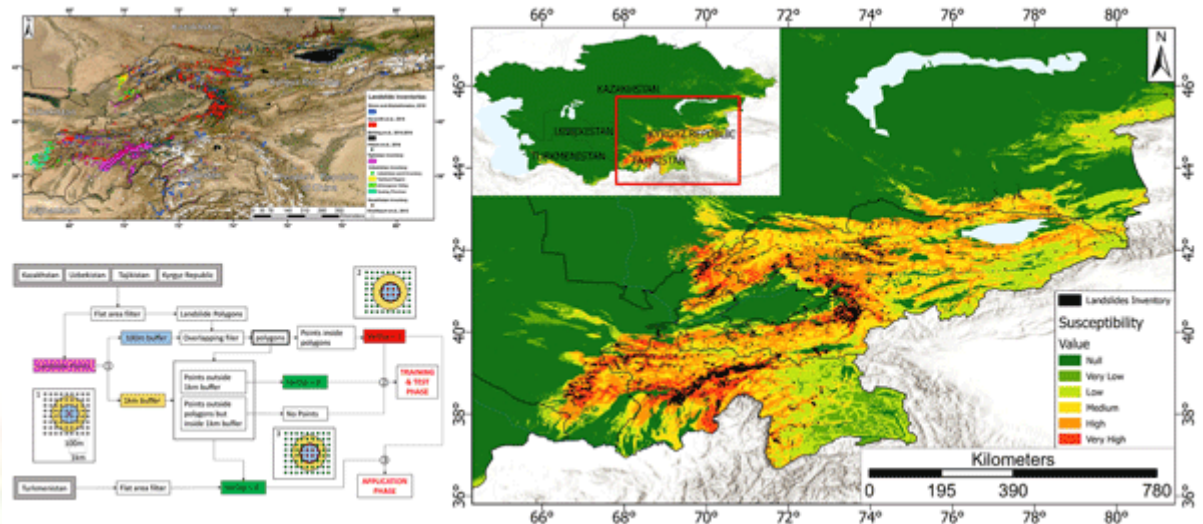
3. Regional Case Analysis: Mudflow Hazards in the Foothill and Mountainous Regions of Uzbekistan

Uzbekistan serves as a critical geomorphological case study where intensive mountain development for economic and recreational use has exacerbated the vulnerability of national infrastructure. The nation’s unique topography hosts approximately one thousand active mudflow channels [1], [7].

3.1 Distribution of Registered Mudflow Hazards and Transboundary Risk

The Fergana Valley is the nation's primary hazard zone, accounting for 41% of total registered mudflows across more than 270 active channels (16% in Fergana directly, 19% in Namangan) [1]. For international policymakers, it is vital to recognize that these hazards are not confined by administrative borders; mudflow

activity in Uzbekistan often involves transboundary territories, necessitating international data-sharing protocols [4].



3.2 The Seasonal Precipitation Pulse

Effective mitigation must account for the precipitation-driven "Seasonal Pulse" of mudflow activity. Strategic resources must be prioritized during the spring escalation [1]:

- **April:** 25% of annual mudflow events.
- **May:** 35% of annual mudflow events.

4. The Hidden Threat: Sea-Level Rise (SLR) and Coastal Groundwater Dynamics

While mountain-borne hazards are violent and visible, a parallel "hidden" threat is emerging in coastal urban zones. Sea-level rise (SLR) influences coastal groundwater decades before surface inundation becomes visible [5]. Subsurface impacts occur via two primary mechanisms: the elevation of the water table and the landward shift of salinity profiles.

4.1 Data Visualization: Tidal Signal Propagation and Decay

Coastal aquifers respond dynamically to ocean tides, acting as a porous "bed" through which tidal signals propagate. Based on the Jacob (1950) equation, these subsurface signals undergo two physical transformations as they move inland [6]:

1. **Exponential Amplitude Decay:** The height of the tidal pulse decreases exponentially with distance from the coastline.



2. **Phase Lag:** There is a distinct time delay between the peak of the ocean tide and the corresponding groundwater peak inland [6].

Even areas over 400 meters inland can experience tidally-driven "heaving" in the water table, subjecting infrastructure to constant stress.

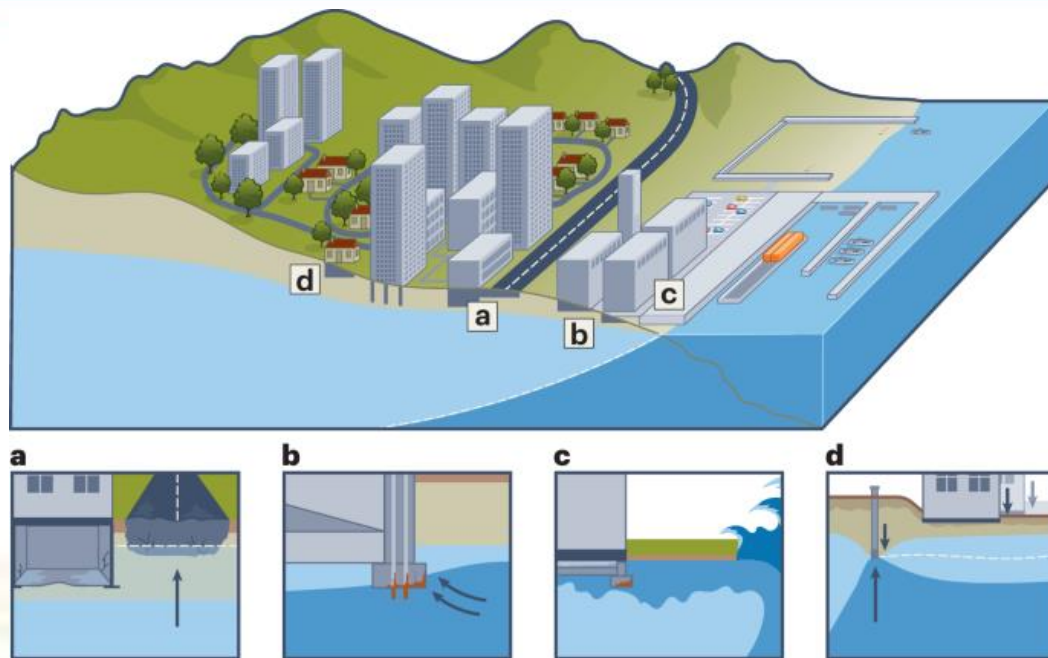
4.2 Impact on Global Functional Urban Areas (FUAs)

A 1.5-meter SLR scenario identifies 1,546 FUAs at risk, affecting approximately 1.42 billion people [1], [5].

Country	Affected FUAs	Population at Risk (Millions)
China	150	236.07
Indonesia	111	110.73
India	81	109.04
USA	69	108.11
Japan	62	95.40

5. Critical Infrastructure Vulnerability and Convergence of Impacts

The "convergence of impacts" occurs when subsurface damage accumulates undetected until catastrophic failure. Applying the UMEM's principles of "erosion-thrust" to the urban context reveals that as groundwater rises, it destabilizes the erodible bed of urban fill, leading to the subsurface erosion of supporting soils [1], [5].



- **Roadways & Buildings:** Shallow groundwater infiltrates unbound base layers, reducing service life by 50-90%. Salinity shifts cause rebar corrosion, spalling, and a catastrophic loss of carrying capacity [1].
- **Public Health:** On-Site Sewage Disposal Systems (OSDS) require at least 60cm of unsaturated soil to neutralize pathogens. When this space is lost to groundwater rise, infectious viruses persist.
- **Chemical Entrainment:** Rising groundwater mobilizes legacy industrial contaminants, while anaerobic degradation of pollutants generates explosive gases like methane and hydrogen sulfide [1], [7].

6. Strategic Recommendations and Adaptive Management

Municipal leaders must transition to "no-regrets" adaptive management that addresses the subsurface as a dynamic mechanical system [1], [7].

1. **Monitoring & Transient Simulation:** Install comprehensive groundwater monitoring networks and mandate the creation of publicly available simulations that account for compound flooding.
2. **Mandatory Assessments:** Implement strict structural assessment requirements for high-rise buildings in shallow-groundwater zones to detect corrosion early.



3. **Mitigation Logic:** Reject "aquifer pumping" as a primary strategy to avoid land subsidence. "Elevating on fill" is the superior strategy for long-term isolation from both rising water and mobilized contamination [5].

Failure to integrate mechanical erosion modeling into municipal planning disproportionately exposes vulnerable communities to hidden hazards. We must utilize these integrated insights to protect the global frontlines of geophysical change.

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