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Maintaining Irrigation Infrastructure Under Rising Climate Hazards: An Optimal Control Analysis of Financing Regimes with Reference to Vietnam

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Abstract

Irrigation networks in low-lying deltas are deteriorating faster than their design assumed, as salinity intrusion, floods and land subsidence add to ordinary wear. Whether they are kept in working order depends less on engineering than on how maintenance is financed and who decides when it is done. This paper builds a deterministic optimal control model in which a maintenance agency chooses the path of maintenance outlays to sustain the service capacity of an irrigation network whose deterioration rate rises with climate hazard intensity. Financing arrangements enter through two interpretable parameters: the social cost of one unit of maintenance funding and the discount rate applied by the deciding agency. The analysis is analytical and qualitative. We derive the steady state, the saddle-path dynamics and a complete table of comparative statics, and we state six propositions. Budget-cycle financing produces chronic under-maintenance, and the resulting gap separates

cleanly into a financing component and a horizon component that call for different remedies. The horizon component widens as hazards intensify. Optimal maintenance spending is hump-shaped in the deterioration rate, and a short-sighted agency reaches the turning point, beyond which it lets the system contract, earlier than society would. The share of maintenance that farmers can afford to pay falls as hazards rise, a mechanism we call the climate squeeze on cost recovery. Finally, maintenance norms calibrated to historical deterioration erode capacity once hazards intensify. Read against Vietnam's shift from irrigation fees to irrigation service prices, the results suggest that multi-year earmarked maintenance funds and affordability-capped prices are the main levers where hazards are moderate, while low-cost climate finance and planned transformation become decisive where hazards are severe.

Keywords: Irrigation Infrastructure, Maintenance, Optimal Control, Cost Recovery, Climate Adaptation, Marginal Cost of Public Funds, Vietnam

JEL Classification: C61, H54, Q25, Q54

1. Introduction

Most of the economic value of an irrigation system is produced after construction is finished. Canals silt up, gates corrode, embankments slump and pumps lose efficiency unless someone pays to keep them in order, and the gap between the area a scheme was designed to serve and the area it actually serves is often explained by maintenance rather than by the original investment. The literature on irrigation pricing has made this point repeatedly from the financing side. In many developing countries water charges recover only a modest part of operation and maintenance cost, so upkeep depends on public budgets that are exposed to fiscal pressure and political timing (Dinar & Subramanian, 1997; Johansson *et al.*, 2002; Easter & Liu, 2005; Molle & Berkoff, 2007) ^[4, 14, 6, 20].

Two developments make this old problem harder. The first is climate change. In deltas such as the Mekong, sea-level rise, saline intrusion, more intense floods and land subsidence accelerate the physical decay of canals, sluices and dykes (Smajgl *et al.*, 2015) ^[30]. In the vocabulary of capital theory, the depreciation rate of irrigation capital has stopped being a fixed engineering constant and has become a function of hazard intensity. The second is institutional. Vietnam exempted farmers from irrigation fees for most of the decade after 2008. The Law on Irrigation of 2017 replaced fees with prices for irrigation products and services, and successive government decrees, first Decree 96/2018/ND-CP and since April 2026 Decree 115/2026/ND-CP, set out how those prices are formed and how the state pays for public-utility irrigation services on behalf of

eligible users. Price formation now has to follow the Law on Prices of 2023 as well. How much of the cost of keeping systems in working order should fall on water users, how much on the budget, and how that division should change as the climate shifts are therefore practical questions for irrigation management companies, provincial authorities and the ministries that oversee them.

This paper addresses those questions with a deliberately compact dynamic model. A public agency chooses a maintenance path to sustain the service capacity of an irrigation network. Capacity yields concave benefits to farmers, maintenance has a convex cost, and capacity decays at a rate that rises with hazard intensity. A financing regime is summarised by two numbers. One is a multiplier on the resource cost of maintenance, which captures the excess burden of taxation when maintenance is tax-financed and the collection cost when it is financed by user charges. The other is the discount rate of the deciding agency, which exceeds the social rate when maintenance budgets are negotiated every year and can be cut whenever money is short. With these two parameters, a single model generates a first-best benchmark, a stylised status quo and a family of reform options, all in closed form.

The paper does not estimate or simulate the model. Its method is analytical: we characterise the solution, sign the effects of every parameter, read the dynamics from the phase diagram and translate the resulting propositions into statements about institutions. We chose this approach for two reasons. The mechanisms we study depend on the signs and orderings of effects, which can be established in general, rather than on magnitudes, which would depend on parameter values that are not yet measured for Vietnamese systems. And a qualitative result that holds for every admissible parameter set gives policy makers a more robust basis for institutional design than a single calibrated scenario.

The paper makes four contributions. It brings the public-capital maintenance literature, developed mostly for aggregate growth models (Rioja, 2003; Kalaitzidakis & Kalyvitis, 2004) ^[27, 15], down to the scale of a single infrastructure system with an explicit financing regime, which allows the welfare cost of short budget horizons to be separated from the cost of public money. It shows that the optimal response to faster deterioration is not monotone: up to a threshold deterioration rate, which we derive explicitly, the planner should spend more on maintenance, and beyond it the planner should accept a smaller system and spend less. A short-sighted agency crosses this threshold too early. It identifies a climate squeeze on cost recovery, in which the share of maintenance that users can afford to finance falls exactly when budget financing becomes most costly. And it shows why maintenance norms tied to historical deterioration, a common feature of cost-based price setting, erode capacity once hazards intensify.

The rest of the paper is organised as follows. Section 2 reviews related work. Section 3 explains the research approach and notation. Section 4 sets out and solves the model. Section 5 develops the qualitative analysis and states the propositions. Section 6 discusses implications for Vietnam. Section 7 discusses limitations, and Section 8 concludes. Proofs are collected in the Appendix.

2. Literature Review

2.1 Irrigation pricing and cost recovery

The economics of irrigation pricing distinguishes between two roles of water charges. Prices can ration water at the margin, and they can recover the cost of supplying it. Tsur and Dinar (1997) ^[31] compare volumetric, per-area, output-based and tiered pricing and show that the most efficient method in theory is often the most expensive to implement, because volumetric measurement at the farm gate is costly in systems with many small users. Johansson *et al.* (2002) ^[14] survey theory and practice and conclude that, outside a few countries, irrigation charges recover only part of operation and maintenance cost. Rogers *et al.* (2002) ^[28] argue for treating water as an economic good while stressing that equity and sustainability objectives constrain how far prices can rise. The case studies collected by Dinar and Subramanian (1997) ^[4] and the critical review edited by Molle and Berkoff (2007) ^[20] add an important qualification: where water is delivered by rotation rather than on demand, charges change farmer behaviour very little. In such systems the main economic role of charges is to finance upkeep, and the relevant question becomes who pays for maintenance and under what institutional arrangement. Easter and Liu (2005) ^[6] reach a similar conclusion from a review of World Bank projects, noting that cost recovery succeeded mainly where revenue stayed with the managing body and was visibly spent on the system.

Our model adopts this perspective. Prices matter in the model because they change the cost of financing and the horizon of the agency, not because they ration water at the margin. This choice is deliberate. In the rice-dominated systems of the Mekong and Red River deltas, water is delivered to command areas rather than metered to individual plots, and the efficiency effects of volumetric pricing are likely to be small relative to the effects of maintenance on delivered capacity. A further reason for caution about using prices to ration water is the evidence that efficiency gains at the farm level can raise total consumption at the basin level (Ward & Pulido-Velazquez, 2008; Grafton *et al.*, 2018) ^[32, 11], which weakens the case for pricing as a conservation tool and strengthens the case for treating it as a financing tool.

2.2 Maintenance of public capital

A second body of work studies maintenance as a distinct use of public resources. Rioja (2003) ^[27] shows in a growth model that shifting spending from new investment to maintenance can raise output when maintenance is underfunded. Kalaitzidakis and Kalyvitis (2004) ^[15] treat maintenance as an endogenous determinant of the depreciation rate of public capital and derive conditions under which the two forms of spending should be combined. Both papers work at the level of the aggregate economy and finance spending with lump-sum or distortionary taxes. The resource cost of raising public money is captured by the marginal cost of public funds, surveyed by Dahlby (2008) ^[3]. Our model borrows the idea that financing has a real resource cost but applies it to a single system and allows the cost to differ between tax and fee financing. It also uses the standard tools of optimal control in economics (Arrow & Kurz, 1970; Kamien & Schwartz, 1991) ^[2, 16] rather than a

full general equilibrium structure, which keeps the results transparent.

2.3 Short horizons, soft budgets and collective action

A third strand concerns the political economy of short horizons. Models of political budget cycles (Nordhaus, 1975; Rogoff, 1990) ^[23, 29] and of strategic fiscal policy (Persson & Svensson, 1989; Alesina & Tabellini, 1990) ^[26, 1] show how electoral timing or uncertainty about future control of the budget leads governments to discount the future more heavily than a social planner would. Maintenance is a natural victim of this bias because its benefits are diffuse and delayed while its costs appear in the current budget. The soft budget constraint literature (Kornai *et al.*, 2003) ^[17] adds a complementary mechanism: when an operator expects to be rescued after a failure, it has weak incentives to prevent the failure through routine upkeep. The theory of regulation (Laffont & Tirole, 1993) ^[18] and of public versus private provision (Hart *et al.*, 1997) ^[13] explains why cost reduction and quality maintenance pull in different directions when a provider is paid on the basis of costs.

The collective-action literature on irrigation offers yet

another view. Ostrom (1990, 1992) ^[24, 25] and Lam (1998) ^[19] document that user organisations which collect their own contributions and keep them for local works often maintain systems better than distant agencies, partly because the money cannot be diverted to other purposes and partly because users monitor each other. We represent these mechanisms in reduced form through a decision discount rate that falls as the share of earmarked financing rises.

2.4 Climate adaptation and infrastructure

A growing literature on adaptation stresses that resilient infrastructure depends at least as much on maintenance as on new construction (Hallegatte *et al.*, 2019) ^[12]. Studies of the Mekong Delta point to the possibility that some protective and irrigation systems will eventually need to be transformed rather than reinforced (Smajgl *et al.*, 2015) ^[30], and Vietnam's Resolution 120/NQ-CP of 2017 explicitly endorses a shift from defending rice cultivation everywhere to adapting land use to salinity and flooding. What is missing is a simple economic criterion for when reinforcement should give way to transformation. Our hump-shaped maintenance result supplies one.

Table 1 positions the paper relative to these strands.

Table 1: Positioning of the paper in the related literature

Strand	Representative studies	Main insight	What this paper adds
Irrigation pricing	Tsur & Dinar (1997) ^[31] ; Johansson <i>et al.</i> (2002) ^[14] ; Molle & Berkoff (2007) ^[20]	Charges rarely recover O&M cost and rarely ration water in rotational systems	Treats prices as a financing instrument and derives an affordability-constrained fee share
Public capital maintenance	Rioja (2003) ^[27] ; Kalaitzidakis & Kalyvitis (2004) ^[15]	Maintenance is underfunded and has high returns	Moves the analysis to a single system with explicit financing regimes
Short horizons and budgets	Persson & Svensson (1989) ^[26] ; Alesina & Tabellini (1990) ^[1] ; Kornai <i>et al.</i> (2003) ^[17]	Budget-dependent decision makers discount the future too heavily	Separates the horizon gap from the financing gap and shows how climate widens it
Collective action	Ostrom (1990, 1992) ^[24, 25] ; Lam (1998) ^[19]	Local, earmarked contributions sustain upkeep	Links earmarking to the decision horizon in a dynamic model
Climate adaptation	Smajgl <i>et al.</i> (2015) ^[30] ; Hallegatte <i>et al.</i> (2019) ^[12]	Maintenance is central to resilience; some systems need transformation	Derives an economic threshold for transformation and its bias under short horizons

3. Research Approach

3.1 Analytical strategy

The paper follows the tradition of theoretical policy analysis in which a model is used to establish the direction of effects and the conditions under which they hold, rather than to produce numerical forecasts. The analysis proceeds in five steps. We first specify the physical, economic and institutional primitives and state them as a dynamic optimisation problem. We then solve the problem with the maximum principle and characterise the steady state and the transitional dynamics. Third, we derive comparative statics by differentiating the closed-form solution with respect to each parameter and signing the derivatives under explicit assumptions. Fourth, we interpret the dynamics graphically in the phase plane, which makes clear how financing

frictions shift the steady state and how a run-down system recovers. Finally, we translate each formal result into an institutional statement and match it to features of the Vietnamese irrigation finance system.

All figures in the paper are schematic. They are drawn for one admissible parameter set to show the shape of the relationships established analytically, but their axes carry no numerical scale, and no conclusion depends on the particular values used to draw them. Every result stated in a proposition holds for all parameter values satisfying the stated assumptions.

3.2 Notation

Table 2 lists the symbols used in the model.

Table 2: Notation

Symbol	Meaning	Restriction
$K(t)$	Service capacity of the irrigation network (reliability and volume delivered)	$K \geq 0$
$M(t)$	Maintenance outlay per unit of time	$M \geq 0$
h	Climate hazard intensity index	$h \in [0,1]$
$\delta(h)$	Deterioration rate of capacity, $\delta_0 + \gamma h$	$\delta > 0$
a, b	Intercept and slope of the marginal farm benefit of capacity	$a, b > 0$
c, ϕ	Linear and convex components of maintenance cost	$c, \phi > 0$
ρ	Social discount rate	$\rho > 0$
ρ_g	Discount rate of a budget-dependent agency	$\rho_g > \rho$
λ	Excess burden of taxation (marginal cost of public funds minus one)	$\lambda > 0$
ε	Collection and administration cost per unit of user charge	$0 \leq \varepsilon < \lambda$
α	Share of maintenance financed by earmarked user charges	$\alpha \in [0,1]$
m_j	Social cost of one unit of maintenance spending in regime j	$m_j \geq 1$
ρ_j	Discount rate applied by the agency in regime j	$\rho_j \geq \rho$
θ	Affordability ceiling, maximum user payment as a share of benefit	$0 < \theta < 1$
$\mu(t)$	Shadow value of one unit of capacity	

4. The Model

4.1 Environment

Time is continuous and the horizon is infinite. An irrigation system serves a command area normalised to one. Its service capacity at time t is $K(t)$, an index that summarises how reliably and in what volume water reaches farm gates. Capacity evolves according to:

$$\dot{K}(t) = M(t) - \delta K(t), \quad K(0) = K_0 > 0 \quad (1)$$

Climate hazards raise the deterioration rate linearly,

$$\delta(h) = \delta_0 + \gamma h, \quad \gamma > 0 \quad (2)$$

Here δ_0 reflects ordinary wear and siltation and γh the additional damage from salinity, floods and subsidence. Because h enters the model only through δ , all results below are stated in terms of δ , and any statement about a higher δ can be read as a statement about a higher hazard intensity. The net farm benefit attributable to irrigation is quadratic and concave,

$$B(K) = aK - \frac{b}{2}K^2 \quad (3)$$

So that the marginal benefit $a - bK$ declines as the system approaches its agronomic ceiling a/b , the capacity beyond which additional water adds nothing to farm output. Maintenance cost is:

$$C(M) = cM + \frac{\phi}{2}M^2 \quad (4)$$

The convex term reflects the rising unit cost of compressing large works into a short period. Canal dredging and gate repair in deltas must be done in dry-season windows between cropping seasons, contractor capacity is limited,

and work done in a rush is more expensive per unit. Convexity gives the agency a reason to spread maintenance over time rather than to restore the system in one step.

4.2 Financing regimes

A financing regime j is described by a pair (m_j, ρ_j) . The parameter $m_j \geq 1$ is the social cost of one unit of maintenance spending. Under hypothetical lump-sum financing $m_j = 1$. When maintenance is paid from general taxation, $m_j = 1 + \lambda$, where λ is the marginal excess burden of taxation (Dahlby, 2008) [3]. When it is paid from user charges, $m_j = 1 + \varepsilon$, where ε is the cost of administering and collecting the charge. The parameter ρ_j is the discount rate that the deciding agency effectively applies. Society discounts at ρ , while an agency whose maintenance money is renegotiated every year, and can be cut whenever fiscal pressure rises, behaves as if it discounted at $\rho_g > \rho$. When a share α of maintenance is financed by user charges that are earmarked for the system and the remainder by the budget, we set:

$$m(\alpha) = 1 + \alpha\varepsilon + (1 - \alpha)\lambda, \quad \rho(\alpha) = \rho_g - \alpha(\rho_g - \rho) \quad (5)$$

The first expression is a weighted average of the two financing costs. The second is a reduced-form assumption motivated by the collective-action and budget-cycle literatures reviewed in Section 2: revenue that the agency collects and keeps is less exposed to annual cuts, so the agency behaves as if its horizon lengthens in proportion to the earmarked share. We also consider an earmarked multi-year budget fund, which sets the decision discount rate to ρ without changing the source of money and therefore without changing m . Comparing the fund with user charges lets us separate the horizon effect of earmarking from its cost effect.

Table 3 lists the regimes used in the analysis.

Table 3: Financing regimes and their parameters

Regime	Description	m_j	ρ_j
First best (FB)	Social planner with costless finance	1	ρ
Far-sighted tax financing (SB)	Budget finance with a credible multi-year commitment	$1 + \lambda$	ρ
Status quo (SQ)	Budget finance negotiated annually	$1 + \lambda$	ρ_g
Earmarked user charges	Share α collected from users and retained for the system	$1 + \alpha\epsilon + (1 - \alpha)\lambda$	$\rho_g - \alpha(\rho_g - \rho)$
Multi-year maintenance fund	Budget money ring-fenced for maintenance over several years	$1 + \lambda$	ρ
Fund with concessional finance	Ring-fenced fund partly financed by grants or low-cost loans	$1 + \lambda', \lambda' < \lambda$	ρ

In regime j the agency solves:

$$\max_{M(t) \geq 0} \int_0^\infty e^{-\rho_j t} [B(K) - m_j C(M)] dt \text{ subject to (1)} \quad (6)$$

Society evaluates the resulting path at the social discount rate and at the true resource cost of the chosen financing,

$$W_j = \int_0^\infty e^{-\rho t} [B(K_j(t)) - m_j C(M_j(t))] dt \quad (7)$$

The distinction between (6) and (7) is central to the analysis. The agency's choice reflects its own horizon, but the consequences of that choice are judged at the social horizon. Under the first best the two coincide.

We maintain throughout the following interior-solution condition.

Assumption 1: $a > m_j c(\rho_j + \delta)$ for every regime and deterioration rate considered.

Assumption 1 says that the marginal benefit of the first unit of capacity exceeds its user cost, which consists of interest and deterioration charges on the marginal cost of maintenance. If it failed, the agency would let the system decay to zero, which is a corner case of limited interest for operating schemes.

Fig 1 summarises the structure of the model.

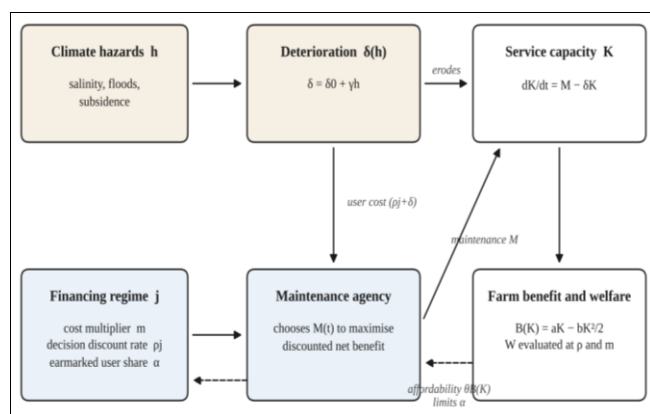


Fig 1: Conceptual structure of the model. Solid arrows show causal links; dashed arrows show the feedback from farm benefit to the affordable user share and from the financing regime to the agency's decision

4.3 Solution

The current-value Hamiltonian of problem (6) is $H = B(K) - m_j C(M) + \mu(M - \delta K)$, where μ is the shadow value of one unit of capacity. The maximum principle gives the maintenance rule and the costate equation:

$$M = \frac{\mu - m_j c}{m_j \phi}, \quad \dot{\mu} = (\rho_j + \delta)\mu - a + bK \quad (8)$$

The maintenance rule has a simple reading: the agency maintains up to the point where the marginal cost of one more unit, $m_j(c + \phi M)$, equals the value of the capacity it creates. Combined with (1), the conditions form a linear system in (K, μ) . Setting $\dot{K} = \dot{\mu} = 0$ yields the steady state:

$$K_j^* = \frac{a - m_j c(\rho_j + \delta)}{b + m_j \phi \delta(\rho_j + \delta)}, \quad M_j^* = \delta K_j^*, \quad \mu_j^* = m_j(c + \phi \delta K_j^*) \quad (9)$$

Steady-state capacity is positive under Assumption 1. The numerator is the margin by which the benefit of the first unit exceeds its user cost, and the denominator combines the curvature of benefits with the curvature of costs scaled by the user cost of capital. The Jacobian of the system has trace ρ_j and determinant $-\delta(\rho_j + \delta) - b/(m_j \phi) < 0$, so the steady state is a saddle point. The stable root is:

$$r_j = \frac{1}{2} \left[\rho_j - \sqrt{(\rho_j + 2\delta)^2 + \frac{4b}{m_j \phi}} \right] < 0 \quad (10)$$

And along the saddle path capacity and maintenance follow:

$$K_j(t) = K_j^* + (K_0 - K_j^*)e^{r_j t}, \quad M_j(K) = \delta K + |r_j| (K_j^* - K) \quad (11)$$

The policy rule in (11) is the main object of interpretation. In steady state the agency simply replaces what deteriorates, $M = \delta K$. When the system has been run down, so that $K < K_j^*$, the agency adds a catch-up term proportional to the maintenance backlog $K_j^* - K$, and $|r_j|$ measures how quickly the backlog is cleared. The half-life of a backlog is $\ln 2/|r_j|$. When the system is above its steady state, for example after a new construction programme has delivered capacity that the financing regime cannot sustain, the catch-up term turns negative and the agency deliberately lets capacity decline.

Fig 2 shows the phase diagram. The $\dot{K} = 0$ locus, $\mu = m_j(c + \phi \delta K)$, slopes upward because a larger system requires more replacement maintenance, which is costlier at the margin. The $\dot{\mu} = 0$ locus, $\mu = (a - bK)/(\rho_j + \delta)$, slopes downward because the present value of a unit of capacity falls as the system approaches its agronomic ceiling. Their intersection is the steady state. The stable arm slopes downward: a run-down system starts with a high shadow value of capacity, which justifies intensive catch-up maintenance, and both the shadow value and the maintenance effort decline as the backlog is cleared.

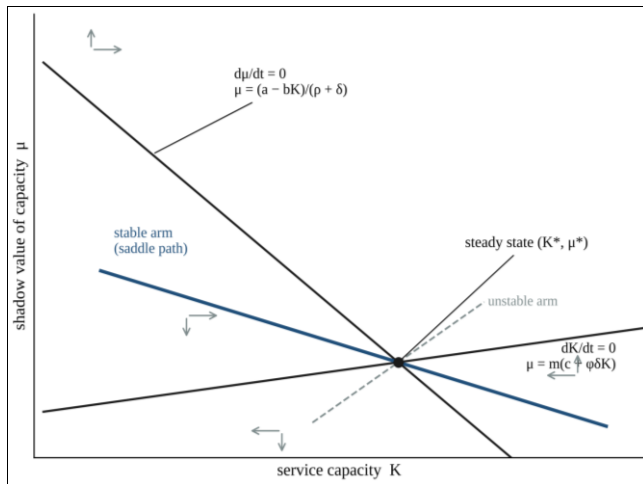


Fig 2: Phase diagram of the maintenance problem (schematic). Arrows show the direction of motion in each region; only the stable arm converges to the steady state

5. Qualitative Analysis

5.1 Comparative statics of the steady state

Because the steady state (9) is available in closed form, the effect of each parameter can be signed directly. Table 4 collects the results. The signs for capacity follow from inspecting the numerator and denominator of (9); those for maintenance follow from $M^* = \delta K^*$; those for the speed of adjustment follow from (10) and are established in Lemma 1 below.

Table 4: Comparative statics of the steady state and the speed of adjustment

Increase in	Capacity K^*	Maintenance M^*	Shadow value μ^*	Speed of backlog clearance $-r$
Benefit intercept a (crop value, water demand)	+	+	+	0
Benefit curvature b (faster saturation)	-	-	-	+
Linear maintenance cost c	-	-	ambiguous	0
Cost convexity ϕ (tight work windows)	-	-	ambiguous	-
Financing cost m_j	-	-	ambiguous	-
Decision discount rate ρ_j	-	-	-	-
Deterioration rate δ (hazard)	-	+ below $\hat{\delta}$, - above	ambiguous	+

Note: Signs hold for all parameter values satisfying Assumption 1. The effect of δ on M^* is established in Proposition 3. For a , b and ρ_j the sign of μ^* follows from $\mu^* = m_j(c + \phi\delta K^*)$, in which only K^* moves; in the remaining cases a direct effect and an effect through K^* work in opposite directions, and the sign is not needed for the results.

Three patterns in Table 4 deserve comment. Every friction that raises the cost of maintenance or shortens the horizon reduces both the size of the system that is sustained and the effort that goes into sustaining it. The deterioration rate is the only parameter with a non-monotone effect on maintenance, which is the subject of Proposition 3. And the financing regime affects not only where the system ends up but also how quickly it gets there, which matters because many Vietnamese schemes start from a state of accumulated backlog after the fee exemption period.

Lemma 1 (speed of recovery): The speed of backlog clearance $|r_j|$ is strictly decreasing in m_j , ρ_j and ϕ , and strictly increasing in b and δ .

Proof. See Appendix A.

Lemma 1 has an intuitive reading. Costlier money and convex costs make it expensive to compress catch-up work into a short period, so the backlog is cleared slowly. A short horizon makes the delayed benefits of catch-up maintenance less valuable, which slows recovery further. Combining (11) with Lemma 1 and Table 4, the initial maintenance outlay of a run-down system, $M_j(K_0) = \delta K_0 + |r_j|(K_j^* - K_0)$, is lower under the status quo than under the first best for two separate reasons: the target K_j^* is lower and the pace $|r_j|$ is slower. A budget-dependent agency therefore under-invests in rehabilitation twice over, once in its long-run ambition and once in its urgency.

5.2 Under-maintenance and its decomposition

Proposition 1 (first best): Under Assumption 1 the first-best problem has a unique steady state $K^{FB} = [a - c(\rho + \delta)]/[b + \phi\delta(\rho + \delta)]$ that is saddle-path stable. From any initial capacity the optimal path converges monotonically at rate $|r_{FB}|$, given by (10) with $m = 1$ and $\rho_j = \rho$.

Proposition 1 follows directly from (9) to (11). The steady state equates the marginal benefit of capacity, $a - bK$, with its full user cost, which is the interest and deterioration charge $(\rho + \delta)$ on the marginal cost of replacement maintenance $c + \phi\delta K$. The benchmark is useful because it allows any other regime to be described by how far, and for what reason, it falls short.

Proposition 2 (under-maintenance): Steady-state capacity K_j^* is strictly decreasing in m_j and in ρ_j . Hence $K^{SQ} < K^{SB} < K^{FB}$. The total gap $K^{FB} - K^{SQ}$ decomposes into a financing component $K^{FB} - K^{SB}$ and a horizon component $K^{SB} - K^{SQ}$, each strictly positive.

Proof. In (9) the numerator is decreasing and the denominator increasing in both m_j and ρ_j , and both are positive under Assumption 1.

Fig 3 shows the two components in the phase plane. A higher financing cost rotates the $\dot{K} = 0$ locus upward, because each unit of replacement maintenance now costs more in social terms. A shorter horizon rotates the $\dot{\mu} = 0$ locus downward, because the present value of a unit of capacity falls. Both movements shift the steady state to the left, but through different channels.

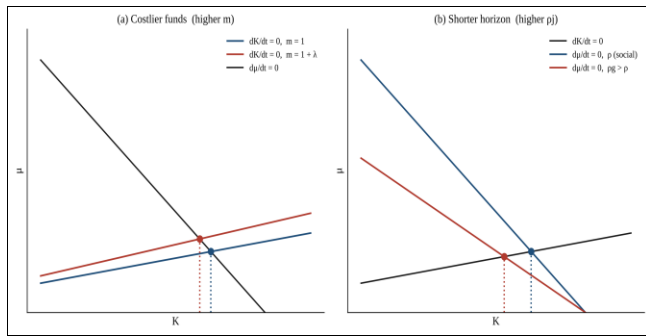


Fig 3: How financing frictions shift the steady state (schematic). Panel (a): a higher cost of funds raises the $\dot{K} = 0$ locus. Panel (b): a shorter decision horizon lowers the $\dot{K} = 0$ locus. Dotted lines mark steady-state capacity

The decomposition matters for policy because the two components call for different remedies, summarised in Table 5. The financing component can only be reduced by cheaper money, which means either shifting financing towards sources with a lower excess burden or reducing the excess burden of the budget itself. The horizon component can be reduced by institutional commitment even if the money comes from exactly the same budget, for example through a ring-fenced multi-year maintenance fund whose allocations are governed by technical norms rather than by annual negotiation. In practice the second remedy is often easier to adopt, because it requires no new revenue and no increase in what farmers pay.

Table 5: Sources of under-maintenance and matching remedies

Component	Model expression	Economic cause	Matching remedy	Instrument changes
Financing gap	$K^{FB} - K^{SB}$	Raising public money destroys resources	Cheaper sources of funds	m falls
Horizon gap	$K^{SB} - K^{SQ}$	Annual budgets favour the present over delayed benefits	Commitment devices, ring-fencing	ρ_j falls towards ρ
Slow rehabilitation	$-r_{SQ} < -r_{FB}$	Both frictions lower the value of catch-up work	Either remedy, plus rehabilitation windows	m or ρ_j falls

5.3 Faster deterioration and the case for transformation

How should maintenance respond when hazards intensify? Intuition suggests that faster decay calls for more maintenance. The model shows that this is true only up to a point.

Proposition 3 (hump-shaped maintenance): In any regime (m, ρ_j) , steady-state capacity K^* is strictly decreasing in δ , while steady-state maintenance $M^* = \delta K^*$ is strictly increasing in δ for $\delta < \hat{\delta}$ and strictly decreasing for $\delta > \hat{\delta}$, where:

$$\hat{\delta}(m, \rho_j) = \frac{-bmc + \sqrt{b^2 m^2 c^2 + abm\phi(a - mc\rho_j)}}{am\phi} \quad (12)$$

Moreover, $\hat{\delta}$ is strictly decreasing in ρ_j .

Proof. See Appendix A.

Two forces are at work. Faster deterioration raises the replacement requirement per unit of capacity, which pushes maintenance up. It also raises the user cost of capacity, which makes a smaller system optimal and pushes maintenance down. At low deterioration rates the first force dominates, so the planner spends more to defend the system. Beyond $\hat{\delta}$ the second force dominates: defending the full system has become so expensive that the planner should let it contract, spend less, and redirect resources elsewhere. Fig 4 illustrates the result.

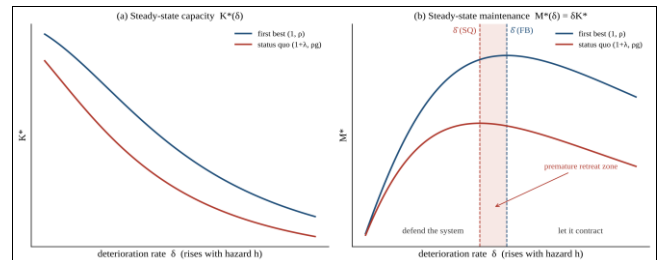


Fig 4: Steady-state capacity and maintenance as functions of the deterioration rate (schematic). The shaded band is the range of deterioration rates in which a budget-dependent agency already reduces maintenance while the social planner would still increase it

The turning point $\hat{\delta}$ gives an economic meaning to the distinction, common in adaptation planning, between incremental and transformational adaptation. On the left of the hump, adaptation consists of doing more of the same: more frequent dredging, more gate repairs, reinforced embankments. On the right of the hump, the economically efficient response is to accept a smaller or different system, for instance by converting part of a rice command area to salinity-tolerant farming that needs less freshwater delivery. Equation (12) shows that the threshold depends on observable features of the system. A steeper decline in marginal benefits (higher b), more convex maintenance costs (higher ϕ) and costlier funds (higher m) all bring the threshold forward.

The last part of Proposition 3 has a sharper policy implication. Because $\hat{\delta}$ falls with ρ_j , a short-sighted agency starts to retrench at a lower deterioration rate than society would. In the shaded zone of Fig 4, the budget-dependent agency is already reducing maintenance and letting the system shrink, while a planner using the social discount rate would still be increasing maintenance. Decisions about whether to downgrade or abandon a scheme are therefore biased towards premature retreat if they are made through the lens of the annual budget.

5.4 Climate change widens the horizon gap

Proposition 2 showed that short horizons reduce capacity. The next result shows that this damage grows with hazard intensity.

Proposition 4 (climate widens the horizon gap): Fix m and let $\rho_g > \rho$. The relative horizon gap $\frac{1 - K^*(m, \rho_g)}{K^*(m, \rho)}$ is strictly increasing in δ whenever $\delta < \sqrt{b/(m\phi)}$.

Proof. See Appendix A.

The intuition is the following. A higher discount rate penalises capital whose benefits arrive late. Faster deterioration does not change when benefits arrive, but it raises the maintenance cost needed to keep each unit of capacity alive and makes that cost recur more often, so the

burden of sustaining the system shifts towards the present relative to its benefits. An agency that discounts the future heavily feels that shift more acutely. The condition $\delta < \sqrt{b/(m\phi)}$ is mild. It compares the deterioration rate with the rate at which the system would adjust if deterioration were negligible, and it holds whenever capacity decays more slowly than the agency can rebuild it, which is the relevant case for operating irrigation schemes. Proposition 4 matters because it reverses a common presumption. It is often argued that institutional weaknesses such as annual budgeting are second-order problems compared with the physical challenge of climate change. The model suggests the opposite ordering in at least one respect: the physical challenge magnifies the institutional weakness. The value of commitment devices that lengthen the decision horizon rises as hazards intensify.

5.5 The climate squeeze on cost recovery

If budget financing is costly and short-sighted, why not shift maintenance to users? The model gives a qualified answer.

Proposition 5 (climate squeeze on cost recovery): Let maintenance be financed according to (5) with $\varepsilon < \lambda$. Then:

1. Steady-state capacity $K^*(\alpha)$ is strictly increasing in the earmarked user share α ;
2. Under the affordability constraint:

$$\alpha C(M^*(\alpha)) \leq \theta B(K^*(\alpha)) \quad (13)$$

Which caps user payments at a share θ of the irrigation benefit, the largest affordable share $\bar{\alpha}$ is strictly decreasing in δ whenever $0 < \bar{\alpha} < 1$, provided that $\delta < \hat{\delta}(m(\alpha), \rho(\alpha))$ and $K^*(\alpha) < a/b$ for all $\alpha \in [0, 1]$.

Proof. Part (i) follows from Proposition 2, since $m(\alpha)$ and $\rho(\alpha)$ both decrease in α when $\varepsilon < \lambda$. Part (ii) is proved in Appendix A.

Part (i) says that, setting aside distributional concerns, moving financing from the budget to earmarked user charges raises capacity and welfare, because it lowers the cost of funds and lengthens the horizon at the same time. Part (ii) identifies the limit of that argument. When hazards intensify on the rising side of the hump, the maintenance bill rises while the benefit that farmers derive from the system falls. The affordable share is squeezed from both sides, as Fig 5 shows.

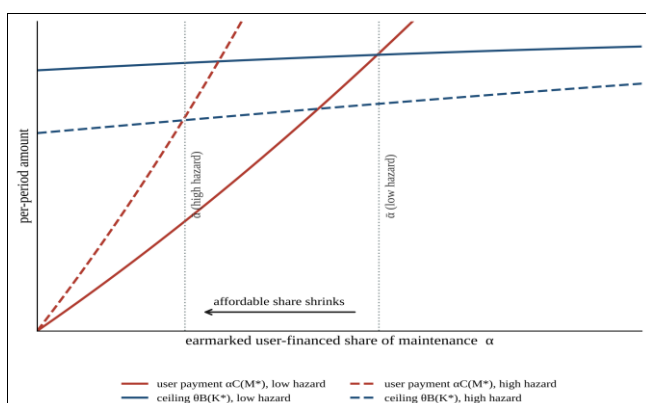


Fig 5: The climate squeeze on cost recovery (schematic). User payments rise more steeply with the fee share under high hazard, while the affordability ceiling falls; the largest affordable share moves to the left

The squeeze has an uncomfortable implication. The areas where budget financing is least effective, because hazards are severe and the horizon gap is widest, are exactly the areas where user financing can contribute least. Cost recovery and climate vulnerability pull in opposite directions. A uniform national target for the share of maintenance recovered from users would therefore be either too timid for low-hazard areas or unaffordable for high-hazard ones.

The affordability ceiling θ deserves to be treated as a design parameter rather than an afterthought. A charge that farmers cannot sustain will either go uncollected, which raises the effective collection cost ε and erodes the advantage of user financing, or lead farmers to reduce the cultivated area, which lowers a and with it the whole benefit stream that justified maintenance in the first place.

5.6 Maintenance norms in a changing climate

In practice, maintenance budgets for public irrigation systems are rarely set by solving a dynamic optimisation problem. They are typically derived from techno-economic norms, which specify maintenance work per kilometre of canal, per structure or as a share of asset value, and these norms feed into the cost base from which service prices are calculated. Norms are calibrated on past conditions. The next result shows what happens when the climate moves away from the conditions on which they were calibrated.

Consider two simple rules, each calibrated so that it reproduces the optimal steady state under the baseline deterioration rate δ_0 . Under a proportional norm the agency spends $M = vK$ with $v = \delta_0$. Under a fixed allocation it spends $M = \bar{M}$ with $\bar{M} = \delta_0 K^*(\delta_0)$.

Proposition 6 (rigid norms): Suppose the deterioration rate rises permanently from δ_0 to $\delta_1 > \delta_0$ and the regime (m, ρ_j) is unchanged.

1. Under the proportional norm, capacity declines exponentially at rate $\delta_1 - \delta_0$ and converges to zero.
2. Under the fixed allocation, capacity converges to $(\delta_0/\delta_1)K^*(\delta_0)$. This is below the re-optimised steady state $K^*(\delta_1)$ if $\delta_1 \leq \hat{\delta}$, and above it if $\delta_0 \geq \hat{\delta}$.

Proof. See Appendix A.

Fig 6 compares the three paths. The proportional norm is the more dangerous of the two rules because it contains no restoring force: as capacity falls, the norm prescribes less maintenance, which lets capacity fall further. A fixed allocation at least stabilises the system, but at a level that is too low when hazards are moderate. Beyond the hump the same fixed allocation over-maintains, because the efficient response there is retreat. In both cases the problem is the same: a rule that was right for the old climate is wrong for the new one, and the error grows with the size of the shift.

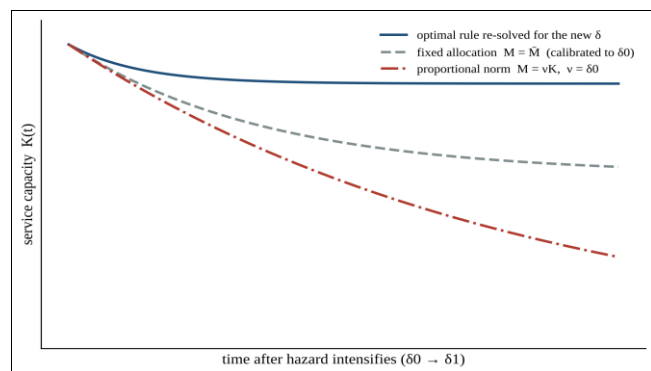


Fig 6: Capacity paths after a permanent increase in deterioration under three maintenance rules (schematic)

Proposition 6 links the abstract model to a concrete administrative task. Techno-economic norms for the management and operation of irrigation works, and the cost bases built from them, should be indexed to hazard exposure and revised as deterioration accelerates, rather than updated only for input prices. Where cost-based prices are capped at the rate of general inflation, the cap reproduces the logic of the fixed allocation and carries the same risk.

5.7 Synthesis

Table 6 summarises the six propositions, their mechanisms and the policy reading that follows from each. Table 7 then combines them into a qualitative scenario matrix that crosses hazard intensity with the decision horizon.

Table 6: Summary of analytical results

Result	Statement	Mechanism	Policy reading
Proposition 1	Unique, stable first-best steady state	Marginal benefit equals full user cost of capacity	Benchmark for assessing any regime
Proposition 2	Capacity falls with financing cost and with the decision horizon	Two frictions act through different loci	Separate remedies for money and for commitment
Lemma 1	Recovery from a backlog is slower under frictions	Costly, convex catch-up work is valued less	Rehabilitation lags are partly institutional
Proposition 3	Maintenance is hump-shaped in deterioration; short horizons bring the turning point forward	Replacement need versus user cost of capacity	Economic threshold for transformation; risk of premature retreat
Proposition 4	The horizon gap widens with hazard	Faster decay front-loads the cost burden	Commitment devices gain value as climate worsens
Proposition 5	User financing raises capacity, but the affordable share falls with hazard	Rising cost meets falling benefit	Differentiated cost recovery; public finance essential in high-hazard areas
Proposition 6	Norms calibrated to the past erode capacity after a hazard shift	Rules without a restoring force, or with the wrong level	Index norms and cost bases to hazard exposure

Table 7: Qualitative scenario matrix

	Long horizon (earmarked, multi-year funding)	Short horizon (annual budget negotiation)
Low hazard (δ well below $\hat{\delta}$)	Capacity close to the first best except for the financing gap; backlog cleared at a moderate pace; user charges can cover a substantial share	Moderate under-maintenance; slow rehabilitation; the horizon gap is the main reform target and can be closed without new revenue
Rising hazard (δ approaching $\hat{\delta}$)	Maintenance rises to defend the system; user share must fall; public finance carries more of the bill	Horizon gap widens; affordable user share falls; agency may start retreating while society would still defend the system
Severe hazard (δ beyond $\hat{\delta}$)	Planned contraction and transformation, timed at the social discount rate	Retreat occurs early and unplanned; assets decay before alternatives are in place

Table 8: Correspondence between model parameters and institutional features in Vietnam

Model element	Institutional counterpart	Direction suggested by the analysis
Capacity K and maintenance M	Service capacity of irrigation systems operated by state-owned irrigation management companies and local cooperatives; maintenance and repair carried out under annual plans	Treat maintenance as an investment in capacity with its own long-term plan
Deterioration $\delta(h)$	Ordinary wear plus salinity, flooding, erosion and subsidence, most severe in coastal provinces of the Mekong Delta	Make hazard exposure an explicit input to maintenance planning
Financing cost m	Budget payment for public-utility irrigation services on behalf of eligible users under Decree 96/2018/ND-CP and its successor, Decree 115/2026/ND-CP	Lower m through cheaper funds and lower collection costs
Decision horizon ρ_j	Annual price appraisal, ordering of public services and budget allocation	Lengthen the horizon with multi-year, ring-fenced maintenance funding
User share α	Prices for irrigation products and services under the Law on Irrigation (2017), formed according to the Law on Prices (2023); near zero for subsidised public-utility services	Raise where affordable, differentiated by hazard zone
Affordability ceiling θ	Ability of users to pay, which the Law on Irrigation lists among the bases for pricing	Make affordability an explicit, published design parameter
Norms (Proposition 6)	Techno-economic norms for management and operation of irrigation works that underpin the cost base of prices	Index norms to hazard exposure, not only to input prices
Transformation threshold $\hat{\delta}$	Land-use adaptation under Resolution 120/NQ-CP (2017) on climate-resilient development of the Mekong Delta	Evaluate downgrading decisions at the social discount rate

6. Implications for Vietnam

6.1 Mapping the model to Vietnamese institutions

The model is stylised, but its main components correspond to identifiable features of irrigation finance in Vietnam. Table 8 sets out the correspondence.

Since the Law on Irrigation took effect in 2018, irrigation services have been priced rather than charged as fees. The law states that prices should cover operation and maintenance cost, depreciation, other reasonable costs and a profit, and that the ability of users to pay should be considered alongside cost. For public-utility irrigation services, however, the state pays the price on behalf of eligible users through budget transfers to the managing organisations, first under Decree 96/2018/ND-CP and now under Decree 115/2026/ND-CP of April 2026. The detailed rules on the classification of works and on the capacity of operating organisations were also renewed in early 2026 by Decree 40/2026/ND-CP. In the language of the model, the user-financed share α for subsidised services is close to zero, maintenance depends on budget allocations that are set and appraised annually, and those allocations compete with other spending. The status quo regime $(1 + \lambda, \rho_g)$ is therefore a reasonable first description of many public schemes. Read in this light, the propositions of Section 5 suggest five sets of implications.

6.2 Sequencing reforms: Commitment before charges

Proposition 2 shows that part of the shortfall comes from short horizons rather than from the source of funds. This part can be addressed without asking farmers to pay more, by making maintenance allocations multi-year and ring-fenced. One option is a maintenance reserve held by each irrigation management company, replenished from the budget according to technical norms and protected from in-year reallocation. Another is a multi-year ordering contract for public irrigation services that specifies maintenance obligations and the corresponding payments for several years at a time. Either arrangement lowers the effective decision discount rate towards the social rate while leaving the source of money unchanged. Because it imposes no new burden on farmers, this reform is politically easier than raising user charges, and the model suggests that its benefits grow as hazards intensify (Proposition 4).

6.3 User charges as an earmarked, differentiated contribution

Proposition 5(i) supports a role for user contributions, but the mechanism in the model works only if the money is earmarked. Charges that flow into the general budget raise the financing cost without lengthening the horizon. The experience summarised by Ostrom (1990, 1992) [24, 25] and Easter and Liu (2005) [6] points to arrangements in which water user organisations collect contributions for tertiary-level canals and keep them for local works, with transparent accounts. Proposition 5(ii) adds that the affordable contribution falls with hazard exposure. A uniform national contribution rate would be either too low for stable inland systems or too high for vulnerable coastal ones. Contributions should therefore be differentiated by hazard zone, with the affordability ceiling published and reviewed alongside price appraisals.

6.4 Public and climate finance where hazards are severe

In high-hazard areas the model implies that maintenance

will have to be financed mainly from public and concessional sources, and that the efficiency of those sources becomes the decisive factor. A lower effective excess burden, achieved through grants or concessional loans earmarked for maintenance, directly lowers m and shifts the $\dot{K} = 0$ locus back down. At present, climate finance tends to favour new construction, such as sluice gates and dykes, over the routine upkeep that keeps existing assets working. The analysis supports directing part of that finance to multi-year maintenance programmes, in line with the emphasis on maintenance in recent work on resilient infrastructure (Hallegatte *et al.*, 2019) [12].

Fig 7 combines these implications into a qualitative policy map. In the lower-left zone, where hazards and the cost of public funds are both moderate, institutional levers dominate. In the upper zone, where public money is costly or hazards are rising, the cost of money becomes the binding constraint. Beyond the transformation threshold, the right response is planned contraction.

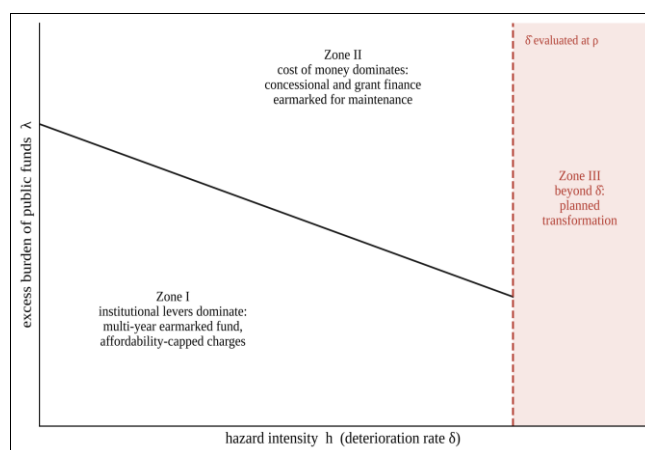


Fig 7: Qualitative policy map (conceptual). Zone boundaries are illustrative and indicate the dominant lever implied by Propositions 2 to 5; the vertical line marks the transformation threshold evaluated at the social discount rate

6.5 Norms, prices and the cost base

Proposition 6 bears on the technical work behind price setting. Techno-economic norms for the management and operation of irrigation works determine how much maintenance enters the cost base and therefore how much the state pays for public-utility services. If norms are revised only to reflect input prices, or if price adjustments are limited to the general rate of inflation, the resulting allocation behaves like the fixed rule in Proposition 6 and erodes capacity as hazards intensify. Norms should include a hazard adjustment, for instance higher dredging frequencies in canals exposed to sediment-laden floodwater or more frequent gate maintenance where salinity accelerates corrosion, and they should be reviewed on a schedule that tracks observed deterioration. Asset inventories and operation records kept by irrigation management companies under the asset-management rules for irrigation infrastructure could provide the evidence for such reviews.

6.6 Deciding when to transform

Proposition 3 shows that, past a threshold deterioration rate, the efficient response is to let a system contract and to redirect resources, for example towards the salinity-adapted farming systems envisaged in Resolution 120/NQ-CP.

Equation (12) indicates which information is needed to locate that threshold: the slope of marginal farm benefits, the convexity of maintenance cost and the discount rate. Because a short-sighted agency reaches the threshold too early, decisions to downgrade or abandon schemes should be appraised at the social discount rate and outside the

annual budget cycle, preferably in provincial or regional planning processes that can arrange the alternative land uses before the old system is allowed to decline.

Table 9 brings the policy options together and records, for each, which model parameter it changes, which proposition supports it and where it is most relevant.

Table 9: Qualitative assessment of policy options

Policy option	Parameter changed	Supporting result	Expected effect on capacity	Most relevant setting
Multi-year ring-fenced maintenance fund	$\rho_j \rightarrow \rho$	Propositions 2 and 4	Closes the horizon gap; faster rehabilitation	All schemes; gains rise with hazard
Earmarked user contributions within an affordability ceiling	α up; m and ρ_j down	Proposition 5(i)	Raises capacity where affordable	Low and moderate hazard areas
Hazard-differentiated contribution rates	$\bar{\alpha}$ varies with δ	Proposition 5(ii)	Avoids unaffordable charges and arrears	Coastal and flood-prone provinces
Concessional or grant finance for maintenance	λ down	Propositions 2 and 5	Closes part of the financing gap	High-hazard areas where users cannot pay
Hazard-indexed maintenance norms	Rule approaches optimal response to δ	Proposition 6	Prevents gradual erosion after hazard shifts	Price appraisal and cost-base revisions
Transformation appraisal at the social discount rate	δ evaluated at ρ	Proposition 3	Avoids premature retreat; plans contraction where efficient	Severely affected systems

7. Limitations and directions for further research

The model is intentionally simple, and several of its simplifications suggest extensions. Hazards are treated as a deterministic shift in the deterioration rate, whereas real hazards arrive as shocks: a saline intrusion season or a large flood can destroy a substantial part of capacity at once. A stochastic version with jump risk would allow precautionary maintenance and the option value of waiting before transformation to be analysed with the tools of investment under uncertainty (Dixit & Pindyck, 1994) [5]. Farmers are passive in the model. Letting cultivated area and cropping choices respond to service quality and to charges would make the affordability ceiling endogenous and would capture the feedback through which unaffordable charges reduce the benefit base.

The reduced-form link between earmarking and the decision horizon in (5) could be grounded in an explicit political-economy model with turnover of decision makers or uncertain future budgets. The model also treats the network as a single asset. Real systems have head works, main canals and tertiary canals with different deterioration processes and different owners, and the allocation of maintenance responsibility across these levels is itself a policy question. Finally, the analysis is qualitative. Estimating the deterioration function, the benefit function and the convexity of maintenance cost from the asset inventories and operation records of irrigation management companies would allow the thresholds identified here, in particular δ and $\bar{\alpha}$, to be located for actual schemes and would turn the qualitative results into quantitative guidance.

8. Conclusion

This paper has developed a compact optimal control model of irrigation maintenance in which financing arrangements and climate hazards enter through a small number of interpretable parameters. Because the model has a closed-form solution, its implications can be established analytically and without reliance on particular parameter values. Six results follow. Budget-cycle financing leads to chronic under-maintenance, and the shortfall separates into a financing gap and a horizon gap that call for different remedies. Frictions slow rehabilitation as well as lowering

its target. Optimal maintenance is hump-shaped in the deterioration rate, which gives an economic threshold for transformation that a short-sighted agency reaches too early. The horizon gap widens as hazards intensify. The affordable share of user financing falls as hazards rise, so cost recovery and climate vulnerability pull in opposite directions. And maintenance norms calibrated on past conditions erode capacity once the climate moves.

For Vietnam, where irrigation services are now priced but public-utility services are largely paid for by the state on behalf of users, the analysis points to a sequence of reforms. Institutional commitment, in the form of multi-year ring-fenced maintenance funding, is the first and cheapest lever. Earmarked, affordability-capped user contributions differentiated by hazard exposure come next. In the most vulnerable areas, low-cost public and climate finance for maintenance, hazard-indexed maintenance norms and transformation decisions appraised at the social discount rate become decisive. Keeping irrigation systems in working order under a changing climate is, in this sense, as much a question of financial institutions as of engineering.

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