
PASSIVE HYDRAULIC INTELLIGENCE: MODELLING GOA'S KHAZAN WETLANDS THROUGH AN INDIAN KNOWLEDGE SYSTEM LENS

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403001**ABSTRACT**

Coastal water management in Goa is an old practice that has continued for many generations. Khazan is a traditional system where local communities use coastal wetlands and mangroves for farming and fishing, in a sustainable way. In this system, low-lying fields are protected and regulated by earthen embankments known as Bunds, while traditional sluice gates called Manos control tidal water exchange. The arrangement sustains rice farming and brackish-water aquaculture; and helps to comprehensively reduce flood risk in the surrounding settlements. Khazan wetlands function through a locally developed hydraulic design supported by traditional community institutions known as Comunidade. The sluice gates operate naturally without pumps, electricity, or mechanical control. Although the long-term effectiveness of these systems has been observed in practice, however, their hydraulic behaviour has not been adequately examined using mathematical modelling. In this paper, we represent the operation of the Khazan system using a coupled system of ordinary differential equations and simulate its response under both dry and monsoon conditions using published hydrographic parameters from the Mandovi-Zuari estuarine system. The results demonstrate substantial tidal attenuation of 93% during the dry season and 70.8% during the monsoon, indicating effective passive seasonal regulation. This paper also suggests that, Poiem acts as a buffering reservoir that reduces short-term tidal fluctuations, contributing to the system's long-term hydraulic stability. The study highlights that the Khazan system of Goa represents a low-cost coastal infrastructure that is prevailing 'climate-responsive' in its design and function. The system has strong potential for future coastal adaptation strategies and may contribute to resilience towards the projected sea-level rise. Dedicated simulation studies are needed to better understand its future performance.

Keywords: Goan Khazans; Indian Knowledge Systems; Tidal Wetland Management; Passive Hydraulic Regulation; Climate-Responsive Infrastructure; Community Governance

1. INTRODUCTION

The Khazans of Goa represent one of the most enduring examples of community-engineered coastal landscapes along the Arabian Sea, sustaining agriculture and fisheries for centuries. These landscapes were created through long periods of local observation, shared knowledge, and community management, making them one of the oldest examples of community-led coastal engineering in India. However, despite increasing sea levels and more unpredictable monsoon rainfall (ICLEI South Asia, 2024), the underlying water-management principles of the Khazan system have received limited attention in modern mathematical studies (Sonak, 2014).

Across coastal South Asia, sea level rise and changing monsoon patterns are increasing the risk of floods, storms, and other extreme events. To reduce these risks, modern coastal protection usually depends on hard structures such as seawalls, embankments, and pump-driven drainage systems that keep seawater out. Although these methods can work well within their design limits, they require constant maintenance, external energy, and regular upgrades as environmental conditions change (Brater et al., 1996; Munson et al., 2013).

Along the west coast of India, the average sea level has been rising at approximately 2.75 mm per year (Indian National Centre for Ocean Information Services, 2025). Coupled with inter-annual variations in monsoon rainfall and strong semi-diurnal tides (two high and two low tides every lunar day), this trend raises questions about the long-term effectiveness of rigid coastal defence structures (Sundar & Shetye, 2005).

In contrast, the Khazan systems of Goa are traditional tidal-reclamation landscapes found along the coast and tidal river plains. They support agriculture and fish farming using earthen embankments and gravity-operated wooden sluice gates called 'Manos'. These systems are maintained collectively by village institutions known as the Comunidade. Instead of completely blocking tidal water, Khazans carefully control the flow of water in and out during tidal cycles, allowing the landscape to adapt naturally to changing conditions (Kamat, 2004; Sonak, 2014; Sawaiker et al., 2023).

2. LITERATURE CONTEXT AND RESEARCH GAP

Previous studies on Khazan systems have primarily examined their ecological significance, landscape evolution, community governance, and traditional management practices (Kamat, 2004; Sonak, 2014; Sawaiker et al.,

2023). Most studies focus on the qualitative and descriptive aspects of water management, with water processes largely presented in subjective terms. Although the management of Khazans has been well documented through historical records and studies of local community practices; the way these systems actually function as dynamic water systems under changing tidal conditions has not been thoroughly analysed mathematically.

This gap becomes especially clear when compared to the wider progress made in modelling traditional water systems around the world. Lansing and Kremer (1993) showed through computer-based simulations that Bali's *subak irrigation networks* can effectively control pests and distribute water efficiently through local, decentralised coordination, without the need for central planning. Lightfoot's (1996) research on *qanat systems* in the dry regions of Iran and the Middle East showed how these underground, gravity-driven water channels could reliably deliver water across long distances without the need for pumps or external power. Pandey et al. (2003) studied *johad and baoli stepwell systems* in Rajasthan and measured their ability to recharge groundwater using mass-balance methods, providing a quantitative assessment of how effectively these traditional structures restore water resources. In all these examples, mathematical modelling helped explain how the systems actually function, revealing important mechanisms that simple descriptions could not fully capture. Although, the Khazan system is equally ancient and hydraulically sophisticated, no comparable mathematical modelling study has yet been conducted for it.

Global research on nature-based coastal protection mainly focuses on outcomes such as wave reduction and carbon storage. However, the internal mechanisms of traditional tidal drainage systems have received limited attention from a modelling perspective. This has created a gap between qualitative understanding of traditional practices and their representation through formal objective modelling approaches.

3. RESEARCH QUESTIONS AND CONTRIBUTION

This study addresses this gap by representing the operation of the traditional sluice gate (Manos) and the internal buffer reservoir (Poim) using differential equations.

Three questions guide the analysis:

- (1) How can the behaviour of the Manos gate be represented mathematically, and what functional insights emerge from such a representation?
- (2) How does the coupled Khazan system respond under tidal, seasonal, and projected sea-level variations?
- (3) How does the internal reservoir influence short-term oscillations and seasonal response?

This study makes the following contributions:

- **Differential equations-based dynamical representation of Khazan hydraulics:** We develop a coupled ordinary differential equation model of the Khazan sluice–reservoir system, providing a formal dynamical systems representation of a traditional Indian coastal water management structure.
- **Quantified tidal attenuation:** The simulations provide initial estimates of tidal attenuation within the Khazan fields—around 93% in the dry season and 70.8% during the monsoon— providing a basis for comparison with modern coastal engineering standards.
- **IKS–engineering synthesis framework:** The study demonstrates that principles documented in classical Indian Knowledge Systems texts, including the *Arthaśāstra* and *Brhat Saṃhitā*, can be mapped onto modern hydraulic theory; providing a replicable framework for interdisciplinary engagement between IKS scholarship and engineering analysis.

This work uses a simplified dynamical modelling approach to analyse Khazan systems, providing quantitative insights into how these traditional water management systems function in comparison with contemporary coastal engineering approaches.

This paper is organised as follows.

Section 4 situates the Khazan system within the context of Indian hydraulic traditions and the Indian Knowledge Systems (IKS) framework.

Section 5 describes its physical structure and operational characteristics.

Section 6 outlines the mathematical formulation used to represent the system.

Section 7 presents simulation outcomes and the observed behaviour of the system.

Section 8 explores the wider implications of the findings.

Section 9 discusses limitations and policy recommendations. Lastly,

Section 10 presents the conclusions of the study.

4. INDIAN KNOWLEDGE SYSTEMS AND KHAZAN WATER MANAGEMENT HERITAGE

4.1 Water Engineering in the Indian Intellectual Tradition

The Khazan system is one of the most distinctive coastal expressions of the water management tradition across the Indian subcontinent. Historical manuscripts and archaeological sites confirm a centuries-old expertise in hydraulic infrastructure, evident from embankments, irrigation channels, reservoirs, and collective maintenance practices. The use of gravity to move water in the Khazan system embodies the categories described in the *Arthaśāstra*. Kautilya emphasised that the most efficient systems work with natural flows rather than requiring manual lifting or pumping. In verse 2.24.18, the highest efficiency is attributed to *uddhātam*—the passive release of water.

U2.24.18 स्वसेतुभ्यो हस्तप्रावर्तिमं उदकभागं पञ्चमं दद्युः, स्कन्धप्रावर्तिमं चतुर्थं,
स्रोतोयन्त्रप्रावर्तिमं च तृतीयं, चतुर्थं नदीसरस्तटाककूप उद्धाटम्

Translation: "Those who cultivate by manual labour shall pay one-fifth of the produce, but for those who allow water to flow from rivers, lakes, and tanks (*uddhātam*), the rate is one-fourth." — Kautilya, *Arthaśāstra*, Book 2, Chapter 24, Verse 18 (Kautilya, trans. Shamasastry, 1915).

The term *uddhātam* means opening a sluice so that water flows naturally under its own pressure. The Khazan system follows this idea in practice. Its sluices, called Manos, operate without constant human control. They respond automatically to differences in tidal and gravitational water levels. This reflects an important feature of Indian Knowledge Systems (IKS), where practical engineering knowledge is built directly into the structure itself.

The Khazan system also shows technical understanding similar to that described in *Bṛhat Saṃhitā* (c. 550 CE) by *Varāhamihira*, which explains repeating patterns in water movement and tides. Khazan sluices open and close with the regular rise and fall of the tides, showing that local communities had a long-standing knowledge of tidal cycles. In certain estuaries, including the Mandovi–Zuari, Khazan sluices operate in a synchronized manner with tidal fluctuations, reflecting the local communities' detailed knowledge of tidal cycles. This traditional understanding aligns closely with the dominant semi-diurnal M2 tidal cycle identified by modern science, which governs water-level changes in the Mandovi–Zuari estuary with a period of about 12.42 hours (Sundar & Shetye, 2005).

The structural stability of the Khazan embankments reflects geometric principles reminiscent of those articulated in the *Śulbasūtras*. In the *Baudhāyana Śulbasūtra* (*Adhyāya* 3), the *Mahāvedī* altar is described as a trapezoidal form constructed with precise proportional ratios to ensure geometric balance:

त्रिंशत्पदानि प्रक्रमाः पश्चिमात् तिर्यक् भवति ।

षट्त्रिंशत् प्राची चतुर्विंशतिः पुरस्तात्तिर्यक् इति महावेदी विज्ञायते ॥

This specification defines a trapezoidal form constructed with precise proportional ratios to ensure geometric balance. In a comparable manner, the trapezoidal cross-section of Khazan bunds distributes tidal forces effectively, contributing to hydraulic stability.

4.2 Analytical Perspective

This study presents simple mathematical equations to describe the Khazan system, using parameter values drawn from published literature. Simulations show how water flows and stabilises within the system, while historical knowledge provides context for these design choices. The analysis does not imply that past engineers wrote equations; rather, it highlights how generations of empirical refinement created systems whose behaviour can now be described mathematically.

4.3 The Comunidade as Institutional Infrastructure

The Khazan system relies on a long-standing village institution called the Comunidade, which manages land allocation, maintenance of embankments, and operation of sluice gates. Regular inspections and repairs, especially after the monsoon, are essential to keep the system working. This governance is integral to the engineering design, ensuring the hydraulic system remains functional over time. The Comunidade also follows common principles of sustainable resource management, including membership rules, collective decision-

making, monitoring, and conflict resolution (Ostrom, 1990). Technical design and community governance concomitantly make the Khazan landscape durable and effective.

5. PHYSICAL ARCHITECTURE OF THE KHAZAN SYSTEM

5.1 Overview and Functional Variants



Figure 1: Overview of the Khazan system

A Khazan is a low-lying coastal area that has been reclaimed from tidal land and protected by earthen embankments, locally called bunds. These embankments prevent uncontrolled flow of seawater. The area is connected to a nearby estuary through a wooden sluice gate that operates using gravity. The gate opens and closes automatically depending on the difference in water levels inside and outside the system, allowing for controlled tidal exchange.

There are three main types of Khazan systems:

- (1) Rice–fish systems, where rice is cultivated during the monsoon season and fish are reared during the dry season;
- (2) Fish-only enclosures (locally known as Khani or Agor), which are used mainly for aquaculture; and
- (3) Salt–fish systems (called Mithagor), where salt production and fish farming are carried out in different seasons.

Although these types differ in how the land is used, they all depend on the same basic structure for water management.

5.2 Earthen Embankments

Khazan fields are enclosed by earthen embankments (bunds) made of laterite-rich clay, often reinforced by mangroves. These flexible structures absorb wave energy and adapt to seasonal moisture changes, allowing slow, detectable damage that can be repaired by local maintenance groups.



Figure 2: Bund structures of the Khazan system

5.3 The Sluice Gate (Manos)

The Manos is a hinged wooden gate at the Poiem–Estuary interface. It opens when internal water exceeds the Estuary level, draining freshwater, and closes when tides rise to prevent saltwater entry. This gravity-driven mechanism requires no motors or manual operation and follows the natural tidal rhythm.



Figure3: Sluice Gate (Manos)

5.4 The Poiem Reservoir

The Poiem functions as an internal storage basin, absorbing excess rainfall and tidal inflows to moderate water level fluctuations within the field.



Figure 4: Poiem (buffer reservoir)

5.5 Integrated System Operation

The Khazan system works by combining bunds, Manos, and Poiem to control water without any active intervention, and its behaviour is best understood by tracing the sequence of events across a single complete tidal cycle.

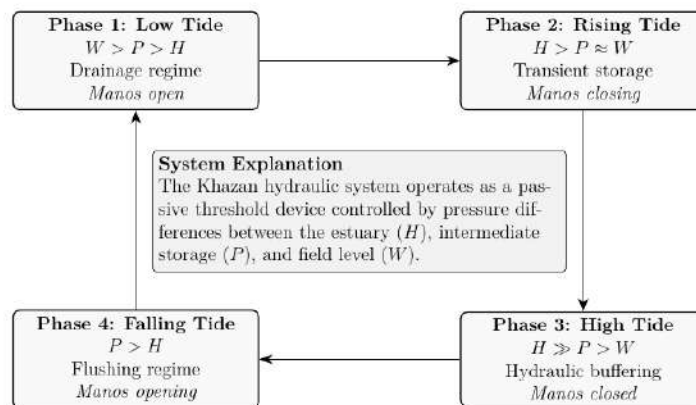


Figure 5: Sluice Gate Operation in tidal system

5.5.1 Working of the Sluice Gate (Manos)

- **Low tide:** The Estuary level falls below the field level, creating a pressure difference that opens the Manos gate. Excess freshwater drains out naturally, lowering the field water level.
- **Rising tide:** As the Estuary level rises, the pressure difference decreases. Drainage slows and the gate gradually closes, stopping further outflow and preventing saltwater entry.
- **High tide:** The Estuary level exceeds the field level, but the gate remains closed because it opens only outward. The bunds resist the water pressure.
- **Falling tide:** When the tide drops, the pressure difference is restored. The gate reopens and drainage resumes, completing the cycle.

- **Manual Intervention:** Although the Manos gate usually works automatically based on tidal and water level differences, it can be adjusted manually when needed. In the dry season, it may be partly opened to let a limited amount of water into the fields for irrigation.

5.5.2 Role of the Poiem (Buffer Reservoir)

During heavy rainfall or sudden inflow, excess water flows into the Poiem, reducing flood risk in the field. After drainage lowers the field level, the Poiem slowly releases stored water back, helping maintain a stable level. This two-way exchange smooths rapid fluctuations caused by tides and rainfall. The system therefore works as a natural self-regulating hydraulic system without pumps or external energy, functioning as a passive hydraulic circuit that continuously adapts to tidal cycles and seasonal changes.

6. MATHEMATICAL MODEL AND KEY RESULTS

6.1 Overview and Variables

The physical processes described in Section 5 can be expressed using a system of ordinary differential equations. Each term in the model corresponds directly to a measurable physical process. The variables and parameters used throughout the analysis are listed in Table 1.

Table 1: Model variables and parameters with physical interpretation

Symbol	Meaning	Units
$W(t)$	Internal water level in the field	m
$T(t)$	Tidal water level in the Estuary	m
$R(t)$	Freshwater input (rainfall and runoff)	m^3s^{-1}
$P(t)$	Water level in the Poiem	m
$Q_{out}(t)$	Volumetric outflow through the Manos gate	m^3s^{-1}
A	Field surface area	m^2
A_p	Poiem surface area	m^2
a	Gate opening area	m^2
k	Seepage conductance per unit area (through gate structure)	s^{-1}
k_p	Discharge per unit width	m^2s^{-1}
Cd	Gate discharge coefficient	—
ϵ	Threshold head for gate	m
$H(\cdot)$	Heaviside switch function (0 = closed, 1 = open)	—

Tidal Attenuation: A key performance metric used throughout this study is the tidal attenuation ratio, defined as:

$$\eta = 1 - (\Delta W / \Delta T) \tag{*}$$

where ΔW is the peak-to-peak amplitude of the internal field water level $W(t)$, and ΔT is the peak-to-peak amplitude of the external tidal signal $T(t)$. A value of $\eta = 1$ indicates complete attenuation (no tidal influence on the field interior), while $\eta = 0$ indicates no attenuation (full tidal transmission). All attenuation values reported in Sections 7.1 and 7.2 are computed using this definition.

6.2 Mathematical Formulation

The internal water level in the Khazan field evolves according to conservation of volume. The field exchanges water with the Poiem through the level difference ($W - P$), and receives freshwater input from rainfall and runoff. For a field of surface area A , the volume balance gives:

$$A \frac{dW}{dt} = R(t) - k_p(W(t) - P(t)) \tag{1}$$

The first term on the right-hand side is the freshwater inflow. The second term represents volumetric exchange with the Poiem: when $W > P$, water drains from the field into the Poiem; when $W < P$, the Poiem recharges the field. The Manos gate and all tidal exchange is located at the Poiem– Estuary interface; the field itself has no direct hydraulic connection to the tidal Estuary.

6.3 Drainage Through the Manos

The Manos gate sits at the boundary between the Poiem and the Tidal Estuary. Drainage flow is modelled as pressure-driven discharge through a submerged orifice, with the driving head given by the difference between the Poiem level P and the tidal level T :

$$Q_{out} = C_d a \cdot \sqrt{2g \cdot \max(P(t) - T(t), 0)} \cdot H_{smooth}(P(t) - T(t) - \epsilon) \tag{2}$$

The function $H(\cdot)$ is the Heaviside unit step function, defined as:

$$H(x) = \begin{cases} 0, & \text{if } x < 0 \\ 1, & \text{if } x \geq 0 \end{cases}$$

Applied here as $H_{smooth}(P(t) - T(t) - \epsilon)$, it takes the value 1 (gate open) only when the Poiem level exceeds the tidal level by more than the threshold ϵ , and 0 (gate closed) otherwise. The square root term reflects standard orifice hydraulics, in which discharge increases with the pressure head, a fundamental principle of fluid mechanics (Brater et al., 1996; Munson et al., 2013). Because the gate responds to P rather than W , the Poiem acts as a true hydraulic buffer between the field interior and the tide.

6.4 Tidal Forcing and the Poiem Subsystem

The system is forced by a semi-diurnal tidal oscillation:

$$T(t) = T_{mean} + A_{tide} \sin \omega t \tag{3}$$

The Poiem receives water from the field, then discharges to the Estuary through the Manos gate and through passive seepage across the gate structure. This two-reservoir topology yields the following coupled ODE system:

$$A \frac{dW}{dt} = R(t) - k_p(W(t) - P(t)) \tag{4}$$

$$A_p \frac{dP}{dt} = k_p(W(t) - P(t)) - Q_{out}(P, T) - k \cdot a(P(t) - T(t)) \tag{5}$$

In Equation (4), the field level rises with freshwater input and falls as water drains into the Poiem. In Equation (5), the Poiem level rises as it receives that inflow, and falls through two pathways: active discharge $Q_{out}(P, T)$ through the Manos gate when $P - T > \epsilon$, and passive seepage $k \cdot a(P - T)$ proportional to the head difference across the gate structure at all times. Because all tidal exchange is mediated through the Poiem, this coupled configuration functions as a low-pass filter: the Poiem absorbs short-term surges from both rainfall and tidal fluctuation, and the field interior responds only to the slower, smoothed signal.

7. DRY AND MONSOON SEASON SIMULATION

The governing equations (4)-(5) were integrated using a fourth-order Runge–Kutta scheme over 72-hour intervals to capture multiple tidal cycles. Nominal parameters for the Mandovi–Zuari estuarine system are listed in Table 2. Two seasonal forcing scenarios were considered: dry season ($R = 0.02 \text{ m}^3\text{s}^{-1}$) and peak monsoon ($R = 0.15 \text{ m}^3\text{s}^{-1}$), representing the annual hydraulic extremes for a typical Khazan field. These parameters are chosen to be consistent with the documented tidal propagation and asymmetry observed in the Mandovi–Zuari estuarine system (Shetye et al., 1995; Manoj et al., 2009).

Table 2: Nominal parameters used in the simulation model

Parameter	Value	Units	Reference / Reasoning
<i>Tidal Forcing</i>			
Mean tidal level (T_{mean})	1.00	m	Representative mean tide
Tidal amplitude (A_{tide})	0.60	m	Neap-to-mean amplitude
M2 tidal period (T_{M2})	12.42	hr	Dominant semi-diurnal constituent
Angular frequency (ω)	1.41×10^{-4}	rad s^{-1}	Derived from period
<i>Geometric and Hydraulic Parameters</i>			
Field surface area (A)	10,000	m^2	Typical Khazan field
Poiem surface area (A_p)	2,000	m^2	20% of field
Gate opening area (a)	0.80	m^2	Wooden Manos gate
Discharge coefficient (C_d)	0.62	—	Sharp-edged orifice
Gate threshold head (ϵ)	0.05	m	Minimum opening head

Seepage conductance (k)	1.0×10^{-4}	s^{-1}	Lateritic soil conductivity (Terzaghi et al., 1996; dos Santos & Esquivel, 2018)
Discharge per unit width (kp)	0.30	$m^2 s^{-1}$	Assumed
Seasonal Forcing			
Dry runoff	0.02	$m^3 s^{-1}$	Baseflow
Monsoon runoff	0.15	$m^3 s^{-1}$	Peak rainfall
Initial Conditions and Numerical Settings			
Initial field level	0.50	m	Near equilibrium
Initial Poiem level	0.48	m	Below field level
Time step	10	s	Numerical resolution
Simulation duration	72	hr	Multiple tidal cycles
Gravity (g)	9.81	$m s^{-2}$	Standard value

7.1 Dry Season Response

Under dry-season forcing, the system converges to a stable equilibrium $W^* = 0.615$ m. Although the external tide oscillates with a 1.20 m range, the internal field level varies by only 0.084 m, corresponding to 93% tidal attenuation ($\eta = 0.93$, using (*)) (Figure 6). The gate opens briefly near extreme low tide, producing short drainage pulses with peak discharge of 131.2 L/s. The gate opens for approximately 19.9% of the tidal cycle, indicating that drainage occurs intermittently during low-tide windows while the Manos remains closed for the majority of the cycle. The Poiem reservoir further smooths internal fluctuations, absorbing short-term surges during rainfall and releasing stored water gradually between drainage events.

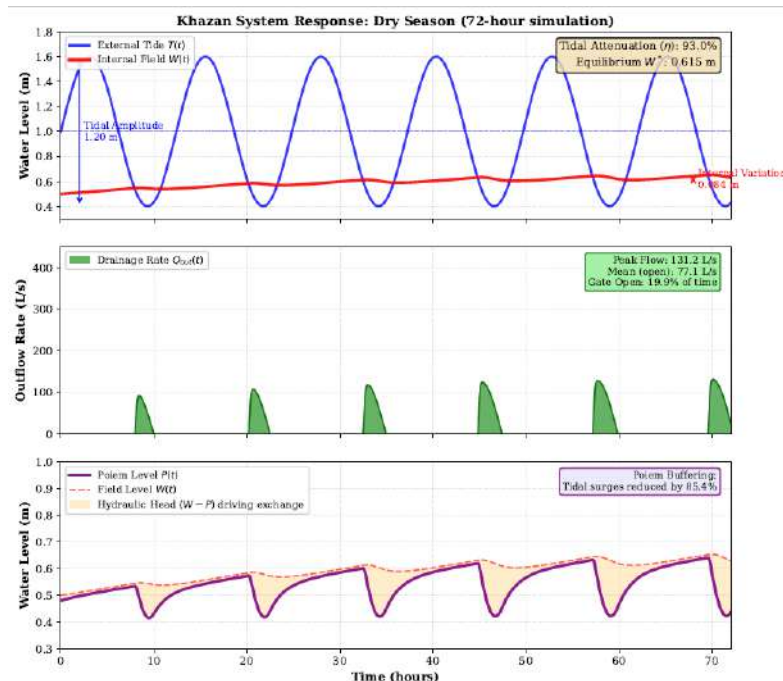


Figure 6: Dry-season hydraulic response ($R = 0.02$ m³/s). Internal oscillations remain small (0.084 m) relative to the 1.20 m tidal range, yielding 93% attenuation.

7.2 Monsoon Season Response

During monsoon conditions, increased runoff raises the equilibrium to $W^* = 1.414$ m. Internal oscillation amplitude increases to 0.350 m, reducing tidal attenuation to 70.8% ($\eta = 0.708$, Equation (*)) (Figure 7). Peak discharge increases to 384 L/s and the gate opens 51.2% of the time, reflecting more frequent drainage

windows. Despite higher hydraulic loading, the system maintains bounded water levels without structural modification, demonstrating passive seasonal adaptability.

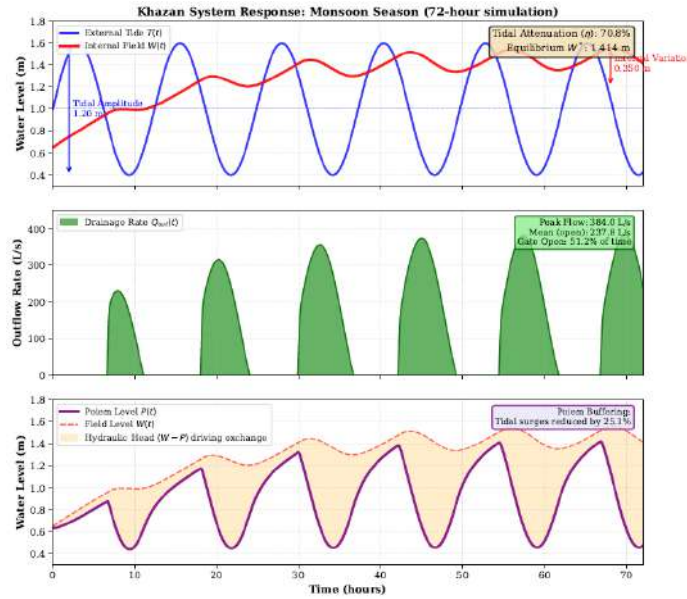


Figure 7: Monsoon hydraulic response ($R = 0.15 \text{ m}^3/\text{s}$). Higher equilibrium levels reduce tidal attenuation to 70.8% and increase gate activity.

7.3 Poiem Buffering Effect

The coupled system (Equations (4)– (5)) shows that the Poiem acts as a passive hydraulic buffer. Water is absorbed when $(W - P) > 0$ during runoff surges and released gradually between drainage events.

In the dry season, the water level changes in the Poiem are reduced by about 85.4% compared to the outside tide. This strong reduction shows that the field inside is mostly protected from tidal changes.

In the wet season, the buffering effect decreases to about 25.1%. This happens because the water level is higher and the gates open more often. Even so, the system still reduces the effect of tides inside the field.

8. DISCUSSION

8.1 Design Logic

Contemporary coastal protection often enforces fixed water levels, requiring structural reinforcement under extreme events. In contrast, the Khazan system relies on adaptive hydraulic coupling: the Manos gate responds to head difference, Bund seepage dissipates water gradually, and the Poiem reservoir buffers short-term fluctuations. Our model shows bounded, locally stable behaviour, demonstrating that adaptive accommodation can be rigorously described with dynamical systems.

8.2 Comparative Performance

Table 3 compares Khazan systems with concrete seawalls. Khazans offer passive operation, gradual failure, incremental adaptation, low maintenance, and potential carbon co-benefits, whereas seawalls are pump-dependent, may fail abruptly, require major redesign for sea-level rise, and incur high carbon and maintenance costs.

Table 3: Indicative comparison: Khazan vs. concrete seawall

Dimension	Khazan	Concrete Seawall
Energy Use	Passive	Pump-based
Failure Mode	Gradual	Sudden
Sea Level Rise Adaptation	Incremental	Major Redesign
Carbon Balance	Mangrove-supported	Cement-intensive
Maintenance Cost	Low	High
Life Span	Centuries*	30–50 years

* *The multi-century operational lifespan of Khazan systems is documented in historical records of continuous Comunidade governance and land use dating back nearly 2,000 years (Kamat, 2004; Sonak, 2014). This comparison is indicative; carbon and cost estimates are site-specific.*

8.3 Implications for IKS

The *Arthaśāstra* describes self-regulating water principles in Book 2, Chapter 24, which can be characterised using the Sanskrit *concept of svayam-pravartita* — self-directing flow — referring to systems that operate without continuous external intervention — a concept that maps directly onto the negative-feedback regulation demonstrated in our model. The quantitative results presented in Sections 7.1 through 7.3 show that the passive self-regulation described in the *Arthaśāstra* and *Bṛhat Samhitā*, is not merely a philosophical principle but a mathematically demonstrable hydraulic property — one that can be measured, simulated, and compared against contemporary engineering alternatives.

9. LIMITATIONS AND POLICY IMPLICATIONS

9.1 Limitations and Future Work

The study utilises a simplified lumped-parameter model without direct field data or survey validation. Initial conditions were assumed rather than measured, and the results are intended to characterise qualitative system behaviour. Only the dominant tidal component was considered, and processes such as sediment transport, bund deformation, gate wear, and structural failure were not included. Future work should incorporate field measurements, site surveys, and more detailed hydrodynamic and sediment processes to improve accuracy and real-world relevance.

9.2 Policy Implications

- **Recognising Hydraulic Function:** Khazan bunds should be treated as functional coastal infrastructure. The high attenuation observed in this study (93% in the dry season and 70.8% during monsoon) provides quantitative support for their inclusion in formal flood risk management frameworks.
- **Ecosystem Services and Climate Finance:** Mangroves reinforcing Khazan bunds provide important blue carbon benefits through long-term carbon storage in waterlogged soils. This creates potential opportunities for climate finance and carbon credit mechanisms that could support community-led maintenance.
- **Climate Forecasting Integration:** Integrating rainfall and climate projections into the modelling framework would enable better scenario planning and proactive maintenance by anticipating changes in freshwater inflow, gate operation, and seasonal water levels.

10. CONCLUSION

Goa's Khazan wetlands can be modelled as a nonlinear system with passive feedback control. The system keeps water levels stable and reduces tidal effects by 93% in the dry season and 70.8% during the monsoon. It adjusts naturally to seasonal water changes, showing potential resilience to future sea-level rise. The wetlands are structurally strong and offer energy-efficient and ecological benefits. Knowledge from the *Arthaśāstra* and *Bṛhat Samhitā* can be studied using modern system analysis. Although field measurements are still needed, this approach can help include traditional water systems in coastal adaptation planning.

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