Institutions for Provision of Shared Infrastructure:

Insights from Irrigation Systems in India

by

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ABSTRACT

In many social-ecological systems, shared resources play a critical role in supporting the livelihoods of rural populations. Physical infrastructure enables resource access and reduces the variability of resource supply. In order for the infrastructure to remain functional, institutions must incentivize individuals to engage in provision and maintenance. The objective of my dissertation is to understand key formal and informal institutions that affect provision of shared infrastructure and the policy tools that may improve infrastructure provision. I examine these questions in the context of irrigation systems in India because infrastructure maintenance is a persistent challenge and system function is critical for global food production.

My first study investigates how the presence of private infrastructure, such as groundwater pumps, affects the provision of shared infrastructure, such as shared tanks or surface reservoirs. I examine whether formal institutions, such as water pricing instruments, may prevent under-provision of the shared tanks. My findings suggest that in the absence of rules that coordinate tank maintenance, the presence of private pumps will have a detrimental effect on system productivity and equality. On the other hand, the combination of a fixed groundwater fee and a location-based maintenance fee for tank users can improve system productivity and equality.

The second study examines the effect of power asymmetries between farmers, caused by informal institutions such as caste, on the persistence of political institutions that govern infrastructure provision. I examined the effect of policy tools, such as non-farm wage employment and informational interventions, on the persistence of two types of political institutions: self-governed and nested. Results suggest that critical regime shifts in political institutions can be generated by either intervening in formal institutions, such as non-farm wage employment, or informal institutions, such as knowledge transmission or learning mechanisms.

The third study investigates how bureaucratic and political corruption affect public good provision. I examine how institutional and environmental factors affect the likelihood of corruption and infrastructure provision. I demonstrate that cracking down on corruption is only beneficial when infrastructure provision is poor. I also show that bureaucratic wages play an important role in curbing extralegal transactions and improving infrastructure provision.

DEDICATION

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Chapter 1

INTRODUCTION

In many social-ecological systems, shared resources play a critical role in supporting the livelihoods of rural populations. Examples of such systems include irrigated agriculture, community forestry, and coastal fisheries. In these systems, human interactions with the resources are mediated by physical infrastructure, which is often consciously designed by humans and enables access to the resource (Anderies, 2015). Examples of such physical infrastructure include irrigation canals, fishing gear, etc.

A fundamental problem faced by human societies concerns the provision and maintenance of shared physical infrastructure (Cárdenas *et al.*, 2017). Provision decisions may include whether or not to participate in construction and cleaning of shared irrigation canals, in reforestation, or in using appropriate fishing gear that protects fish. Often, individual provision decisions depend on the proportional equivalence between the benefit of resource appropriation and cost of provision (Ostrom, 1990). Designing institutions that shape these incentives is, therefore, a critical endeavor.

Numerous empirical cases suggest that institutions can effectively manage provision of shared infrastructure. A few examples of such cases include irrigation communities in India and Nepal (Bardhan, 2000; Lam and Ostrom, 2010), small-scale fisheries in Northwest Mexico (Lindkvist *et al.*, 2017), and forests in the middle hills of Nepal (Gautam and Shivakoti, 2005). These cases provide an important foundation for understanding institutional designs that succeed in mitigating the emergence of dilemmas regarding provision of shared infrastructure. However, to apply these lessons more broadly, we need to understand how and why institutions are crafted and sustained, and what consequences they generate in diverse settings.

In this dissertation, I will attempt to address these objectives by analyzing small-scale irrigation systems in India.

Small-scale irrigation systems, which are used by nearly 84% of farms worldwide (Lowder *et al.*, 2016), contribute to nearly 40% of the world's food production (Bruinsma, 2017). In India, a country that holds nearly a quarter of the world's agricultural land, 44% of the land is under irrigation (Gleeson and Wada, 2013). Agriculture contributes to nearly 20% of India's Gross Domestic Product (Bhattacharya, 2017). In order to improve agricultural productivity, the Indian government has invested more than $10 billion since 1990, to repair, rehabilitate, and build irrigation infrastructure (Shah, 2009; Smilovic *et al.*, 2015). Yield and water productivity, however, continue to decline due to poor irrigation infrastructure (Shah, 2009) and concern for food insecurity and inequity is increasing.

Several factors affect the provision of irrigation infrastructure and these may be understood through a coupled infrastructure systems (CIS) approach. Figure 1 shows the CIS framework, which has been adapted from Anderies (2015) to understand how the interactions between irrigators and irrigation water are mediated by institutions, irrigation infrastructure, and irrigation agencies. I will explore different components of this framework in my thesis to broadly understand (i) the key political-economic factors that affect the incentives to maintain shared irrigation infrastructure, and (ii) the policy instruments that may improve the provision of irrigation infrastructure.

Chapter 2 examines how private infrastructure affects provision of shared infrastructure. It explores how private infrastructure affects individuals' incentives to engage in provision of shared infrastructure as well as the corresponding effect on overall resource availability. I operationalize this broad research question by examining how groundwater pumps affect the collective maintenance of surface reservoirs in tank irrigation systems in South India (Mosse, 2008). The focus of this chapter is on links 1, 4, and 6 in Figure 1.

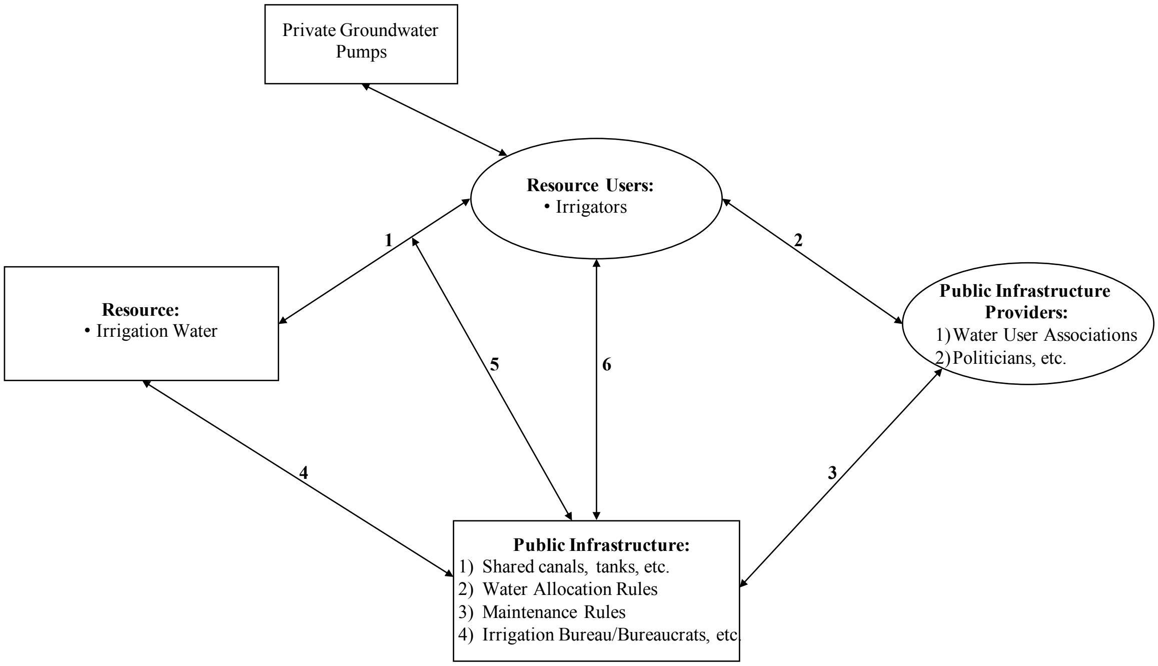

Figure 1. The Coupled Infrastructure Systems (CIS) Framework. Adapted from (Anderies, 2015) to represent an irrigation system.

For those that are able to invest in private infrastructure, access to private pumps may reduce reliance on shared infrastructure and, therefore, the importance of its maintenance. This can negatively impact the groups of irrigators that still rely on the shared infrastructure for their water (Ostrom, 2003), and reinforce the adoption of groundwater pumps (Palanisami, 2006). The tension between provision of shared infrastructures and adoption of private infrastructure is a problem that also persists in other types of systems. One example is the problem of the utility-death spiral in the electricity industry (Castaneda *et al.*, 2017). As adoption of solar PV by households (private technology) increases, utility companies increase tariffs to compensate for reduced revenue in order to be able to maintain the grid (shared infrastructure). This further prompts solar PV adoption. There has been relatively little work on which types of policy interventions are required to improve the provision of public goods in these contexts.

I developed a stylized replicator dynamic model to investigate the effects of pricing instruments, such as volumetric fees, on the maintenance of the shared tanks in systems where users have access to private groundwater pumps. I demonstrate that the combination of a fixed groundwater fee and a volumetric fee on tank users that is differentiated based on where users are located in the system can improve system productivity and equality.

Chapter 3 examines how heterogeneity among resource users determines the political institutions that persist in an irrigation system and the resulting effect on provision of irrigation infrastructure. Heterogeneity refers to the social stratification of users determined by cultural norms, such as caste, that may lead to power asymmetries among resource users (Ruttan, 2006). The focus of this chapter is also on links 1, 4, and 6 in Figure 1.

Much of the literature on institutions recognizes their importance for economic performance in a society (North, 1994; Acemoglu and Robinson, 2006). There is limited understanding, however, of what determines the persistence of institutions. Specifically, how does the presence of power asymmetries in a system affect the persistence of political institutions that govern public good provision? To answer this question, I developed a stylized compartmental model that traces the institutional choice of individuals in an irrigation system. Using this mental model of elites and non-elites, I examined the effect of policy tools, such as non-farm wage employment and informational interventions, on the persistence of two political institutions: self-governed and nested. I demonstrate that critical regime shifts in political institutions can be generated by either intervening in formal institutions, such as non-farm wage employment, or informal institutions, such as knowledge transmission or learning mechanisms in the system. I also show that in systems where public infrastructure depreciates at a given rate, changes in the rate of learning in mental models of elites relative to the rate of infrastructure decay can result in a shift to political institutions that enable better infrastructure provision. This is contrary to situations in which elites' mental models are strongly influenced by non-economic considerations, such as their cultural beliefs, and the system persists in political institutions with inferior infrastructure provision (Baker, 2011).

In Chapter 4, I examine how public infrastructure providers determine the level of infrastructure provision in a system facing environmental shocks. I operationalize this research objective by examining how the presence of extralegal side payments between politicians and bureaucrats affects the provision of irrigation infrastructure in a government-managed irrigation system. The focus of this chapter is on links 3, 6, and 2 in Figure 1.

Irrigation reform discussions focused on enhancing the role of bureaucrats have previously dissociated politics from their analysis and assumed benevolence on the part of the bureaucrat (Moe, 2006). However, research shows that in developing countries like India, infrastructure provision efforts of bureaucrats can be affected by the demands for extralegal payments by their superiors (Muneepeerakul and Anderies, 2017). In this case, the superior is the politician (Wade, 1982). Through these side payments, bureaucrats are guaranteed their jobs even if they undersupply the public good. Failure to comply with their superior's demands, however, can result in the bureaucrat's removal from office. On the other hand, the politician's incentives to demand extralegal side payments are shaped by the electorate, or the irrigators, who require the irrigation infrastructure to be functional for their livelihoods.

I developed a stylized principal-agent model to examine how institutional and environmental factors affect (i) the likelihood of corruption, and (ii) the provision of infrastructure. My model results suggest that a crackdown on extralegal side payments can result in lower provision of infrastructure when the system experiences high uncertainty in environmental shocks to the infrastructure. In other words, cracking down on corruption is only beneficial when infrastructure provision is bad. I also show that bureaucratic wages play an important role in curbing extralegal transactions and improving infrastructure provision.

Finally, in Chapter 5, I summarize my findings, and outline the theoretical and practical implications for irrigation policy in India.

Chapter 2

EFFECT OF PRIVATE INFRASTRUCTURE ON THE PROVISION OF SHARED IRRIGATION INFRASTRUCTURE IN SOUTH INDIA

2.1 Introduction

In many social-ecological systems (SES), shared infrastructure mediates interactions between humans and resources. For example, smallholder agricultural systems, which are important for food security and economic growth in many developing countries (World Bank, 2008), depend on irrigation infrastructure through which farmers appropriate water. Though traditionally, resource users relied upon shared infrastructure to access resources in a SES, increasing resource scarcity and changing opportunity costs have made private infrastructure more desirable. A core problem in these SESs is that people who still rely on shared infrastructure for their livelihoods are now faced with the challenge of maintaining livelihoods because the shift to private infrastructure is often made at the expense of the shared infrastructure. How does the presence of private infrastructure affect the ability of individuals to solve collective action problems related to the provision of shared infrastructure and distribution of resources? What policy instruments are required for improving the provision of shared infrastructure under these circumstances? This study examines these questions using a stylized model of a small-scale irrigated agricultural system. This is important because half a billion people manage agriculture systems around the world rely on shared infrastructure (Frenken and Gillet, 2012; Suhardiman and Giordano, 2014).

In many small-scale irrigation systems, agricultural productivity depends heavily on the quality of shared irrigation infrastructure, such as tanks (or surface reservoirs), canals, and weirs. Three empirical findings emerge from a comparative case-study analysis of such systems. First, is the social dilemma associated with provision of public goods, such as canals and related irrigation infrastructure (Olson, 1993; Janssen *et al.*, 2011; Muneepeerakul and Anderies, 2017; Cárdenas *et al.*, 2017). Second, is the dilemma associated with appropriation of commons, such as groundwater (Burness and Brill, 2001; Hellegers *et al.*, 2001; Cody *et al.*, 2015; Smith *et al.*, 2017). Third, is the challenge of efficient distribution of water in irrigation systems with asymmetric access to the resource (Ostrom and Gardner, 1993; David *et al.*, 2015).

The literature highlights the feedbacks between individuals' provision and appropriation decisions given the dependence on shared infrastructure in a system. However, individuals using private infrastructure to access a resource may also negatively affect the provision of the shared infrastructure (Ostrom, 2003). For example, adoption of private groundwater pumps may result in reduced maintenance of shared infrastructure, such as reservoirs and canals. On the other hand, poor quality of the shared infrastructure may reinforce the adoption of pumps and over-appropriation of the groundwater resource (Wade, 1989). The institutions required for addressing negative externalities caused by the interaction between different types of infrastructures is not well understood.

In this study, I develop a stylized replicator dynamic model to examine how price-based interventions may improve the overall productivity and equity between upstream and downstream communities in an irrigation system with both shared and private infrastructures and an asymmetric distribution of irrigation water. I contextualize the model predictions using the case study of tank irrigation systems in South India. The two primary economic instruments often used in irrigation management are water markets and water fees (Johansson *et al.*, 2002). The difference between these two instruments is in their implementation.

Water fees, such as volumetric and non-volumetric pricing, require the presence of a central agency, such as a water user association, to set the price of water, monitor water use, and collect the fees (Wade, 1989; Tsur and Dinar, 1997). Water markets, on the other hand, provide more flexibility in setting the price of irrigation water based on scarcity, and have been proven to eliminate water allocation inefficiencies in systems where there is no central authority or the central authority fails to respond to changing water demands (Shah and Zilberman, 1991; Easter *et al.*, 1999). However, for water markets to work, there needs to be an irrigation agency, such as the state, which defines tradable water rights, enforces property rights, and resolve potential disputes among farmers (Zilberman *et al.*, 1997).

I focus on water fee instruments in the study for three reasons. First, it is well-known that policy instruments, such as volumetric pricing of water, may serve as signals for scarce resources and induce farmers to change their appropriation and provision decisions accordingly (Ostrom *et al.*, 1994; Dinar and Mody, 2004; Tsur, 2005; Johansson *et al.*, 2002). Second, in the systems that I examine, there is often a water user association, which makes the implementation of these instruments feasible. Third, water markets may be less relevant because in the absence of other fees, they will tend to gravitate towards a single price instrument for water and ration water scarcity within the catchment. However, they don't address provisioning of shared infrastructure, , making them a panacea incapable of handling all the dilemmas in the system.

In this study, I examine three important challenges: (i) the provision dilemma associated with tanks, which is exacerbated by the presence of private groundwater pumps, (ii) the over-appropriation of the groundwater, which may be reinforced by the provisioning dilemma, and (iii) the negative externality caused by the withdrawal of water by upstream communities on the productive use of tank water by downstream communities.

In systems that face multiple challenges, it is usually not feasible to achieve an efficient outcome using a single policy instrument (Tinbergen, 1952). I postulate that the overall productivity and distributional outcomes at system equilibrium may be improved with the use of multiple instruments compared to the use of a single policy instrument. Specifically, I examine three types of instruments: (i) a volumetric fee on tank users, which may be differentiated based on their location; (ii) a volumetric fee on groundwater users; and (iii) a fixed fee on groundwater users.

Three conclusions emerge from the analysis. First, the analysis shows that in the absence of rules for provision of shared infrastructure, the presence of a private infrastructure, like a groundwater pump, to access a common-pool resource is an unmitigated bad and can push farmers into a poverty trap. Second, the model results suggest that by using multiple price instruments, we may not only improve total system productivity, but also improve equality in the system. Specifically, the results show that a differentiated fee on tank users and a fixed fee on groundwater users play a key role in addressing both the provisioning and water allocation challenges. The differentiated volumetric fees for tank users help mitigate the externality caused by the upstream users due to their position. The fixed water fee reduces the number of groundwater users in the system and disincentivizes groundwater pumping on the extensive margin. This fee also helps mitigate water scarcity through improving the condition of the tank infrastructure.

2.2 Empirical Background

Tanks, or surface reservoirs, are human-constructed earthen structures that capture rainfall and surface run-off, and are the most important sources for irrigation in the southern states of India dating as far back as 300 BC (Rangarajan, 1992; Mosse, 2006). Tank irrigation accounts for about 55 percent of the total irrigated area in the state of Andhra Pradesh in South India and approximately 25 percent of the total rice production in India (Meinzen-Dick *et al.*, 2010). They usually range in sizes from 20 to 1,000 hectares. Water from the tank is distributed to agricultural fields in the command area by gravity flow, through a variable number of sluices and canals. Collective maintenance of the shared tank and related physical structures is, therefore, critical for the infrastructure to remain functional.

The share of tank-irrigated area in Andhra Pradesh declined by around 30 percent between 1990-1991 and 2000-2001, and many tanks are now physically in disrepair (Palanisami, 2006). The reasons for the decline of tanks are complex and historically specific. These include colonial tax systems, deforestation, land use change, intensified cropping patterns, encroachment of tank beds, and siltation (Mosse, 1999). Adequate examination of all these reasons is well beyond the scope of this paper. However, a particularly prominent diagnosis of these systems has long been that individualized water control through adoption of private infrastructure, such as groundwater pumps, has impinged upon the functioning of tank systems.

Provision and maintenance of tanks, in the form of labor or money, often requires collective action among farmers. On the other hand, farmers may access shared groundwater through privately installed pumps that do not require collective action. Farmers using groundwater irrigation, often, do not contribute towards the maintenance of tanks (Meinzen-Dick, 1984). Reduced maintenance leads to excessive siltation and decline in performance of the shared infrastructure, thereby incentivizing more farmers to shift to groundwater irrigation.

To make matters worse, access to tank water may be further diminished in systems with an upstream-downstream asymmetry to water distribution. The size of tanks is often determined based on the water requirement of crops and the number of farms in their command area, and they are designed to meet the water requirements of both upstream and downstream farmers. However, when siltation makes water availability scarce, upstream farmers, by virtue of their location, may over-appropriate in the absence of effective rules for coordination (Wade, 1989). This results in an inefficient distribution of the tank water to the downstream farmers and pushing them to adopt groundwater technology.

In such systems, an engineering solution in the form of expanding the size of tanks is not feasible due to constraints on land availability and the high fixed costs involved in building new infrastructure. Moreover, in the absence of rules that prevent upstream farmers from over-appropriation, simply increasing the size of the tank may not guarantee more water availability to downstream users (Wade, 1989).

The fact that groundwater can play an important role as a buffer against water scarcity needs no elaboration. It has been well documented that agriculture productivity in systems with groundwater irrigation are generally higher than those with surface water irrigation in India (Shah, 2010). Furthermore, strong arguments have been made that access to groundwater plays a critical role in poverty alleviation in India (Kerr, 2002; Dubash *et al.*, 2002).

One problem, however, with groundwater is that access is not uniformly distributed. A major share, about 40 percent, of the tank irrigated area in South India is accounted by small-holder farmers (less than 2 hectares) (Meinzen-Dick *et al.*, 2010). Since these farmers are mostly poor, they often cannot afford cost-intensive irrigation technologies, such as groundwater pumps. Even in cases where farmers are able to access the technology through government subsidies, the benefits of groundwater tend to disproportionately favor the early adopters, who are typically wealthy farmers. As aquifer levels decline, the fixed costs of drilling the wells and the variable pumping costs increase. Early adopters of the technology often accumulate sufficient capital to diversify their incomes or to be able to deepen their wells as the aquifer level declines. Considering the irreversible nature of the high initial investments made by farmers in groundwater technology, later adopters are locked into the technology and risk being pushed into a chronic poverty trap (Barrett and Swallow, 2006; Janakarajan and Moench, 2006).

A large body of work in economics has analyzed the externalities of groundwater extraction and offers clear prescriptions in the form of optimal policy instruments (Gisser and Sanchez, 1980; Burt, 1967; Smith *et al.*, 2017). Much of this work examines optimal groundwater management through the lens of appropriation dilemmas caused by competitive patterns of water extraction. However, the competition for groundwater may be exacerbated by the provisioning dilemma and locational asymmetry associated with a shared infrastructure, such as a tank. In such cases, there may be a need for an integrated set of institutions to coordinate the infrastructure provision and water distribution processes.

2.3 Model Structure

To explore the interdependencies between the appropriation and provision dilemmas in an irrigation system explicitly, I develop a model of farmers' choice of infrastructure and their appropriation decisions conditional on this choice. The model is loosely parameterized based on data gathered from 40 focus group discussions and 80 interviews conducted in 10 irrigation communities in the state of Andhra Pradesh in South India. I also draw upon the ethnographic work of Mosse (2008, 1999), Palanisami (2006), and Meinzen-Dick (1984) on tank irrigation systems in South India.

In the model, individual farmers have two strategies for irrigation: R and G. Rs rely on the shared tank infrastructure to receive their irrigation water. Gs use private groundwater pumps for irrigation. I examine how the strategies of farmers and the resource availability change over time. For the remainder of the the discussion, I use the notation that subscripts refer to the village and superscripts refer to the type of infrastructure the farmers rely upon for irrigation water. For example, π_1^R refers to the profit of tank users in the upstream village and π_1^G refers to the profit of groundwater users in the upstream village.

Consider N farming households spread across two villages (village 1 and village 2) that manage a shared irrigation tank and access the groundwater aquifer through private groundwater pumps (Figure 2). Tank users have an asymmetric access to the tank water, whereas groundwater users in both villages access a shared aquifer.

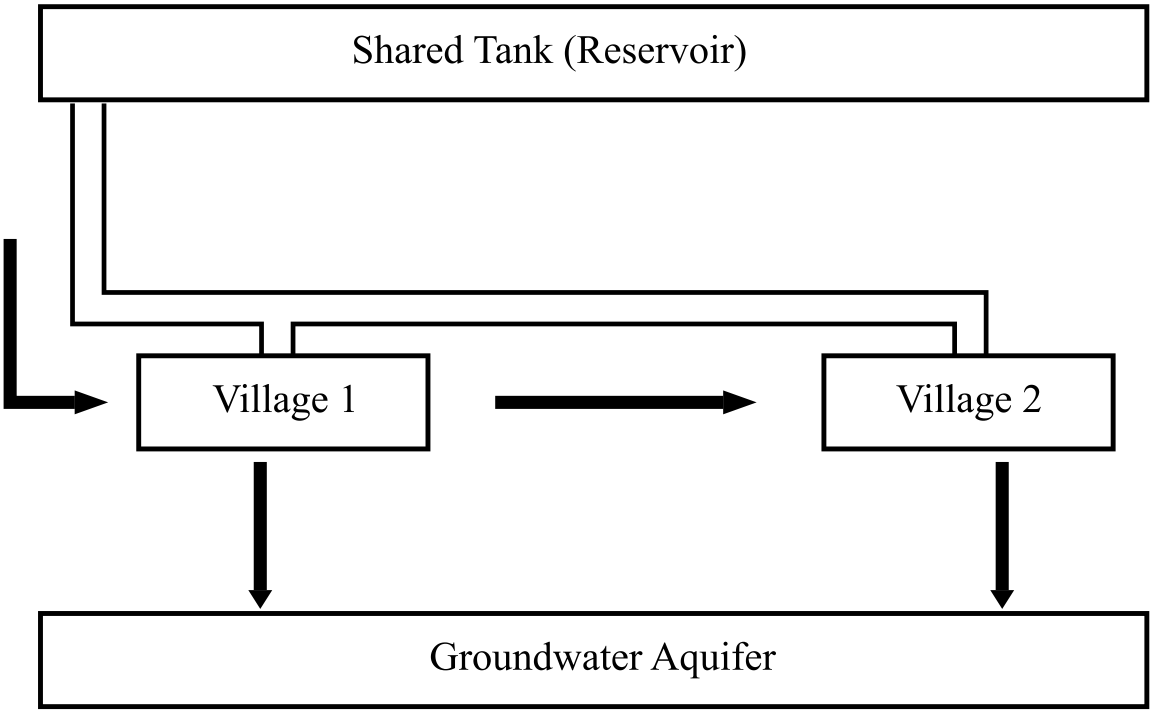

Figure 2. Graphical representation of the system layout. Villages 1 and 2 have asymmetric access to the tank water. Village 1 has an advantage over village 2 in receiving water from the shared tank. Both villages have a symmetric access to the groundwater through private pumps.

There are N_1 and N_2 households in each village, respectively, with $N_1 + N_2 = N$.[1] Farmers may choose one of two irrigation technologies for water: the fraction of farmers who rely on tank irrigation in village 1 and village 2 are X_1 and X_2 respectively. Conversely, the fraction of farmers who rely on groundwater pumps in each village are $(1 - X_1)$ and $(1 - X_2)$.

I assume that farmers are endowed with the same acreage. This assumption is consistent with my observations in Andhra Pradesh where a majority of farmers own small farms (2-4 acres). I also assume that sufficiently strong monitoring and enforcement mechanisms exist in the irrigation system, which ensure that all tank users contribute towards maintenance of the

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[1] Lack of human capital, liquidity and other entry barriers to rural non-farm employment prevent migration in these systems (Meinzen-Dick, 1984).

shared infrastructure. I assume that the maintenance efforts are coordinated by an irrigation agency, such as the *Panchayat Samiti*, or Regional Irrigation Ministry of Andhra Pradesh. This agency may either be a farmer managed water user association or the state.

I assume that the tank infrastructure and groundwater aquifer are in pristine states initially, i.e., the tank is at full capacity and the groundwater availability is at 100%. This assumption mimics the initial conditions of the tank irrigation systems I examine. I also assume that a small fraction (0.1%) of the populations in upstream and downstream villages are groundwater users. This assumption is made to overcome the limitation of replicator dynamics in dealing with strategy innovation in the system (Gintis, 2009).

2.3.1 Shared Infrastructure Dynamics

The function of the tank is to capture a monsoon's worth of rain that flows into the system and distribute water availability for the planting season. In the analysis, I assume that the area of the tank remains fixed. Consequently, the amount of water that is available in the tank for irrigation is equal to the capacity (or depth) of the tank. As the tank becomes more silted, its capacity reduces and consequently, the water available for irrigation decreases.

Farmers must maintain the shared infrastructure each year through desilting and repair works. If too few farmers contribute towards maintenance, the infrastructure is heavily silted and water availability is reduced. In the model, I assume that there is always sufficient monsoon flows to fill the tank, regardless of its capacity. This assumption allows me to treat the tank capacity as analogous to the water available in the tank. I denote the capacity of the shared infrastructure with R. The dynamics of R are assumed to be:

$$\frac{dR}{dt} = \theta\Big(\frac{M}{R}\Big)^{\mu} - \sigma R \tag{2.1}$$

where $R \leq R_{\text{max}}$, M is the total maintenance revenue collected from farmers in villages 1 and 2, θ scales the marginal productivity of the maintenance investment, and σ is the natural rate of siltation of the tank. μ is a scaling parameter between 0 and 1, which relates how the effect of maintenance and infrastructure capacity change across different levels of maintenance investment.

The term $\left(\frac{M}{R}\right)^{\mu}$ assumes a diminishing effect of maintenance on capacity of the infrastructure at the margin. That is, as more silt is removed and the depth of the tank increases, more effort is required to remove an equal amount of silt because of biophysical factors, such as water logging and soft sediment.

2.3.2 Resource Dynamics

The equation of motion for groundwater stock, derived from simplified mass-balance equations, assumes the "bathtub" aquifer model (Provencher and Burt, 1993). I assume that dynamics of the tank and aquifer are physically decoupled, i.e., there is no recharge of the aquifer from the tank. The equation of motion describing the height of water table, G, in an underground aquifer is:

$$\frac{dG}{dt} = \rho - \kappa(N_1(1 - X_1)g_1 + N_2(1 - X_2)g_2) \tag{2.2}$$

where $G \leq$ the surface of the farmland, χ, ρ is the recharge to the basin, g_i is the groundwater appropriated by an individual farmer in village i, and κ is a parameter reflecting the influence of a unit withdrawal on the water table height. This parameter will depend on the size, shape, and porosity of the aquifer. In the model, I assume κ is equal to 1.

2.3.3 Benefit Components

An individual farmer's profit flow is the outcome of an instantaneous optimization problem in which the farmer chooses the amount of water they appropriate. I assume that all inputs, including capital, are adjusted for a given amount of water or are fixed. Moreover, I assume that the prices of inputs and outputs are fixed. Under these assumptions, the quadratic seasonal benefit accrued by a farmer in village i is:

$$B_i^R = \beta r_i - 0.5 r_i^2 \tag{2.3}$$

$$B_i^G = \beta g_i - 0.5 g_i^2 \tag{2.4}$$

where r_i is the quantity of tank water appropriated by an individual farmer in village i. The intercept of the benefit functions, β, represents the monetary value of the additional output generated by the first unit of irrigation water.

The first derivative of equations 2.3 and 2.4 allows me to solve for the factor demand for water under all the aforementioned assumptions. This demand curve has a negative slope, an assumption common in previous studies of irrigation water use (Khan and Young, 1979; Howe *et al.*, 1990). This assumption implies that the marginal benefit diminishes as a function of the supply of irrigation water to farmers. The diminishing function occurs because of the biological response of crops to water (Small and Carruthers, 1991). To simplify the analysis, I also assume that the connectivity between the soil and groundwater salinization is negligible. This assumption allows me to define similar benefit functions for tank and groundwater users.

2.3.4 Cost Components

The marginal fee paid by a tank user towards the maintenance of the shared infrastructure in village i is assumed to be α. I assume that the cost of pumping water out of irrigation canals for a tank user is negligible. Therefore, the total cost for a tank user in village i is proportional to their water usage and is given by: αr_i.

The price instrument I envisioned for groundwater users is a unit fee, γ, which is charged per unit of groundwater extracted. Therefore, the total cost for a groundwater user in village i is: γg_i. The revenue generated from this fee will go towards the maintenance of the tank. I observed that in nine out of the ten study sites, γ is equal to zero. This is also consistent with the several other irrigation communities in South India (Meinzen-Dick, 1984). However, there are a few cases, such as the *Pani Panchayat* system, where groundwater users pay a marginal fee on groundwater use (Keremane *et al.*, 2006). The revenue generated from this fee is spent on provision of the shared tank.

Furthermore, the cost of pumping to a groundwater user depends on both the quantity of water pumped to surface and the height of the water table. Cost is increasing in depth of water and in total water pumped. The marginal cost of pumping water from the aquifer to the surface is assumed to be a linear function of the lift of pump, $(\chi - G)$. The total cost for a groundwater user in village i is equivalent to:

$$c_i(G) = \tau(\chi - G)g_i + \gamma g_i \tag{2.5}$$

where χ is the surface of the farmland (in m), G is the height of the water table (in m), and τ is the cost of pumping a unit of water ($1m^3$) to a unit height (($1m$). τ depends on the efficiency of the pump and energy price.

2.3.5 Profit Functions

Individual farmers choose the amount of water to appropriate that maximizes their profits. The profits of tank users in both villages may be summarized as:

$$\pi_1^R(R, X_1) = \max_{r_1} \ \beta r_1 - 0.5r_1^2 - \alpha r_1 \tag{2.6}$$

$$s.t. \ 0 \leq r_1 \leq \frac{R}{N_1 X_1} \tag{2.7}$$

$$\pi_2^R(R, X_1, X_2) = \max_{r_2} \ \beta r_2 - 0.5r_2^2 - \alpha r_2 \tag{2.8}$$

$$s.t. \ 0 \leq r_2 \leq \frac{R - N_1 X_1 r_1}{N_2 X_2} \tag{2.9}$$

The constraints in the equations 2.7 and 2.9 demonstrate that during water scarcity, i.e., when the water available is less than their unconstrained optimum, the upstream farmers consume the available water in the tank and downstream farmers do not receive any water from the tank. This reflects the asymmetry in distribution of tank water to downstream farmers. I also assume that during water scarcity, water is distributed equally among tank users within the upstream village.

The profits of groundwater users are equivalent to:

$$\pi_i^G(G, X_1, X_2) = \max_{g_i} \; \beta g_i - 0.5 g_i^2 - c_i(G) g_i \tag{2.10}$$

$$s.t.\; 0 \leq g_i \leq \frac{G}{\kappa(N_1(1-X_1) + N_2(1-X_2))} \tag{2.11}$$

The constraint in equation 2.11 implies that when the groundwater available is less than the unconstrained optimum, the upstream and downstream farmers share the groundwater equally. This represents the competition over groundwater resources between upstream and downstream farmers. That is, water pumped by farmers in village 1 affects the availability of groundwater for farmers in village 1 and vice-versa. I also assume that water is shared equally among groundwater users within each village.

To maximize the total agricultural income, farmers should choose the amount of water to appropriate, which may be derived by solving equations 2.6, 2.8, and 2.10:

$$\frac{d\pi_i^j}{dx_i} = 0 \tag{2.12}$$

where $j = \{R, G\}$. Solving equation 2.12 results in:

$$r_1^*(R, X_1) = \min\left(\beta - \alpha_1, \frac{R}{N_1 X_1}\right) \tag{2.13}$$

$$r_2^*(R, X_1, X_2) = \min\left(\beta - \alpha_2, \frac{R - N_1 X_1 r_1^*}{N_2 X2}\right) \tag{2.14}$$

$$g_1^*(G, X_1, X_2) = \min\Big(\beta - c_1(G), \frac{G}{\kappa(N_1(1 - X_1) + N_2(1 - X_2)}\Big) \tag{2.15}$$

$$g_2^*(G, X_1, X_2) = \min\Big(\beta - c_2(G), \frac{G}{\kappa(N_1(1 - X_1) + N_2(1 - X_2)}\Big) \tag{2.16}$$

Given the choice of water appropriated by individuals, the aggregate maintenance revenue collected in the system is:

$$\begin{aligned} M(X_1, X_2) = \alpha[&N_1 X_1 r_1(R, X_1) + N_2 X_2 r_2(R, X_2)] \\ &+ \gamma[N_1(1 - X_1) g_1(G, X_1, X_2) + N_2(1 - X_2) g_2(G, X_1, X_2)] \end{aligned} \tag{2.17}$$

2.3.6 Decision Making

I develop a replicator dynamic model in order to understand the conditions under which farmers decide to appropriate water from the tank and contribute to its maintenance versus engage in groundwater extraction. Replicator dynamics model how individuals change their strategies over time based on comparison of payoffs of tank and groundwater users in both villages (Cressman and Tao, 2014).

The underlying assumption of replicator equations is that strategies with higher payoffs do better and therefore, the frequency of a strategy changes at a rate equal to the difference between its expected payoff and the average payoff of the population. Replicator dynamics also make a plausible assumption that individuals make decisions based on limited and localized knowledge concerning the system (Gintis, 2009). The replicator equations track the fraction of tank users,

X_i, in each village and may be summarized as:

$$\frac{dX_1}{dt} = \phi X_1(\pi_1^R - \overline{\pi}_1) \tag{2.18}$$

$$\frac{dX_2}{dt} = \phi X_2(\pi_2^R - \overline{\pi}_2) \tag{2.19}$$

where ϕ represents factors, such as fixed costs of switching strategies, problems of credit availability, and learning spillover effect, that may inhibit or enhance individual adoption and experimentation with profitable technologies (Foster and Rosenzweig, 2010). π_i^R is the payoff to a tank user in village i. $\overline{\pi_i}$ the average payoff of a farmer in village i and is calculated as $\overline{\pi}_i = X_i\pi_i^R + (1 - X_i)\pi_i^G$.

2.4 Analysis and Discussion

Before I turn to the analysis, let me recall that I am analyzing the following system of four differential equations:

$$\begin{aligned}
\frac{dR}{dt} &= \theta\Big(\frac{M}{R}\Big)^{\mu} - \sigma R \\
\frac{dG}{dt} &= \rho - \kappa(N_1(1 - X_1)g_1 + N_2(1 - X_2)g_2) \\
\frac{dX_1}{dt} &= \phi X_1(\pi_1^R - \overline{\pi}_1) \\
\frac{dX_2}{dt} &= \phi X_2(\pi_2^R - \overline{\pi}_2)
\end{aligned}$$

with all terms and functions defined in the Table 1. I focus on three key challenges in the analysis. To reiterate the earlier discussion, the system faces three challenges: (i) the dilemma of adequately funding the shared tank, (ii) the dilemma of efficient rationing of water between upstream and downstream users when upstream users have priority of physical access, and (iii) the over-appropriation dilemma for the groundwater aquifer.

The theory of second best states that if the Pareto optimum in a system cannot be achieved due to multiple challenges, then addressing only one of the challenges may not result in a

Table 1. Definitions of State Variables and Parameters

Symbol	Definition
Dynamical and decision variables	
R	Capacity of the shared infrastructure
G	Height of water table
X_i	Fraction of shared infrastructure users in village i
π_i^R	Payoff of shared infrastructure user in village i
π_i^G	Payoff of groundwater user in village i
t	Time
Parameters	
θ	Marginal productivity of the maintenance investment
μ	Scaling parameter
σ	Natural siltation rate of the tank
ρ	Replenishing rate of the groundwater resource
β	Marginal benefit of water
α_i	Marginal fee paid by tank users in village i
γ	Marginal fee paid by groundwater users
ψ	Fixed fee paid by groundwater users
τ	Marginal cost of pumping water
ξ	Surface of the farmland
ϕ	Responsiveness of individuals to economic payoffs

welfare improvement (Lipsey and Lancaster, 1956). For instance, using a single well-crafted policy instrument, such as a volumetric fee, may improve the provision of the tank (Meinzen-Dick, 1984). However, such a fee increase costs and may reduce profitability and drive the adoption of the non-taxed, private groundwater pumps, resulting in exhaustion of the groundwater aquifer. In such cases, the interaction effect of these challenges must be considered to achieve a relatively efficient outcome. Such an outcome, by definition, is a second-best optimum.

While it may still be worthwhile to target the single challenge, understanding the multiple challenges facing the system is critical for setting the optimum second-best fee for the single instrument. In a second-best world, multiple policy instruments may be necessary to achieve an efficient outcome. As it turns out, in general, there must be at least one policy instrument for each policy target (Tinbergen, 1952).

I consider three instruments in the analysis and focus on the behavioral responses of farmers to each combination of instruments: (i) volumetric fee on tank users, which is differentiated based on their location (DP), (ii) the differentiated tank fees plus a volumetric fee on groundwater users (IM), and (iii) the preexisting instruments plus a fixed fee on groundwater users at the extensive margin (EM). In the next few sections, I will discuss the relevance of each instrument and their effect on the decisions of farmers.

Last, I will examine the effect of the price instruments based on the assumption that the revenue generated through fees is fully reinvested in the maintenance of the shared infrastructure. This assumption is consistent with empirical evidence, which shows that water user associations that levy the fees do not typically have the authority to use the revenue from fees beyond the confines of the irrigation district (Meinzen-Dick, 1984).

2.4.1 Grid Search Optimization

I begin the analysis by first calculating the optimum time-invariant values of each instrument that maximizes the total profit when the system reaches equilibrium.[2] For this, I use a grid search optimization algorithm, which is explained below. Then, using the optimal values, I examine the effect of the instruments on system productivity and equity.

The grid search method is a "hyper-parameter search algorithm" that utilizes an objective function to perform a nonlinear optimization (Ruud *et al.*, 2000). It involves setting up a grid with suitable spacing, evaluating the objective function at all the points in the grid, and identifying the grid point corresponding to the maximum value of the function. In the model, I use this method to search through a range of possible values for each of the instruments and identified the values for which the system productivity (total profit) is maximum at equilibrium. I run the

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[2] I do not examine the optimal approach path because in the "real-world", rigid policies make it excessively costly to implement feedback-control rules that optimize fees adaptively based on changing infrastructure condition and resource availability.

grid search algorithm each time I introduce a new instrument in order to reevaluate the existing policy instruments and iteratively search for the optimum.

2.4.2 Profit Normalization and Model Calibration

In order to compare the profits across the different instruments, I rescaled the profits in villages 1 and 2 between 0 and 1, using the min-max normalization method, where the minimum profit that an individual can make in the system is zero. Maximum profit is obtained in the system when individuals are economically unconstrained, without the volumetric fees. This may be given by: $\pi_{\text{max}} = 0.5\beta^2$. I calculated the total system productivity by summing across the rescaled individual profits.

I calibrated the model using both interview data and existing literature. I deduced the rate of depreciation for the tank infrastructure from the interview questionnaire on changes in the size of the tank over the past 10-15 years. Then, I verified the results with existing literature on the biophysical properties of tanks in South India (Shah and Raju, 2002; Jayatilaka *et al.*, 2003). I calibrated the parameter values for groundwater recharge and unit cost of pumping using existing groundwater research in South India (Anuraga *et al.*, 2006; Reddy *et al.*, 2009; Reddy, 2005). The parameter value in the production functions, namely the marginal benefit of water, was derived based on the interview questions on farmers' income as well as the literature (Sakurai and Palanisami, 2001; Anbumozhi *et al.*, 2001). The full set of parameter values along with the model code is provided in the Appendix.

2.4.3 Collapse of Tank Irrigation Systems in South India

In several irrigation systems where tanks are centrally-constructed and shared structures, if the upstream farmers ignore the scarcity that they generate for those lower in the system, then they get most of the water. Farmers at the upstream may even maintain the shared infrastructure by themselves, such that only they receive sufficient water for irrigation (Palanisami, 2006). Consequently, those at the downstream have even less reason contribute to the continual maintenance of the tank. Indeed, these considerations suggest that downstream farmers have the greatest incentives to leave the current state and seek out a new system in the form of groundwater irrigation. In order to replicate these observations from my field work, the model includes a volumetric fee, α, only on the tank users in this part of the analysis.

I first identified the value of α for which the total profit is maximum. For this, I created a row vector of 1,000 uniformly spaced points in the interval [0,1] and ran the grid-search algorithm. Figure 3 shows the results of the grid-search algorithm.

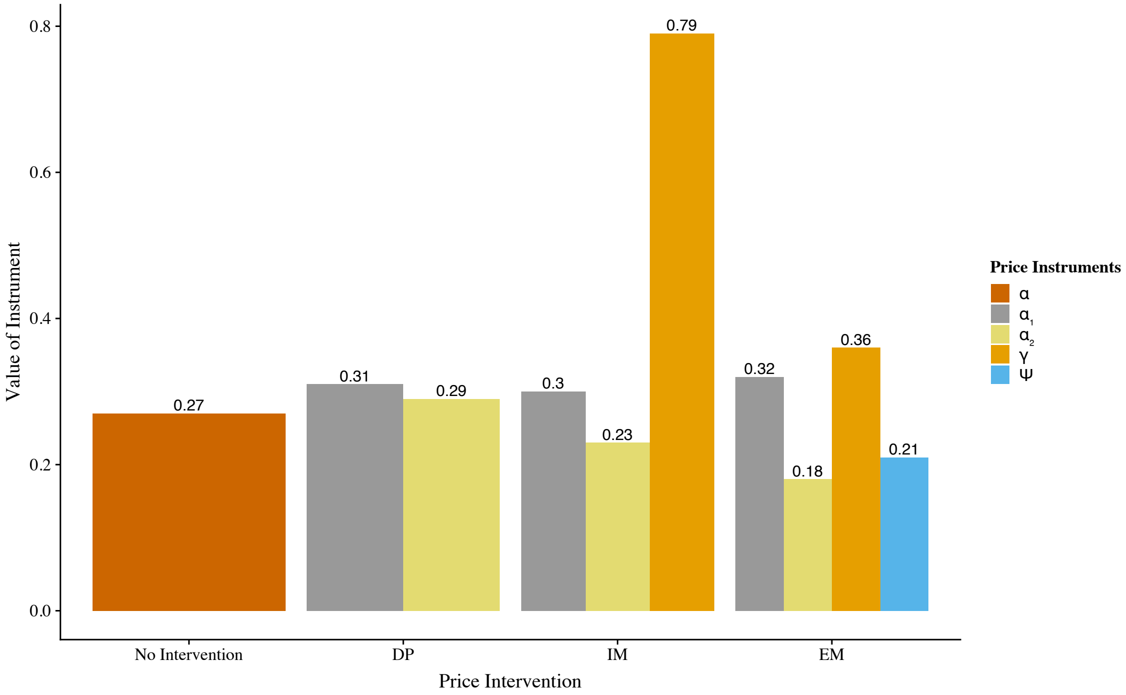

Figure 3. The graph shows the results of the grid search optimization at system equilibrium. The X-axis represents the type of price intervention and the Y-axis shows the value of price instrument at system equilibrium. α is the marginal appropriation fee paid by tank users under No Intervention. α_1 and α_2 are the marginal fees paid by upstream and downstream tank users. γ is marginal groundwater pumping fee. ψ is the fixed groundwater fee.

Figures 4 and 5 show the capacity of the tank and groundwater availability in the system respectively. When the system is at equilibrium, the capacity of the shared tank is at roughly 65 percent. Since the water available in the tank is less than the unconstrained optimum of the upstream users (Figure 7), they consume all the available water. Therefore, all the downstream farmers shift to groundwater resources (Figure 8), resulting in over-extraction of the groundwater resources. In the absence of groundwater pumping fees, groundwater availability is reduced to 1.25% when the system reaches equilibrium (Figure 5).

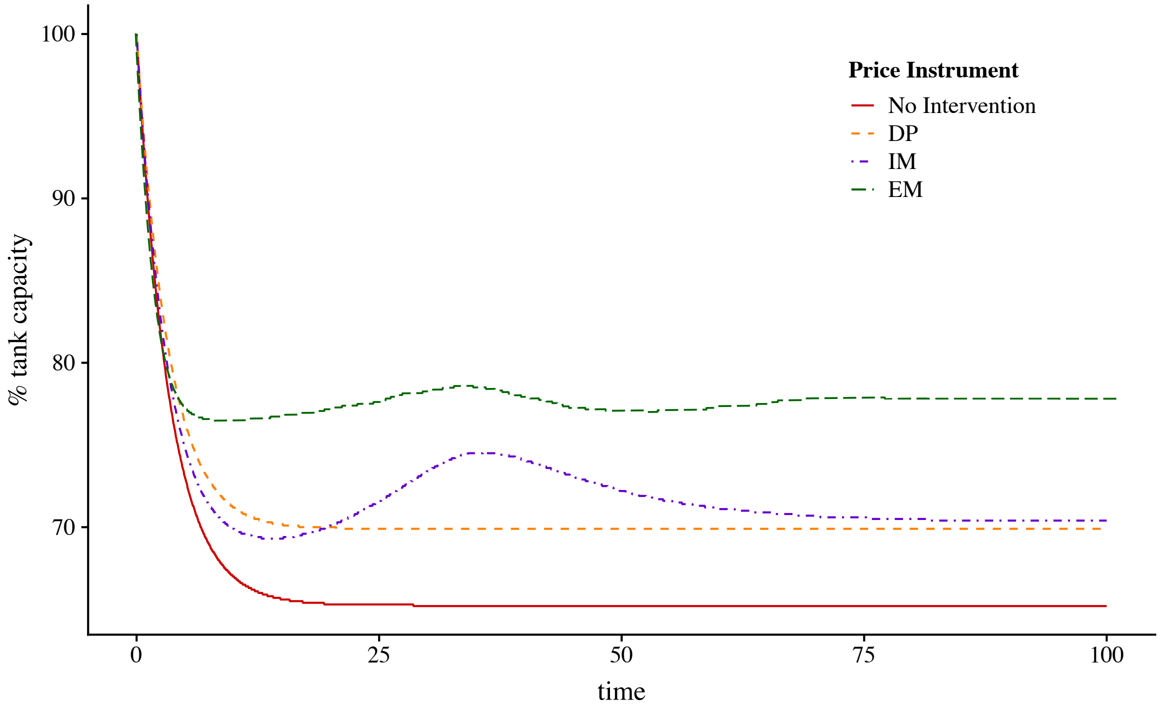

Figure 4. The graph show the results for the four price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ.. The X-axis is time and the Y-axis shows the capacity of the shared tank in percentage.

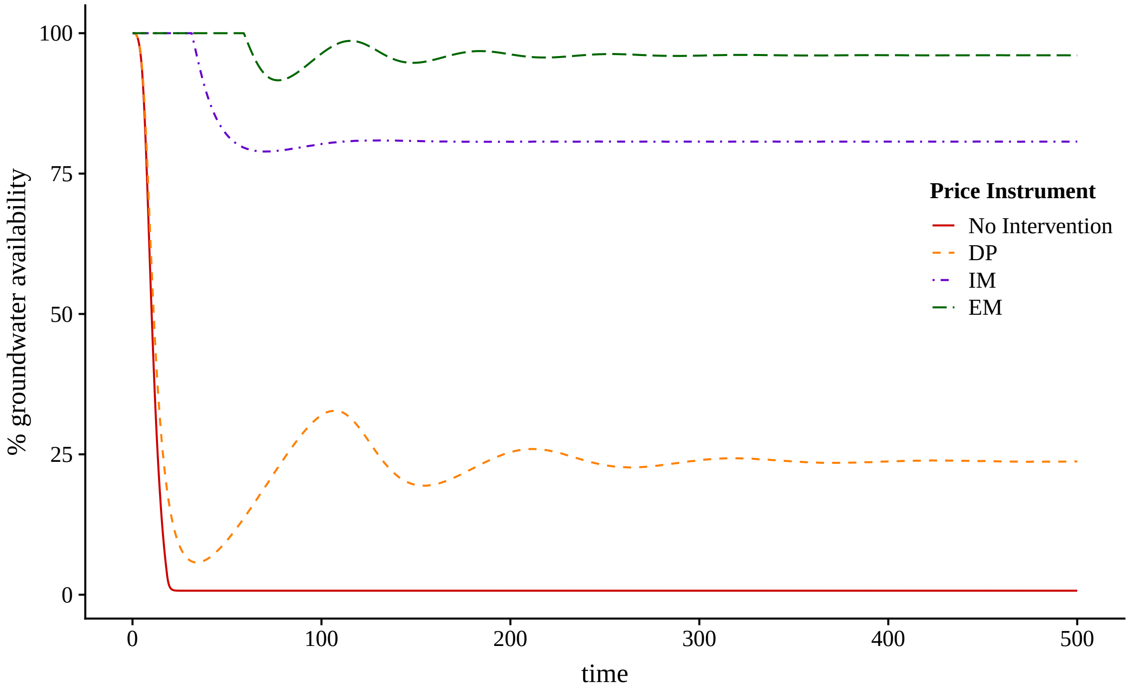

Figure 5. The graph show the results for the four price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ. The X-axis is time and the Y-axis shows the groundwater available in the aquifer in percentage.

Figure 6 shows the normalized profits in villages 1 and 2, and overall system performance. In the absence of rules that offset the distributional advantage of the upstream farmers, the system's profits are concentrated within upstream farmers (Figure 6). Downstream farmers receive only 1.4% of the total benefits from irrigation because of the poor condition of shared infrastructure and depletion of groundwater resources. This is the case even when the level of the infrastructure fee is optimized to maximize total system profits. The single policy instrument of an undifferentiated fee on tank water use cannot secure sufficient tank capacity to supply water to downstream users without inducing their exit from the system to groundwater due to the strategic appropriation advantage of upstream users.

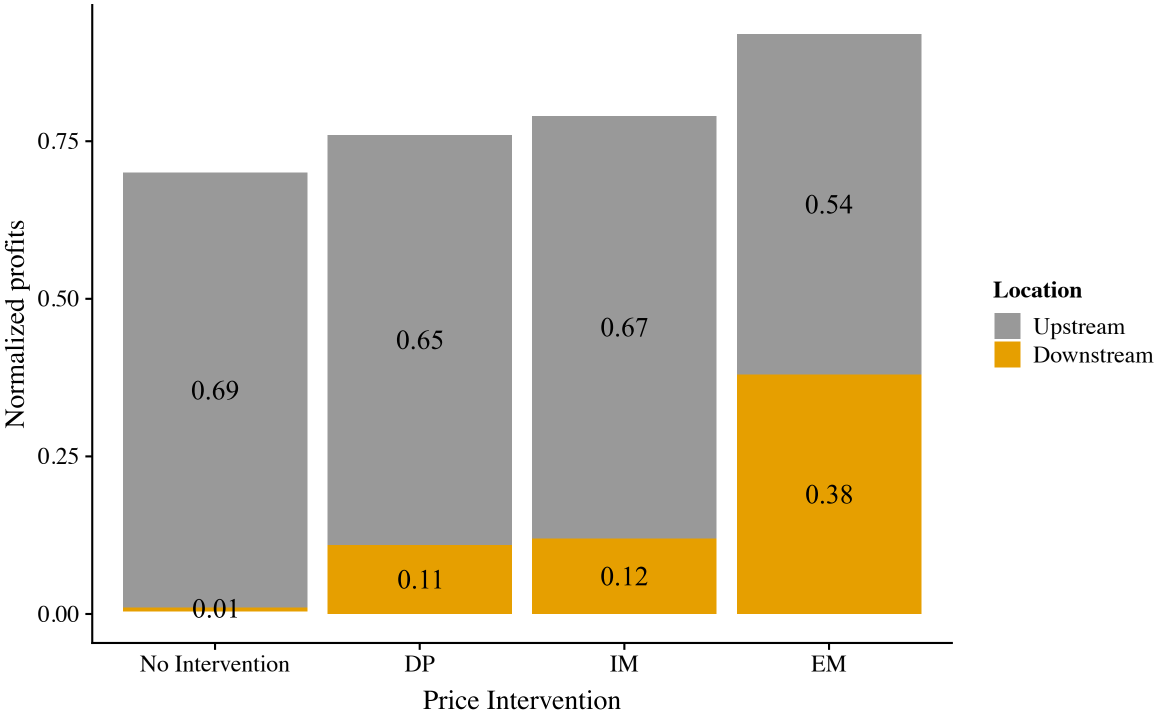

Figure 6. The graph shows the profits of upstream and downstream profits when the system reaches equilibrium. The X-axis shows different price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ. The Y-axis represents the normalized profits.

This result is consistent with empirical observations that downstream farmers are often pushed into poverty traps because of poor maintenance of the shared tank and exhaustion of groundwater resources (Meinzen-Dick, 1984). What is striking about this result is that an examination of case studies of irrigation systems in India, Nepal, and Indonesia shows that

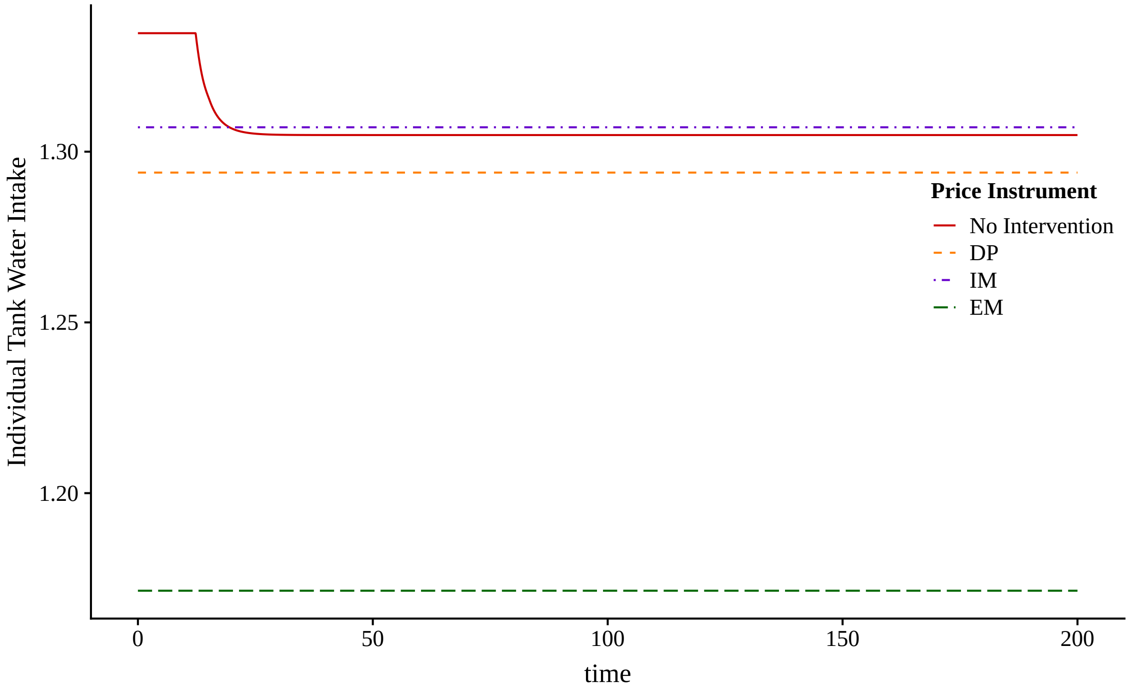

Figure 7. The graph shows appropriation decisions of upstream tank users for different price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ. The X-axis represents time. The Y-axis represents the individual tank water intake by upstream farmers.

in the absence of coordination rules for provision of the shared infrastructure, presence of a private infrastructure may reinforce locational asymmetries in a system (Ostrom and Gardner, 1993; Wade, 1989; Bastakoti *et al.*, 2010).

2.4.4 Differentiated Fee (DP)

The withdrawal of tank water by the upstream farmers creates an externality due to their position. Their withdrawal may prevent productive use of the tank water by downstream farmers. The limitation of using a single instrument for both upstream and downstream users is that if

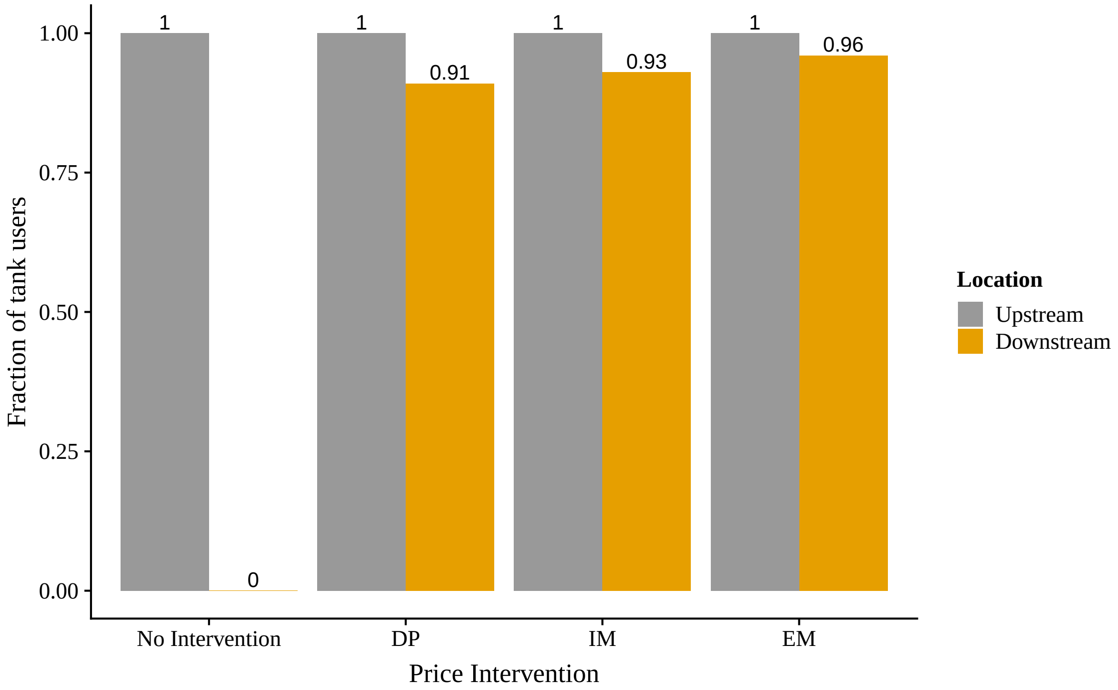

Figure 8. The graph shows the fraction of tank users in upstream and downstream villages at system equilibrium. The X-axis shows different price interventions.: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ.

the fee is low, the capacity of the tank will be low, resulting in water scarcity. As a result, the upstream farmers will consume all the tank water. If the fee is too high, the overall system profitability is reduced in spite of better tank infrastructure, inducing exit to groundwater use. Therefore, the optimum thing to do is to enforce a higher fee on the upstream users. I specify differentiated marginal fees on the upstream and downstream tank users, which are given by α_1 and α_2 respectively.

By levying two different taxes on the farmers, the profit function of tank users may be rewritten as: $\pi_i^R = \beta r_i - 0.5r_i^2 - \alpha_i r_i$, where α_i is the volumetric tax paid by a shared infrastructure user in village i. I ran the grid search algorithm to calculate the optimal values of the fees for upstream and downstream tank users. For this, I created a 2-D grid with 2,5000 uniformly spaced points in the interval [0,1]. Then, I identified the values of α_1 and α_2 for which the system productivity is maximized. The results of the grid search algorithm show that when upstream shared infrastructure users pay 5.13 percent more than the downstream users, maximum total profit is attained (Figure 3). When compared to the earlier scenario, the fees for upstream tank users increase by 15% and downstream tank users are subject to an increase of 7%.

Figures 4 shows the improvement in tank capacity. Capacity of the shared infrastructure is at 70 percent, marking a increase of 5 percent compared to the case of single fee on upstream and downstream tank users. The increase in the tank capacity may be explained by an increase in the fees for both upstream and downstream tank users. In spite of the increase in availability of tank water, upstream users are appropriating less water compared to the previous scenario because of higher fees (Figure 7). Consequently, the profits of upstream users are reduced by 5.8% (Figure 6).

The combination of increased tank water availability and reduced appropriation by upstream users ensures that farmers at the downstream village receive more water (Figure 9). The increase in availability of tank water for downstream farmers may also be observed in the apparent increase in the fraction of tank users in the downstream village, representing a 91% increase in downstream farmers who use tank water for irrigation (Figure 8). Fewer downstream farmers are adopting groundwater technology and therefore, there is a 25% increase in the groundwater availability (Figure 5). To the extent that improved water supply from the tank reaches a greater number of downstream farmers, they experience a 10% increase in their profits, increasing the system profit by 8.6% (Figure 6).

The analysis illustrates the effectiveness of a higher maintenance tax for upstream farmers.

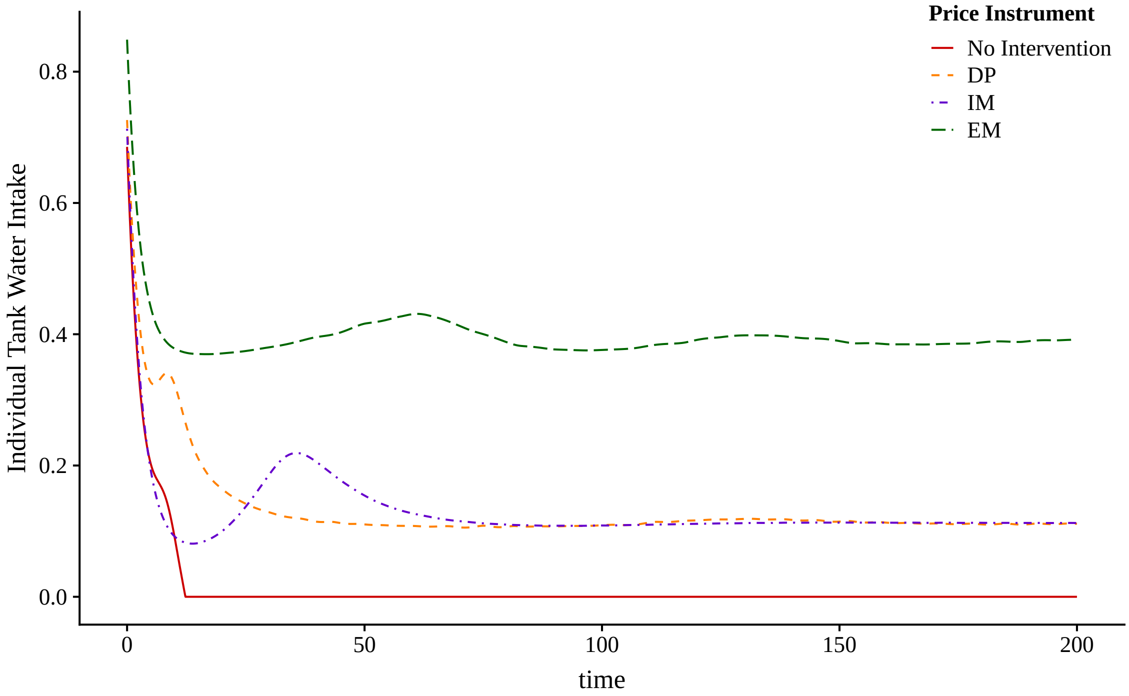

Figure 9. The graphs shows the appropriation decisions of downstream tank users for different price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ.. The X-axis represents time. The Y-axis represents the individual tank water intake by downstream farmers.

The interpretation of this result may be that, if farmers are willing to pay more for reliable water supplies (Bell *et al.*, 2014), and the taxes collected are invested in the maintenance of the shared irrigation infrastructure, then the higher maintenance taxes on upstream farmers may produce efficiency gains.

Empirical cases of differentiated fees are few and far between. However, such an instrument would be consistent with extant literature, which concludes that different taxes for upstream and downstream farmers, based on both water allocated and appropriated, may lead to gains in economic efficiency and improve equity in the overall system (Bell *et al.*, 2016). Implementing such a fee, however, in an actual irrigation system might face opposition because farmers' willingness to pay a higher tax is often contingent upon the expected reliability of water supply (Bell *et al.*, 2014). If their higher contributions do not quickly yield improved tank infrastructure and economic performance, then farmers are likely to oppose such pricing interventions. Implementing a higher tax on upstream farmers may also face opposition from those whose decisions are not guided solely by economic considerations. They may be also be driven by social norms, moral concerns, and power asymmetries (Bowles, 2008; Smith, 2018). For instance, a volumetric fee failed to reduce water appropriation in Netherlands because elite farmers used political power to exempt themselves from paying the fee (Schuerhoff *et al.*, 2013).

2.4.5 Volumetric Groundwater Pumping Fee (IM)

One way to further improve the productivity of the downstream farmers is through creating optimal appropriation incentives for groundwater users. This may be achieved through a volumetric fee on the intensive margin of groundwater users,γ, in addition to the preexisting fee on tank users. The additional revenue collected from this fee is used for maintenance of the tank. This instrument is motivated by the Pani Pachayat institution in South India (Keremane *et al.*, 2006), where owners of groundwater pumps also contribute towards maintenance of the shared irrigation infrastructure.

In order to calculate the optimal value of γ, I used the grid search algorithm. I created a 3-D grid with 27,000 uniformly spaced points in the interval [0,1]. Then, I identified the values of γ, α_1, and α_2 for which the total system profit is maximum (Figure 3). The results of the grid search algorithm show that in the presence of groundwater pumping, the fee for upstream tank users decreased by around 3%, whereas the fee for downstream tank users decreased by 20% (Figure 3). The decrease in the fees results in the upstream tank users appropriating more water in the presence of its increased availability (Figure 7), increasing their profits by 3% (Figure 6). As a result of increased appropriation by upstream tank users, the downstream tank users receive similar quantity of water compared to the DP instrument (Figure 9). However, the profits of the downstream farmers increase by 9%, which may be attributed to the decrease in their fees (Figure 6). The total system productivity marginally improves by 2.6% relative to the DP instrument because of introducing the volumetric groundwater fee.

Figure 8 illustrates the fraction of farmers in both villages who rely on the tank system in the presence of a volumetric tax on groundwater users. I observe that, once again, all upstream farmers are tank users and 93% of downstream farmers have switched to groundwater irrigation. The 2% increase in the fraction of tank users in the downstream village may be explained by the increased level of tank capacity and a higher groundwater fee.

By introducing a groundwater fee, the total revenue towards the maintenance of the tank increases, resulting in an increase of 11% increase in the capacity of the tank relative to the DP instrument (Figure 4). The groundwater fee contributes to nearly 9% of the total revenue collected for maintenance of the tank (Figure 10).

The groundwater fee also reduces the pumping (Figure 11) and increases the groundwater availability to 81%, representing a 57% increase compared to the groundwater availability in the previous scenario with the DP instrument (Figure 5). The reduction in groundwater extraction along the intensive margin is also observed empirically in extant literature, which concludes that policy interventions in the form of Pigouvian-type taxes may internalize pumping externalities and promote sustainable extraction (Gleick, 2010; Edwards, 2016; Smith, 2018).

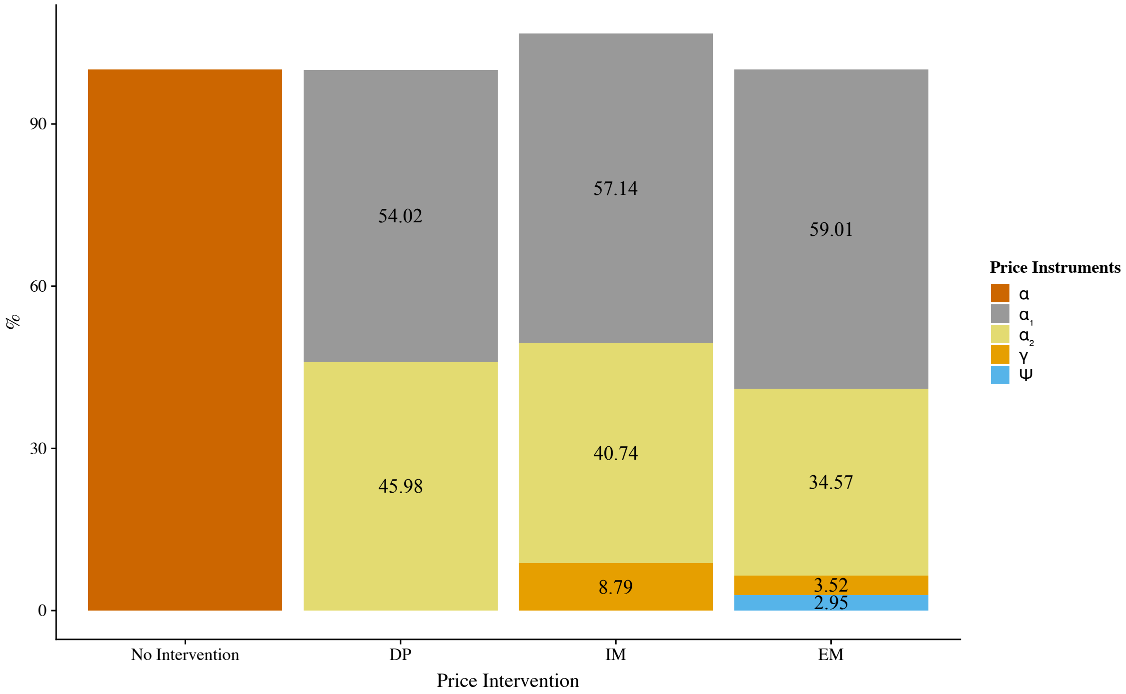

Figure 10. The graph shows the contribution of each instrument towards maintenance when the system reaches equilibrium. The Y-axis shows the percentage contribution of each instrument towards maintenance. The X-axis shows the four price interventions. (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ.

2.4.6 Fixed Groundwater Fee (EM)

The volumetric fees that create efficient appropriation incentives for tank and groundwater systems may not sufficiently fund the infrastructure, leading to degradation of the tank and the aquifer. This creates a need for additional funds to improve the capacity of the tank infrastructure. However, raising volumetric fees on tank users will force too many users to exit to groundwater and raising groundwater pumping fees may price groundwater too dearly for appropriation purposes. Moreover, raising groundwater fees may work against raising revenue

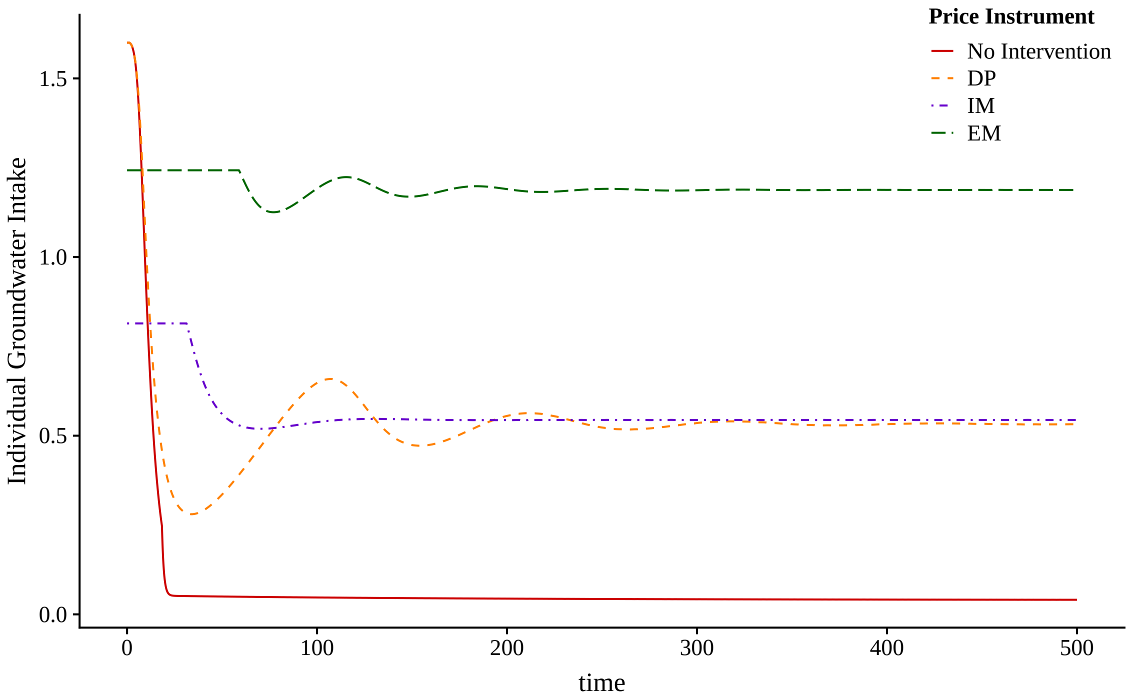

Figure 11. The graph shows the pumping decisions of groundwater users over time for different price interventions: (i) No Intervention (solid red line): in this scenario, tank users pay a marginal fee: α; (ii) DP (dashed orange line): in this scenario, upstream tank users pay a marginal fee, α_1 and downstream tank users pay a marginal fee, α_2; (iii) IM (purple dot-dash line): in this scenario, in addition to the differentiated tank water fees, groundwater users pay a marginal fee, γ; and (iv) EM (long-dash green line): in this scenario, in addition to the preceding instruments, groundwater users pay a fixed fee, ψ. The X-axis represents time. The Y-axis represents the individual groundwater intake by farmers.

for tank maintenance by reducing pumping demand. Therefore, I envision an additional instrument, a fixed fee on groundwater users. This fee does not affect the marginal decision-making regarding appropriation for both tank and groundwater users. It can, however, raise additional funds along the extensive margin. Therefore, when combined with the IM price instrument, I expect the fixed fee instrument (EM) to reduce the number of groundwater pumps, while simultaneously increasing the revenue for tank maintenance. The additional revenue collected in the system is, again, invested in maintenance of the tank.

By levying a fixed fee on groundwater users, the profit function of a groundwater user in village i may be rewritten as: $\pi_i^G = \beta g_i - 0.5g_i^2 - c_i g_i - \psi$, where ψ is the fixed fee. Once again, I ran the grid search algorithm to recalculate the optimal values of all the price instruments. I created a 4-D grid with 390,625 uniformly spaced points in the interval [0,1]. Then, I identified the values of α_1, α_2, γ, and ψ for which the total profit is maximized.

The results of the grid search show that the optimal value of the fixed fee is nearly 22% of the total system profits after deducting the fees (Figures 3 and 6). A 7% increase is observed in the fees for upstream tank users, 28% reduction in fees for downstream tank users, and nearly 54% reduction in groundwater pumping fee. The combination of the EM instrument and a higher fee on upstream tank users increases the tank capacity by nearly 7.5% (Figure 4). The increase in the tank capacity means that the upstream tank users can meet their unconstrained optimum, which is now lower compared to the previous scenario due to the higher fee on upstream tank users (Figure 7). The higher fee on upstream tank users ensures there is more water available for the downstream tank users (Figure 9). The fixed fee partially blocks exit to the groundwater system and makes it possible to raise upstream fees to these levels, thus addressing the upstream-downstream externality. Consequently, the number of tank users in the downstream village increased by 3% compared to the previous treatment (Figure 8). Moreover, the reduction in the groundwater fee results in higher rates of pumping (Figure 11), but the fixed fee results in fewer groundwater users (Figure 8), resulting in an overall improvement in the groundwater aquifer (Figure 5).

The economic performance increases significantly by nearly 18% and equality among both villages improves as well (Figure 6). This result suggests that that the groundwater fixed fee is an important part of improving the overall economic performance as well as equality. Resolving the water allocation problem among upstream and downstream users is usually viewed entirely as a matter of water pricing (David *et al.*, 2015). However, the fees that disincentivize high water use by upstream users may also drive them out of the system, especially when groundwater is under-priced, which further exacerbates the water scarcity. On the other hand, the volumetric fees that disincentivize high groundwater pumping may reduce the pumping demand, and consequently the provision of the tank infrastructure. This tension between addressing provisioning and appropriation dilemmas through the same instrument limits the performance of volumetric fees alone. The fixed charge takes the pressure off the volumetric fees to address the provisioning dilemma. The improved equality of upstream and downstream users in Figure 6 shows that differentiated water pricing on tank users is now largely playing an allocative role, and the fixed fee is addressing the provisioning challenge. Figure 10 shows that the fixed fee contributes to nearly 3% of the maintenance revenue collected in the system.

A price instrument on the extensive margin of groundwater users may be relevant in the South Indian context. Between 2002-2012, groundwater declined at an average rate of 1.4 meters per year in the southern states of Tamil Nadu and Andhra Pradesh in India (Chinnasamy and Agoramoorthy, 2015). It was found that groundwater usage was nearly 8 percent more than the annual recharge rates in both these states. A key characteristic of the two states is that groundwater technology is subsidized by the state governments through provision of low-interest loans and subsidized electricity. Low adoption and operational costs resulted in a rapid expansion of groundwater irrigation and excessive pumping rates (Dubash, 2007). Therefore, one way to reduce groundwater use is to increase the adoption costs of groundwater technology so that fewer pumps are installed.

Designing a price instrument that reduces the number of groundwater pumps in the system may also have positive consequences on collective-choice arrangements in the system. Given the high, indivisible fixed costs associated with adopting groundwater technology, farmers may organize collective action for low risk and regular activities, such as allocation of water and maintenance of pumps (Aggarwal, 2007). However, such arrangements may frequently dissolve when confronted with pressures such as electricity shortages and the desire to shift cropping patterns (Ghate, 1980).

2.4.7 Effect of Diminishing Returns of Maintenance on System Productivity

In the final part of the analysis, I examine the effect of diminishing returns of infrastructure provision on the system productivity. There are two ways of redistributing the benefits of maintenance revenue in a system. The first is to utilize the revenue solely for maintenance of the shared infrastructure. Such revenue redistribution may offset the marginal cost of resource appropriation and also, lower the overall cost of public good provision (Oates and Schwab, 1988). The second mechanism is to spend only a fraction of the tax revenue for maintenance of the shared tank. The remaining amount may be redistributed in the system through other mechanisms, such as dividends to farmers (Tsur and Dinar, 1997). Given the assumption of diminishing returns of maintenance investments, there is a risk of over allocating resources for provisioning of the tank infrastructure. Hence, it is important to consider how to redistribute the benefits of the revenue generated from the price instruments.

This possibility is investigated by comparing the system productivity under different levels of the revenue from fees (60%,70%,80%, 90%, and 100%) spent for maintenance of the shared infrastructure. I used the optimal instrument values of the EM intervention for this analysis because it yielded the highest productivity in the preceding analysis. For the cases where only a fraction of the tax revenue (60%,70%,80%, 90%) is spent on maintenance, the remainder maintenance revenue is added to the total profit as a lump-sum benefit. Then, the total profit is normalized using the min-max normalization method described earlier.

Figure 12 shows the profits under different levels of revenue spent on maintenance of the shared infrastructure. As the fraction of maintenance revenue spent on the tank infrastructure is increased, the total profits increase at a decreasing rate. Moreover, when only 90% of the maintenance revenue is spent on maintenance of the shared infrastructure, system productivity is similar to the scenario where the full revenue is spent for maintenance of the tank (Figure 12). This result suggests that due to diminishing returns of investments on tank maintenance, more investments cease to provide any significant benefits in system productivity after a certain point, and is likely to result in "over-provision" of the shared infrastructure. Instead, it may be more efficient to consider alternative mechanisms, such as water dividends to farmers, to redistribute some of the benefits of the fees, while still providing the marginal incentive effects of water pricing and the groundwater fixed charge. A key consideration here is that these lump-sum benefits must be designed such that they are behaviorally neutral and are likely to increase the household income, but do not skew appropriation incentives at the margin.

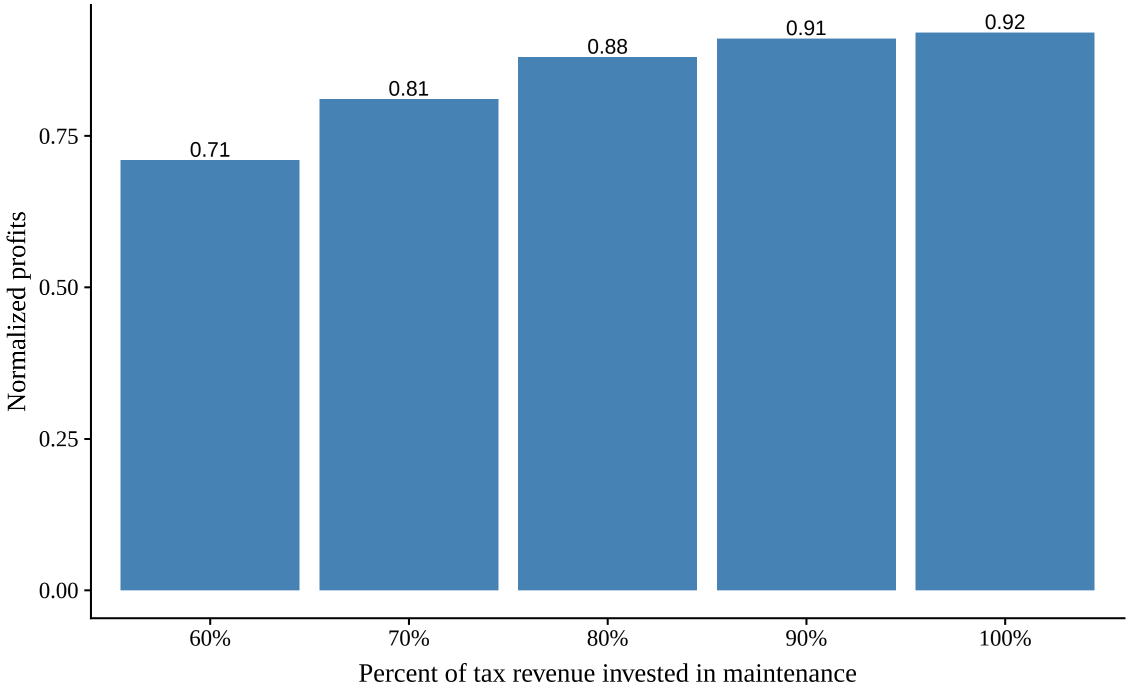

Figure 12. The graph shows the normalized profits of upstream and downstream villages at system equilibrium for different fractions of maintenance revenue investment. The results reported here are for the EM instrument, in which tank users pay a differentiated water fee and groundwater users pay a fixed fee in addition to the marginal pumping fee.

2.5 Conclusion

The use of human-constructed, shared infrastructure to access natural resources has been a central feature of modern societies for centuries. Provision of shared infrastructure for continual delivery of resources is one of the key sustainability challenges we face currently. There are several factors that affect the provision of shared infrastructures. One key factor that has received relatively little attention in existing literature is the role of private infrastructure.

The relationship between private goods and provision of public goods has been widely examined in the economics literature. It has been suggested that private goods will likely improve the provision of public goods, which are supplied by a monopolistic state agency (Pecorino, 2008; Cornes and Sandler, 1989; Vicary, 2004). On the other hand, presence of private infrastructure is also likely to worsen the provision of public goods in the context of scarce resources (Cárdenas *et al.*, 2017). Though much has been written about the relationship between public and private goods in different social-ecological systems (irrigation, transportation, energy, knowledge commons), there has been relatively little work on what types of policy interventions are required to improve the provision of public goods. I examined this problem in the context of tank irrigation systems in South India.

I developed a stylized replicator dynamic model to demonstrate that in the absence of appropriate institutions, access to groundwater resources through private groundwater pumps is an unmitigated bad because it not only contributes to the decline of shared irrigation infrastructure, but also contributes to the chronic poverty of downstream farmers. The results suggest that we require multiple price instruments to not only improve the economic efficiency of the system, but achieve this without compromising on the equity within the system.

The effectiveness of price-based interventions depends on the institutional context of the irrigation system. For instance, volumetric pricing methods typically require information on the quantity of water used by an individual farmer. Collecting such information entails high transaction costs because it requires water meters, periodic water usage readings, and regular maintenance of the meters. Also, in the absence of water markets, a central authority, such as the state or a water user association, is required to set the pumping fee (Tsur and Dinar, 1997). In irrigation systems that lack the institutional capacity to enforce and monitor, efforts to implement a volumetric pricing mechanism to conserve water may be unsuccessful (Yang *et al.*, 2003).

The key result of the model is regarding the importance of the fixed groundwater fee in addressing the provisioning dilemma concerning the shared infrastructure. Given the challenges with monitoring the volumetric fee for groundwater pumping, We may envision an institution, where we retain the differentiated volumetric fees for tank water and enforce the fixed groundwater fee. Under such an institution, over-extraction of groundwater is discouraged on the extensive margin, and doesn't affect marginal decision-making with respect to appropriation for both tank and well users. However, it helps mitigate the problem of water scarcity by improving the infrastructure condition, thereby reducing the importance of volumetric pumping fee.

I must note that the model's simplified features render it only illustrative of the more complex set of choices that farmers actually confront and is not intended to replicate any particular geographic region. For example, I treat farmers' infrastructure choices as binary, whereas a more realistic rendering would be to treat them as continuous and allow for conjunctive use of the two infrastructures. It is, however, worth noting that the model permits an intuitive picture of the central provisioning and appropriation dilemmas that farmers face, and the results are consistent with some notable cases of irrigation systems in the extant literature. I extend the literature by considering how different price instruments can create different incentives for farmers using heterogeneous irrigation infrastructures. The results can help policymakers assess the relative gains to different user groups under different instruments.

Chapter 3

WATER AND ELITES: THE ROLE OF CULTURAL POLITICS IN IRRIGATION DEVELOPMENT

3.1 Introduction

Maintaining a consistent supply of water is a key challenge faced by irrigation systems around the world. Empirical observations of social organization patterns demonstrate the many ways in which societies have responded to this problem. Irrigators can invest in physical infrastructure (storage facilities, etc.) to normalize resource variability (Anderies, 2015). Alternatively, they might use a portfolio of water allocation rules that vary based on water availability (Cifdaloz *et al.*, 2010). Either approach requires political institutions to enforce the water allocation and infrastructure provision rules. These political institutions, which are often an outcome of the endogenous preferences of a society (Muneepeerakul and Anderies, 2017), are a key determinant of economic performance in a society. (North, 1994; Acemoglu *et al.*, 2001; Greif *et al.*, 1994; Greif, 2006; Wade, 1989).

To further understand the role of political institutions in the economic performance of irrigation systems, this study addresses how the presence of power asymmetries perpetuated by cultural norms, such as caste, affect the persistence of political institutions to provide shared infrastructure in an irrigation system. More specifically, I examine the effect of policy tools, such as non-farm wage employment and informational interventions, on the persistence of these two political institutions: self-governed and nested.

Two key perspectives concerning political institutions and economic performance of irrigation systems have developed in the literature. One suggests that community-managed institutions enable irrigation communities to foster local collective action and manage shared resources sustainably (Ostrom, 1990; Agrawal and Ostrom, 2001; McKean, 1992). Another alternate institution that has received substantial focus in the literature is a nested institution, in which the state partakes in creating local organizations (such as water user associations) to allocate water and maintain the infrastructure (Ostrom, 1990; Baker, 2011).

Scholars within the CPR literature argue in favor of nesting local organizations within the state over community-managed institutions because organizing multiple governing authorities at different scales improves provisioning of public goods (Ostrom *et al.*, 1961; Ostrom, 1990). However, empirical work in India (Mosse, 2008; Baker, 2011) shows that in several irrigation communities with substantial differences in social status and landholding size, high-caste farmers (elites) have opposed state intervention through de facto political power, such as bribery and violence.

In such systems, the person responsible for activities such water allocation, collection of maintenance fees, and monitoring water thefts, typically, belongs a lower caste (Baker, 2011). This prevents them from sanctioning high-caste farmers when they either over-appropriate irrigation water or do not contribute towards maintenance of the irrigation infrastructure. Due to greater expected returns in such self-governed regimes, elite farmers may oppose state intervention (Baker, 2011; Kashwan, 2016). This is detrimental to poorer sections of the communities (non-elites) because they do not have the resources required to petition for state intervention and enforcement of legal rights.

I develop a compartmental model that tracks the institutional preferences of farmers in a community-managed irrigation system with caste-based inequalities. The model results suggest that critical regime shifts in political institutions can be generated by intervening in labor market institutions. Such institutions reflect changes in payoffs from non-farm wage employment because of either exogenous market forces or government policy (minimum wage increases).

I found that by increasing non-farm wages to elite farmers, the system can flip from a self-governance regime to a nested institution. However, this might not result in significant improvements in the infrastructure efficiency. That is, even if the political institution eventually changes, because of the depreciation of irrigation infrastructure, the regime shift may occur too late. Therefore, the approach path to the steady state, or the speed of the institutional change, matters and must synchronize with the infrastructure dynamics. This result complements North's (1994) discussion on the importance of learning in changing individuals' perceptions about their payoffs and institutional change in the long-run.

3.2 Model Structure

To explore the interdependencies between informal institutions, such as caste, the stability of political institutions, and the state of provisioning of shared infrastructure, I develop a compartmental model of farmers' institutional choice, which is conditional on their payoffs under the formal institutions. The model is loosely parameterized based on the case-study work by Baker (2011) in the community-managed *Kuhl* irrigation systems in North India.

In the model, farmers may choose between two political institutions: S and J. S is the self-governance regime and J is the nested institution. The difference between these two political institutions is in their water allocation mechanism and maintenance fees, which will be discussed below.

Consider N farming households are spread across one village that co-manage a single canal irrigation system. There are two groups of farmers in the village, E and P, which satisfy $N_E + N_P = N$. Es represent the elites (high-caste farmers) and P represent the poor (low-caste farmers).

I assume that farmers have different "mental models" of which political institution is better. Also, their choice of the political institution does not necessarily does not coincide with the institution that they actually lives under. It's just a voting preference. I define the total number of farmers who prefer Ss as $N_S = N_{E,S} + N_{P,S}$. Consequently, the number of farmers who prefer Js in the village are: $N_J = N_{E,J} + N_{P,J}$. For the remainder of my discussion, I use the notation that the first term in the subscript refers to the farmer's group and the second term refers to their institutional choice.

3.2.1 Shared Infrastructure Dynamics

Irrigation infrastructure, such as canals and weirs, concentrates the availability of the irrigation water for use. It requires an investment of time and effort to maintain its functionality. In my model, I assume that under a self-governance institution, collection of fees and maintenance efforts are coordinated by an individual, who is officially appointed by the farmers. This assumption is based on examples of several irrigation systems in India, in which farmers elect a person within their community to carry out maintenance works (Mollinga, 2001; Mosse, 1999; Baker, 2011). I assume that under a nested regime, these activities are carried out by the state through a local organization, such as a water user association. These assumptions are consistent with the empirical observations of Baker (2011).

I denote the efficiency of the infrastructure with I. The dynamics of I is assumed to be:

$$\frac{dI}{dt} = \nu\left(\frac{M(.)}{I}\right)^{\sigma} - \mu I \tag{3.1}$$

where $M(.)$ is the maintenance function, which depends on the political institution of the system as defined below. ν is the marginal productivity of the maintenance investment, and μ is the natural rate of siltation of the tank. $M(.)$

The term $\left(\frac{M(.)}{I}\right)^{\sigma}$ in assumes a diminishing effect of maintenance on capacity of the irrigation infrastructure at the margin. That is, as more silt is removed, more effort is required to remove an equal amount of silt because of biophysical factors, such as water logging and soft sediment. σ is a scaling parameter between 0 and 1, which relates how the effect of maintenance on infrastructure capacity changes across different levels of maintenance investment.

I assume that there is constant source of irrigation water, Q, from which farmers can appropriate. Therefore, the total irrigation water in the system is then given by $R(I) = QI$.

3.2.2 Payoffs

I assume that each individual is endowed with a unit of household labor. An individual farmer's profit flow is the outcome of an instantaneous static optimization problem in which the individual farmer allocates their household labor among two activities: farming (l) and non-farm employment ($1 - l$). I assume that both elites and poor farmers have the same production function, a Cobb-Douglas function with constant returns to scale, which depends on production inputs: acreage (a_i), farm labor (l_i) and water (r_i).

I assume that the total available acreage in the command area is distributed between P and E in the ratio $\frac{\lambda}{1+\lambda}$ and $\frac{1}{1+\lambda}$. So, the total acreage of P, A_P, can be expressed in terms of acreage of E, A_E, as $A_P = \lambda A_E$. Therefore, the individual-level acreage is given by: $a_i = A_i/N_i$.

The individual shares in the available water supply are defined through the solution of a bargaining game between elite and poor farmers. There is an asymmetry in the bargaining position that is shaped by the political institution. I assume that the other privately supplied production inputs and capital are optimized for a given amount of water. Under these assumptions, a farmer in group i will maximize their net incomes under either political institution, given by:

$$\pi_{i,S}(r(I)) = \max_{l_{i,S}} \ \rho_i a_i^{\alpha} l_{i,S}^{\beta} \Big(r_{i,S}(I)\Big)^{\gamma} + w_i(1 - l_{i,S}) - \psi r_{i,S}(I) \tag{3.2}$$

$$\pi_{i,J}(r(I)) = \max_{l_{i,J}} \ \rho_i a_i^{\alpha} l_{i,J}^{\beta} \Big(r_{i,J}(I)\Big)^{\gamma} + w_i(1 - l_{i,J}) - \theta r_{i,J}(I) \tag{3.3}$$

where $i = \{E, P\}$, ρ_i is the price per unit of production input, w_i is the wage rate for non-farm employment, $r_{i,S}(I)$ is the individual water share for a farmer in group i under the self-governance regime, and $r_{i,J}(I)$ is the individual water share of a farmer in group i under the nested institution. ψ and θ are the marginal maintenance fees on water used under the self-governance and nested institution respectively. α, β, and γ are the output elasticities of acreage, labor, and water respectively, and $\alpha + \beta + \gamma = 1$.

3.2.3 Water Allocation Mechanisms

Under the nested regime, I assume that the state assumes the role of a social planner and wants to maximize system profits with a linear cost of supplying water. Therefore, they fully allocate all the available water and split it evenly across all the farmers. This assumption is consistent with several examples of public water allocation procedures (Dinar and Subramanian, 1997). The individual water share of elite and poor farmers is then given as:

$$r_{E,J}(I) = r_{P,J}(I) = \frac{R(I)}{N} \tag{3.4}$$

Under the self-governance regime, I assume a proportional water distribution model. That is, water is distributed among farmers in the irrigation system on a per-acre basis. This assumption is consistent with empirical observations by Baker (2011). In my model, I assume that the total agricultural land in the command area is distributed between elite and poor farmers as $\frac{1}{1+\lambda}$ and $\frac{\lambda}{1+\lambda}$. Therefore, their respective individual shares of the irrigation water will be:

$$r_{E,S}(I) = \frac{R(I)}{N_E(1+\lambda)} \tag{3.5}$$

$$r_{P,S}(I) = \frac{\lambda R(I)}{N_P(1+\lambda)} \tag{3.6}$$

3.2.4 Institutional Choice

I assume that the irrigation system reflects a democratic society where if there is sufficient dissatisfaction with the current water allocation and management of the infrastructure, there can be a referendum to switch the political institution. In order to track the institutional choice of individuals, I develop a compartmental model (Pulliam, 1988), which assumes that every individual has a discrete preferred institutional choice or "mental model". To recall, the two political institutions are: self-governance (S) and nested (J). I, then, track how the elites and poor farmers change their institutional choice over time.

Let X_E and X_P represent the fraction of elite and poor farmers, respectively, whose preference over governance is J. Then, the fraction of individuals whose preference is S may be given by: $(1 - X_i)$. I assume that farmers have bounded rationality, which refers to the fact that they can make their decision based on limited information, in this case the infrastructure efficiency and their payoffs under the two institutions. The dynamics of X_i may be given by:

$$\frac{dX_i}{dt} = \begin{cases} \phi_i(1 - X_i)\Big(\pi_{i,J} - \pi_{i,S}\Big) & \text{if } \pi_{i,J} > \pi_{i,S} \\ \phi_i X_i\Big(\pi_{i,J} - \pi_{i,S}\Big) & \text{if } \pi_{i,J} < \pi_{i,S} \end{cases}$$

The interpretation of the above equations is that if the profits from nested institution are higher than the self-governance regime, then farmers will switch there preference over governance to the nested institution. On the other hand, if the profits under the self-governance regime are higher, then farmers will change their preference to self-governance.

ϕ_i represents the responsiveness of a farmer in group i to economic payoffs. This adjustment parameter captures the notion that farmers' mental models about their institutional choice may also be influenced by non-pecuniary considerations, such as their cultural beliefs, lack of education, control of information by elites, etc. (Akerlof and Kranton, 2000).

3.2.5 Institutional Change

The dynamical equations in section 3.2.4 represent the mental models of individual farmers. In order for the political institution to actually change, a threshold majority condition, Γ, must be met. This represents institutional inertia in the system and is given by:

$$k(V(X_E, X_P)) = \begin{cases} 1 & \text{if } V(X_E, X_P) \geq \Gamma \\ 0 & \text{otherwise} \end{cases}$$

where $k(.) = 1$ indicates that the system has shifted to the nested regime and $k(.) = 0$ indicates that the system persists in the self-governance regime. $V(.)$ is the voting function that determines the outcome of the voting process and is given by:

$$V(X_E, X_P) = \Omega_E X_E + \Omega_P X_P \tag{3.7}$$

where Ω_E and Ω_P are the voting weights of elite and poor farmers respectively, such that $\Omega_E + \Omega_P = 1$. Baker (2011) illustrates that elite farmers possess *de facto* political power of elites, which emerges from cultural norms, such as caste, and other channels such as lobbying or bribery. In order to capture this, I assume that elites and poor farmers have differential voting weights, such that $\Omega_E > \Omega_P$.

3.2.6 Maintenance Function

The maintenance fee in the self-governance regime, θ, is assumed to be lower than the fee in the nested regime, ψ. This assumption is based on empirical evidence that under nested regimes, the maintenance fees are typically calibrated to acreage and higher than the fees under self-governance regimes (Baker, 2011). The infrastructure maintenance function depends on the political institution governing the system and is given by

$$M(.) = \begin{cases} N\theta & \text{if } k(V(X_E, X_P)) = 1 \\ N\psi & \text{if } k(V(X_E, X_P)) = 0 \end{cases}$$

3.3 Discussion

The political institutions in my model affect the maintenance of the irrigation infrastructure, which subsequently affects the payoffs of the farmers through the provisioning of water, which increases profits monotonically, but with diminishing returns. Therefore, I focus my analysis on the condition of the infrastructure in my analysis and treat this as an indicator of the performance for a given political institution. I examine the effect of voting weights, non-farm labor wages, and the rate of adjustment of the mental model on the regime shift and infrastructure provision. Table 6 summarizes the definitions all the model parameters.

I assume that the system is under the self-governance regime initially. This assumption mimics the initial conditions of several irrigation systems in India (Ostrom, 1990). I also assume a simple majority rule for the voting threshold condition under which the political institution changes, i.e., $\Gamma = 0.51$.

In order to understand the institutional preferences of farmers, I conduct the analysis in three parts. First, I examined how different voting weights, Ω_i may lead to different steady states represented by the two state variables, public infrastructure condition (I) and voting outcome (V). Second, I examined the role of non-farm wage employment of elites, w_E, on the condition of irrigation infrastructure, and the payoffs and voting preferences of elite and poor farmers. Last, I examine the role of informational interventions on the payoffs and voting preferences of elite and poor farmers. For this purpose, I focus on the rate of adjustment of the mental model of poor farmers, ϕ_P.

3.3.1 Analysis I: Effect of Voting Weights

I characterized two voting rules (elitist and egalitarian) that affect the voting outcomes through which the political institutions and the relative payoffs of farmers are determined. Using the parameters for voting weights in equation 3.7, I characterize elitist as $\Omega_E = 0.6$, $\Omega_P = 0.4$ and egalitarian as $\Omega_E = 0.5$, $\Omega_P = 0.5$.

At the outset, the payoffs to the elite farmers are greater under the self-governance institution than the nested institution. This is because elites receive more water and the maintenance fee is lower under the self-governance regime. On the other hand, the payoffs to the poor farmers are greater under the nested institution because of greater water allocation by the state. Moreover, the provision of infrastructure is better under the nested regime due to higher maintenance fees, resulting in higher infrastructure efficiency (Figure 13). The model also predicts that the poor farmers are more likely to choose the nested regime, while the elite farmers choose the self-governance regime (Figure 14).

The actual change in the institution, however, occurs only when the majority threshold, Γ, is met. When the voting weights of poor farmers are lower than the elite farmers, the threshold is not met because the elites' preference for the self-governance regime (Figure 14). On the other hand, when the voting weights are equal, the threshold condition is met and the institution changes to a nested regime. This result suggests that contrary to popular belief, self-governance does not necessarily result in better infrastructure provision, especially in societies with high power asymmetries among farmers.

The role of elites in determining the persistence of political institutions has also been observed by Acemoglu and Robinson (2008). This work, however, is at a macro level and focuses on the role of elites in democratic and autocratic societies. The focus of my model is at a local level, specifically on systems where livelihoods of people are tied to a shared resource. The voting weights in my model represent the de facto political power of elites, which may be used to shape the outcomes of a democratic voting process within a community. Such power may be an outcome of a cultural norm, such as caste.

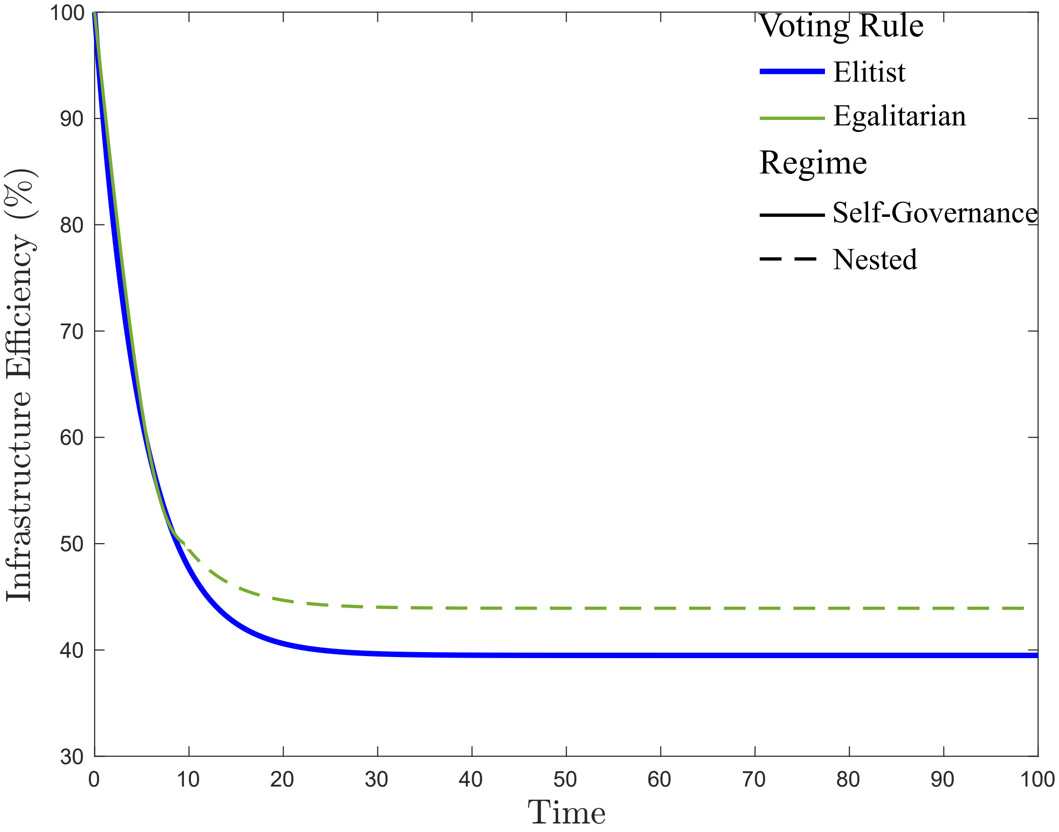

Figure 13. This figure represents the dynamics of infrastructure depreciation over time for two states of the world. The X-axis represents time and Y-axis shows infrastructure efficiency in %. The blue line represents an elitist society ($\Omega_E = 0.6$, $\Omega_P = 0.4$) and the green line represents an egalitarian society ($\Omega_E = 0.5$, $\Omega_P = 0.5$). The solid line indicates self-governance regime and the dotted line indicates the nested regime.

For instance, farmers in the *Ranjya Kuhl* irrigation system in North India voted for the state to take over management of the irrigation system. This would have been achieved by forming a water user association to (i) facilitate the acquisition of government funds for infrastructure repair and maintenance, and (ii) guarantee fair allocation of water to farmers. However, the involvement of the state meant that the high-caste farmers could no longer maintain their authority over water control, which was the main reason for elites to the state intervention and overturn the results of the voting process through bribery and violence (Baker, 2011). On the

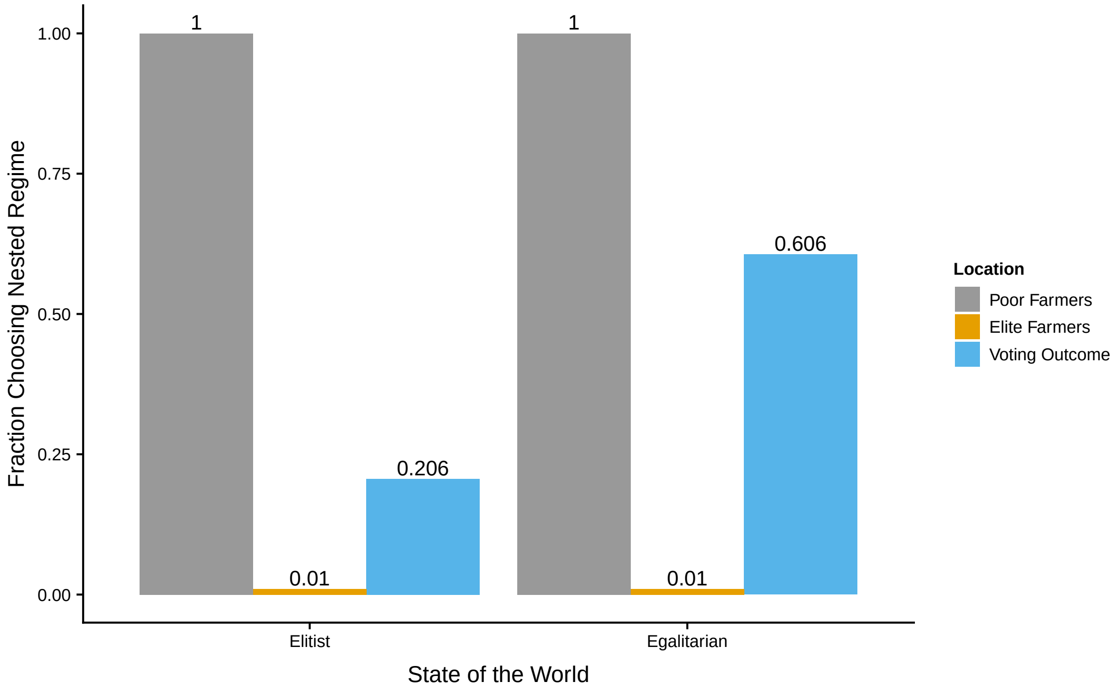

Figure 14. This figure represents the institutional preferences of farmers at system equilibrium for two states of the world. The X-axis represents the state of the world: elitist society ($\Omega_E = 0.6$, $\Omega_P = 0.4$), and an egalitarian society ($\Omega_E = 0.5$, $\Omega_P = 0.5$). The Y-axis shows the fraction of population that chooses the nested institution. The voting majority threshold for the institution to change is $\Gamma = 0.51$.

other hand, in more egalitarian communities, such as the *Bhagotla Kuhl* irrigation system, voting outcomes directly reflect the institutional choices of individuals and state intervention can be successful (Baker, 2011).

3.3.2 Analysis II: Effect of Non-Farm Wages

In Analysis I, we observed that the presence of de facto political power may result in the persistence of an inferior political institution, represented by a lower efficiency of public infrastructure. Empowering poor farmers politically, through their voting weights, may be one way for the system to shift to a nested institution and improving the infrastructure efficiency.

On the other hand, policy makers may suggest formal economic institutions to incentivize the elites to choose the nested institution. For example, the state may improve the non-farm opportunities for the elite farmers. Such a reform can reduce their reliance on farm income, thereby reduce their need for water control. To generate some useful knowledge about such a reform, this section investigates the effect of non-farm wages to elites on infrastructure efficiency and institutional change. The results shown here are for an elitist state of the world. Except for the focal parameter, w_E, the parameter values used in this section are the same as the preceding section. I characterize low wage as $w_E = 0.2$ and high wage as $w_E = 0.8$.

Similar to the earlier case, the payoffs to the elite farmers are higher in the self-governance institution when non-farm wages are low. The reason for this is a higher water share and lower maintenance fee under the self-governance institution. Therefore, the elite farmers choose the self-governance institution. On the other hand, when non-farm wages to the elite farmers are high, their labor allocation to non-farm employment increases. This reduces their farm labor and profit share from farming. The combination of higher profits from non-farm labor and better infrastructure provision under the nested regime results in a higher fraction of the elite farmers choosing the nested institution (Figures 15 and 16). As a higher fraction elite farmers choose nested institution, the majority threshold, Γ, is met (Figure 16) and the system shifts to the nested regime (Figure 15).

The importance of rural non-farm employment has been extensively discussed in the development economics literature (Barrett *et al.*, 2001; Reardon *et al.*, 2007). The general conclusion from this literature is that not all households have equal access to non-farm employment (Barrett *et al.*, 2001). The differential access to non-farm employment can change the pattern of dependence on irrigation water. That is, households with new economic opportunities are less willing to engage in infrastructure maintenance, especially when the opportunity costs of their labor are foregone cash wages (Cárdenas *et al.*, 2017). On the other hand, households with greater constraints to non-farm employments, typically poor households, face increased

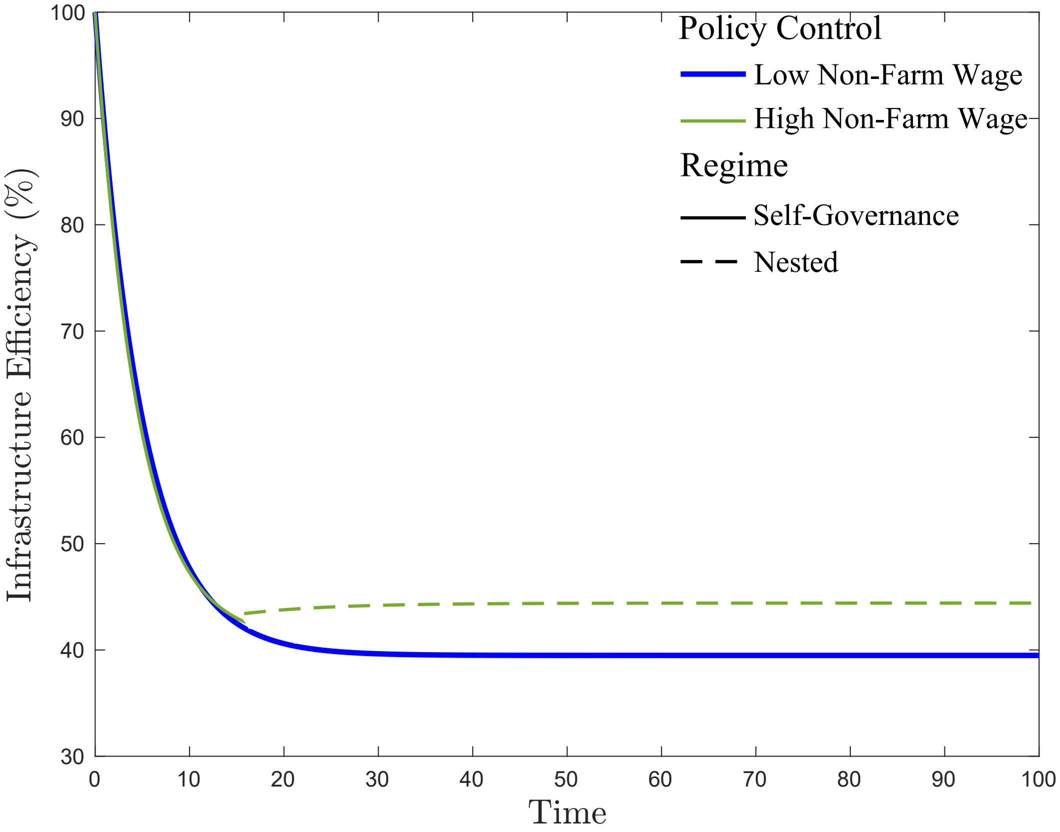

Figure 15. This figure represents the dynamics of infrastructure depreciation over time for for two levels of non-farm wages to the elite farmers: low wage society ($w_E = 0.2$), and high wages ($w_E = 0.8$). The X-axis represents time and Y-axis shows infrastructure efficiency in %. The solid line indicates self-governance regime and the dotted line indicates the nested regime.

burden to maintain the infrastructure. In such cases, state intervention can augment the infrastructure provision (Baker, 2011). Increasing non-farm opportunities can, however, increase the risk of conflicts arising from caste-based inequalities because of reduced dependence on the benefits of the shared infrastructure (Jodha, 1990; Polanyi, 1944).

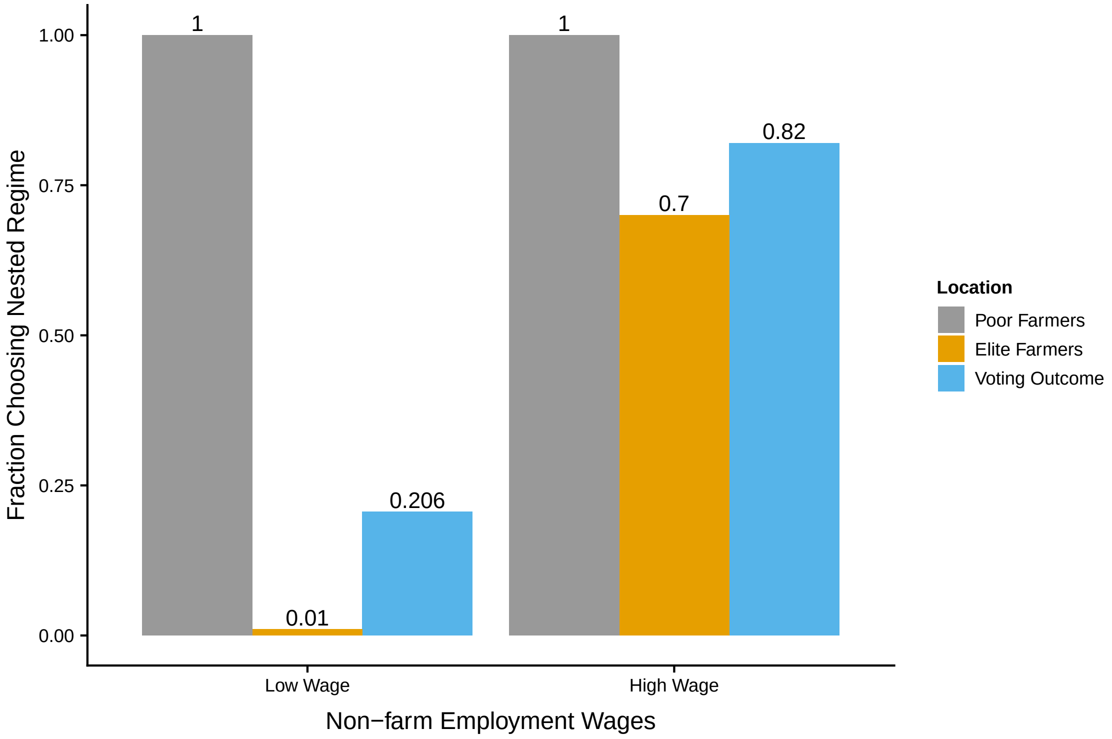

Figure 16. This figure represents the institutional choice of farmers and the voting outcome at system equilibrium for two levels of non-farm wages to the elite farmers: low wage society ($w_E = 0.2$), and high wages ($w_E = 0.8$). The Y-axis shows the fraction of population that chooses the nested institution. The voting majority threshold for the institution to change is $\Gamma = 0.51$.

3.3.3 Analysis III: Effect of Learning

In my model, there is rate of depreciation of the infrastructure. The maintenance effort applied under either political institution offsets this depreciation. In the preceding section, we saw that the interventions through formal economic institutions, such as non-farm wage employment, can flip the system to a nested institution. However, such a flip may not necessarily result in significant improvements in the infrastructure efficiency. So, it is important to examine the approach to the steady state, i.e., the rate at which the change in the political institution occurs, or the steady state is achieved. For this purpose, I examine the parameter ϕ_i, which is the rate of adjustment of the individuals' mental model. ϕ_i may be interpreted as a function of knowledge transmission or rate of learning in the system. Depending on the depreciation rate of the infrastructure and relative adjustment rate of the mental model of the individual, the approach to steady state can be different (Smith, 1969).

Specifically, I focus on the responsiveness of the poor farmers, ϕ_P. I characterize ϕ_P as low learning ($\phi_P = 0.3$) and high learning ($\phi_P = 0.8$). Except for the focal parameter, the remaining parameter values in this section are the same as the high wage scenario in the preceding section.

Figure 17 illustrates change in infrastructure efficiency as a function of time for high and low learning states. Regardless of the value of learning rate of the poor farmers,ϕ_P, the system eventually shifts to the nested regime and the infrastructure efficiency is at around 45%. However, ϕ_P affects the transient dynamics of the shift from one political institution to another. A high value of ϕ_P increases the speed of institutional change. That is, at high learning rate, the system shifts to the nested regime at $t = 15$, whereas at low learning rate, the regime shift occurs at $t = 73$. Even though the regime shift occurs eventually in both cases, the quality of infrastructure is degraded for an additional 59 years before it is is improved (Figure 17). This result highlights the relationship between the quality of the physical infrastructure and the rate of adjustment of the mental model of the elite farmers.

The use of evolutionary dynamics has brought attention to the importance of the norms of behavior that guide individuals' decisions. For example, “traditional codes of behavior” can lead individuals to support social norms even though those norms might be disadvantageous to the society (Akerlof, 1984, pg.72). The mental models of individuals, and thereby the perceptions about payoffs, is often based on belief-systems that promote the capture of resources (or wealth) of poor farmers. However, the model predicts that the elite farmers find it in their own economic interests to abandon the old institution.

The parameter ϕ_i speaks to the durability of mental models of individuals. It controls the

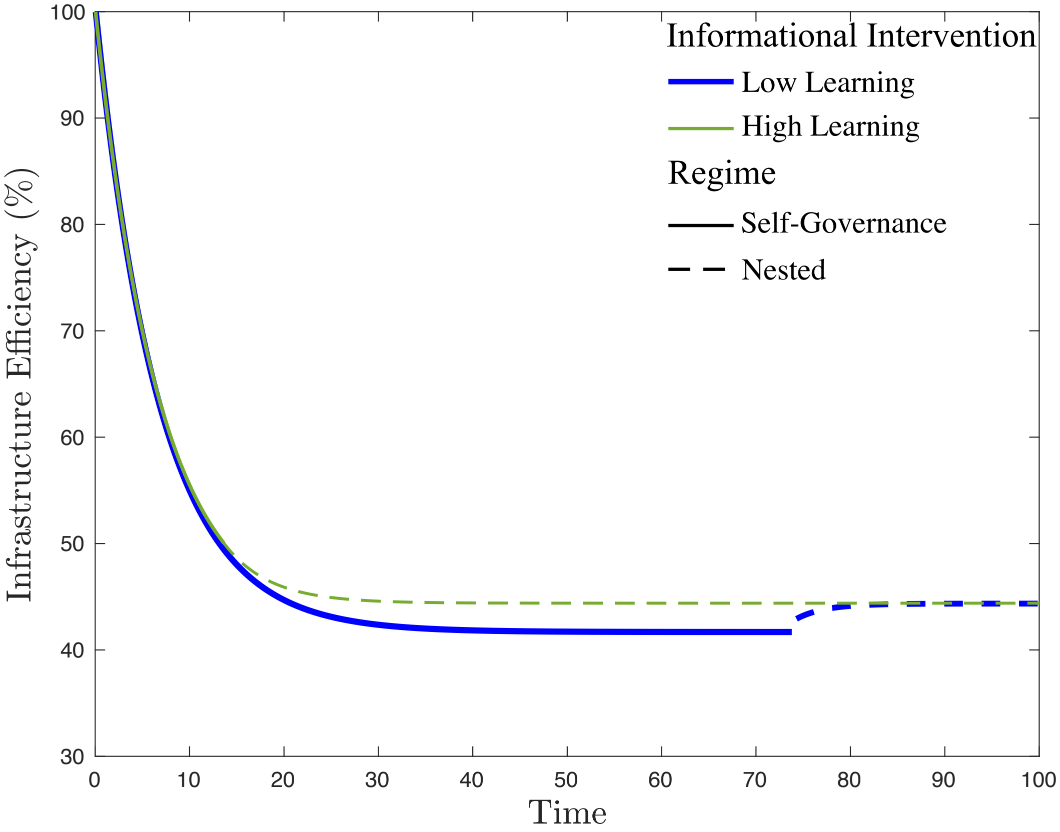

Figure 17. This figure represents the dynamics of infrastructure depreciation over time for two rates of learning in the mental model of the elites. The X-axis represents time and the Y-axis represents infrastructure efficiency in %. The two rates of learning are characterized as low learning ($\phi_P = 0.3$) and high learning ($\phi_P = 0.8$). The voting majority threshold for the institution to change is $\Gamma = 0.51$.

information available to individuals, which may be a function of poor human infrastructure and can be improved through informational interventions, such as access to education. This result highlights the importance of knowledge transmission through learning, which is an most important source of change in the long-run (North, 1994).

3.4 Conclusion

There is a great deal of consensus that economic institutions are a key determinant of economic performance in a society. (North, 1994; Acemoglu *et al.*, 2001; Greif *et al.*, 1994; Greif, 2006; Wade, 1989). These discussions assume that the political institutions required for specifying and enforcing these constraints are present. However, there are several documented examples in developing countries, which lack such political institutions (Bardhan, 2000; Ostrom, 1990). This assumption about the presence of political institutions leads to many important questions, perhaps the most interesting of which is why do political institutions differ across societies? Can a better understanding of the determinants of political institutions enhance my ability to respond to power asymmetries in a society? This chapter is an effort to address these questions through an examination of community-managed irrigation systems in North India.

Research on institutional change has examined key questions such as why inferior institutions persist (Greif *et al.*, 1994; Greif, 2006), and why societies fail to adopt the institutional design of successful ones (Greif, 1998). The work reported here aims to contribute to this body of scholarship through examining, explicitly, the role of political power as a determinant of political institutions in societies.

Given power asymmetries, are there patterns in the way societies organize around environmental variability? Is it possible to characterize individuals' mental models through a more "realistic" comparison of infrastructure efficiency across different political institutions? Is it possible to characterize robustness-vulnerability trade-offs of different political institutions? Further research in this area involves extending my model to address the questions discussed herein. Through an iterative process of model and data refinement, it may be possible to characterize some basic principles concerning the determinants of political institutions in social-ecological systems. These principles can help guide policy development regarding long-term environmental change.

Chapter 4

INSTITUTIONS WITHOUT ROMANCE: CORRUPTION AND PROVISIONING OF PUBLIC INFRASTRUCTURE IN CANAL IRRIGATION SYSTEMS

4.1 Introduction

The performance of government-managed irrigation systems, which cover about 60% of the global irrigated area (Burton, 2010), continues to be at the center of irrigation development debates. Regardless of whether performance is defined based on technical efficiency (Molden *et al.*, 1998), or equity in water distribution (Malano and van Hofwegen, 1999), the literature suggests that performance of such systems in several developing countries continues to decline (Suhardiman and Giordano, 2014; Mukherji *et al.*, 2009; Malano and van Hofwegen, 1999). There is a general agreement that poor performance may be caused by poor maintenance of the irrigation infrastructure, itself a consequence of the existing institutional arrangements for infrastructure management (Groenfeldt *et al.*, 2000). One way to improve the provision of irrigation infrastructure is to build on the role of bureaucrats who may shape irrigation outcomes through their direct interactions with farmers (Senanayake *et al.*, 2015; Suhardiman and Giordano, 2014). Examples of such bureaucrats include canal engineers and other appointed field staff who repair canals and distribute water.

Irrigation reform discussions that focused on enhancing the role of bureaucrats have previously dissociated politics from their analysis and assume benevolence on the part of the bureaucrat (Moe, 2006). Among the most consistent themes in the literature on bureaucracies is the conclusion that a budget-maximizing bureaucrat will oversupply public goods, relative to the level of provision preferred by the typical politician, because of the monopolistic power of the bureaucrat over public resources (Niskanen, 1971, 1975; Breton and Wintrobe, 1975; Tullock, 1965). The objective of the bureaucrats in these models is to maximize their individual utility (wages, benefits, power, etc.) by maximizing the budget of their office. These models, however, do not include corruption as a way to satisfy these objectives.

In contrast to the over-provision hypothesis, empirical evidence indicates that much of the under-investment in canal irrigation systems in the Indian subcontinent has been attributed to corruption in the irrigation bureaus that maintain the irrigation infrastructure (Wade, 1982; Mollinga, 2001, 2003; Rinaudo, 2002). This suggests that bureaucrats may not simply be 'public servants' as assumed by previous studies, and may threaten provision of public infrastructure by their exercise of monopolistic power over public resources.

Existing theories of bureaucratic oversight use the principal-agent framework to propose ways in which politicians may counter the bureaucrat's capacity to manipulate information and limit their monopolistic power over public resources (Wade, 1979; Shepsle and Weingast, 1984). For instance, in the context of budgeting, politicians may restrain bureaucratic manipulation through monitoring (McCubbins *et al.*, 1987; Weingast and Moran, 1983). However, this literature has four limitations.

The first limitation is that most of the existing models that examine corruption focus explicitly on the U.S. system (Becker, 1983; Rose-Ackerman, 1975; Lui, 1986; Klitgaard, 1988), which has relatively lower levels of outright bribery (extralegal cash transfers) in the bureaucracy compared to many developing nations that are characterized by poor infrastructure provision (Corruption Perceptions Index, 2018).

The second limitation is that none of the existing studies on corruption extend the principal-agent framework to study the provision of public infrastructure. So, it is not well understood how monitoring may affect infrastructure provision.

The third limitation is that the studies that take the principal-agent approach to examine corruption are biased towards bureaucratic (agent) corruption and do not consider the potential complicity of the politician (principal). In countries like India, a dishonest politician may, often, misuse their power to pressure the irrigation bureau to rake money off the public funds allocated for provision of public irrigation infrastructure (Wade, 1982; Thompson, 2000). In such cases, corruption among politicians and bureaucrats prevails as an informal norm, and they both act to maximize their own selfish interests rather than being compliant agents maximizing the social welfare of farmers.

Last, due to information asymmetry in principal-agent interactions, monitoring can be an imperfect instrument and impose significant costs for detecting shirking behavior of bureaucrats (McCubbins *et al.*, 1987). The reason for this is that due to irreducible uncertainty, no matter how carefully the consequences of principal-agent interactions are monitored, there can be indeterminacy about the extent to which a bureaucrat applied their best efforts to maintain the infrastructure. In the context of irrigation systems, climate uncertainty may exacerbate the problem of information asymmetry regarding the bureaucrat's provision efforts. The effect of natural stochasticity on the likelihood of corruption and infrastructure provision is not well understood.

To address the gap left by studies on corruption, I developed a stylized principal-agent model that characterizes infrastructure provision under a discrete monitoring technology to examine how institutional and environmental factors affect (i) the likelihood of corruption, and (ii) the infrastructure provision efforts. I focus specifically on the politician's incentive to be corrupt and the infrastructure provision efforts by the bureaucrat under corrupt and non-corrupt regimes.

4.2 The Model

I consider a government-managed agricultural system that is irrigated through gravity flow canal systems. I assume that the central authority is the politician, who appoints the public official or bureaucrat.[3] This assumption is consistent with empirical evidence from irrigation systems in South India (Wade, 1982). The irrigated command area is fed from infrastructure constructed, operated and maintained by the bureaucrat. There is a third population of citizens (farmers), that I do not directly consider in this model. In the model, I assume that the politician's preferences about infrastructure provision capture the importance of infrastructure to the electorate and for being reelected.

The bureaucrat has an appropriated budget that is used to pay for maintenance. This budget is approved by the politician's office. The politician, however, can only observe the quality of infrastructure, which is a noisy signal of the bureaucrat's effort. Therefore, the problem is whether compensation to the bureaucrat can only be adjusted at the margin based on their performance. I examine two institutional responses to this problem.

The first institution defines a output-based contract between the politician and the bureaucrat, where the latter may be removed from office for non-performance. That is, if the bureaucrat's effort (input) falls below a certain level of infrastructure provision (output), they may be fired. This characterizes many bureaus that don't allow for performance-based compensation structures and operate only at the extensive margin of the bureaucrat (Heckman *et al.*, 1997; Heinrich, 1999; Wade, 1982). I characterize this interaction as non-corrupt and treat this as the baseline institutional structure.

The second institutional structure is one where the politician receives a bribe from the bureaucrat that is proportional to the latter's provision efforts. Therefore, the bureaucrat's compensation is variable in the bribe. Under this institutional structure, both the bureaucrat and the politician are subject to governmental oversight, and they might get caught (McCubbins

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[3] The principal-agent model presented here represents hierarchy within a bureaucracy or a politician-bureaucrat relationship. For simple exposition, I assume a politician-bureaucrat interaction.

et al., 1987). Since the complicity of politicians with bureaucrats allows them to utilize public funds for personal gain, I characterize this interaction as corrupt.

The overall decision process on infrastructure provisioning is a two-stage game. In the first stage, the politician chooses between corrupt (C) and non-corrupt (NC) strategies. In the second stage, the bureaucrat chooses their level of effort (M) based on the politician's strategy. I assume that the politician and bureaucrat are risk-neutral. For the remainder of the discussion, I use the following notation to denote the utilities and strategies of the bureaucrat and politician: $U_i(\Gamma_B, \Gamma_P)$, where i denotes the players: bureaucrat (B) and politician (P), and Γ_i denotes the strategy of player i..

4.2.1 Non-corrupt Bureaucrat and Non-corrupt Politician

I start with the interaction of a non-corrupt politician and a non-corrupt bureaucrat. The performance of the bureaucrat, q, is assumed to be equal to their effort in maintenance of the infrastructure, M, plus a shock, ϵ: $q = M + \epsilon$. By shock, I refer to extreme weather events, such as floods, that may result in deterioration of the irrigation infrastructure. I assume that the shock is revealed to the players after the contract is chosen. ϵ is the realization of a weather event.

I characterize the players' beliefs over possible shocks as a diffuse prior with a uniform distribution with zero mean between the limits $[-\beta/2,\beta/2]$. That is, the players' beliefs assign a positive probability to the true state of the world before the shock is revealed. β describes the range of possible weather events. An increase in the value of β reflects uncertainty about the range of possible weather events, which may reflect a more uncertain climate regime (Milly *et al.*, 2002).

The bureaucrat chooses a level of effort,M_{NC}, that maximizes their net earnings and their utility function is represented by

$$U_B(NC, NC) = \max_{M_{NC}} \left[\overline{w}Pr(q > T) - \psi(M_{NC})\right] \tag{4.1}$$

where $\overline{w}$ is the wage earned by the bureaucrat, which is conditional on the infrastructure provision being above the threshold, T. $\overline{w}Pr(q > T)$ reflects an all-or-nothing contract with no performance-based payment. That is, the bureaucrat gets paid if the threshold condition is met and conditional on getting paid, the bureaucrat's compensation does not depend on their performance. For simplicity, the cost-of-effort function is assumed to be quadratic: $\psi(M_{NC}) = \dfrac{\theta M_{NC}^2}{2}$, where θ is the marginal cost of effort.

The politician's benefit, on the other hand, is tied to the bureaucrat's performance and they incur a cost equal to the compensation paid to the bureaucrat. The politician's expected utility function is given by

$$U_P(NC, NC) = \mathbb{E}[q - \overline{w}Pr(q > T)] = M_{NC} + \mathbb{E}[\epsilon] - \overline{w}Pr(q > T) \tag{4.2}$$

The bureaucrat's utility function in expression 4.1 may be rewritten as below. Refer to B.1 for the derivation.

$$\begin{aligned} U_B(NC, NC) &= \overline{w}Pr(M_{NC} + \epsilon > T) - \frac{\theta M_{NC}^2}{2} \\ &= \frac{\overline{w}}{2} - \frac{\overline{w}T}{\beta} + \frac{\overline{w}M_{NC}}{\beta} - \frac{\theta M_{NC}^2}{2} \end{aligned}$$

The bureaucrat balances the increased expected marginal benefit from increasing the probability of receiving their wage versus the marginal cost of their effort:

$$U_B(NC, NC) = \max_{M_{NC}} \frac{\overline{w}}{2} - \frac{\overline{w}T}{\beta} + \frac{\overline{w}M_{NC}}{\beta} - \frac{\theta M_{NC}^2}{2} \tag{4.3}$$

$$FOC : \frac{\overline{w}}{\beta} - \theta M_{NC} = 0$$

$$\implies M_{NC}^*(\overline{w}, \theta, \beta) = \frac{\overline{w}}{\theta\beta} \tag{4.4}$$

Substituting expression 4.4 into expression 4.3, the non-corrupt bureaucrat's maximized utility may then be derived as below. Refer to B.1 for the derivation.

$$U_B(NC, NC) = \overline{w}\Big[\frac{1}{2} - \frac{T}{\beta} + \frac{\overline{w}}{2\theta\beta^2}\Big]$$

Knowing that $M^*_{NC} = \dfrac{\overline{w}}{\theta\beta}$, the non-corrupt politician's maximized utility may be derived as below. Refer to B.1 for the derivation.

$$U_P(NC, NC) = \overline{w}\Big[\frac{1}{\theta\beta} - \frac{1}{2} + \frac{T}{\beta}\Big] - \frac{\overline{w}^2}{\theta\beta^2}$$

4.2.2 Corrupt Bureaucrat and Corrupt Politician

I now consider the interaction between a corrupt bureaucrat and corrupt politician. Here, I assume that the politician demands a bribe from the bureaucrat based on the latter's performance. This assumption is an accurate description of many regimes observed in the developing world (Rose-Ackerman and Palifka, 2016).

Given the well-institutionalized system of corruption that surrounds irrigation in India (Quah, 2008), positions in the irrigation bureau are valuable assets. Not only do bureaucrats have to pay for transfer to desirable positions, but also a bureaucrat who does not perform well or who threatens to enforce the law against those who engage in corruption may simply be transferred somewhere else by the politician. Therefore, given the structure of power and norms, we may visualize a transaction, in which the bureaucrat pays a bribe to the politician.

Unlike the formal compensation in the non-corrupt contract, bribery can be proportional to bureaucrat's performance. That is, the bribes can be adjusted at the intensive margin of the bureaucrat's effort, similar to the linear contracts in the agency literature. I assume that the politician and bureaucrat devise a linear contract of the form:

$$s = \overline{w} - (b - Hq)$$

where, $\overline{w}$ is the fixed wage earned by the bureaucrat, b is the maximum feasible bribe that is a constraint set by norms. I assume that the politician chooses the marginal reduction in the net bribe, H, that is contingent upon on the performance of the bureaucrat, making the effective bribe paid by the bureaucrat to the politician equal to: $b - Hq$. I assume that the maximum feasible bribe is less than the bureaucrat's wage, i.e., $b < \overline{w}$.

Last, I assume that the the probability of being caught and punished when engaging in corruption is $(1 - \sigma)$. When this probability is equal to one, both the bureaucrat and politician get fired and they earn a zero payoff. Hence, σ is the probability of successful corrupt activity.[4] Considering $\sigma \in [0, 1]$, the benefit from corruption is given by, σs.

The bribe includes an implicit promise of protection for the bureaucrat here since there is no longer a threshold of system quality that gets them turned out of their jobs. Presumably, this is part of why a bureaucrat can be corrupt.

The corrupt bureaucrat balances the increased expected marginal benefit from decreasing the probability of being caught and the marginal reduction in the net bribe paid to the politician versus the marginal cost of their effort. Refer to B.2 for the derivation of the first-order condition:

$$\begin{aligned} U_B(C, C) &= \max_{M_C} \mathbb{E}\left[\sigma\Big(\overline{w} - b + Hq\Big) - \frac{\theta M_C^2}{2}\right] \\ FOC : \sigma H_C - \theta M_C &= 0 \implies M_C = \frac{\sigma H}{\theta} \end{aligned} \tag{4.5}$$

The bureaucrat's performance affects the politician's payoffs in two ways. First, the maintenance effort of the bureaucrat improves the condition of infrastructure, and thereby the improves the possibility of the politician's reelection. Second, the bribe that the politician receives from the bureaucrat is proportional to the latter's effort. The politician's problem is then

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[4] I assume that the probability of being caught and punished is exogenous to the game. A more general structure might make this probability an increasing function of the bribe. This assumption simplifies the formal statement of the model and the exposition that follows.

to choose a bribe, H, taking as given the bureaucrat's optimal choice of M_C for a given H. Refer to B.2 for the derivation of H^*:

$$\begin{aligned} U_P(C,C) &= \max_{H}\ \mathbb{E}\left[\sigma\Big(q + (b - Hq) - \overline{w}\Big)\right] \\ FOC: \frac{\sigma^2}{\theta} &- \frac{2H\sigma^2}{\theta} = 0 \\ H^* &= \frac{1}{2} \implies M_C^*(\sigma,\theta) = \frac{\sigma}{2\theta} \end{aligned} \tag{4.6}$$

Knowing the values of H^* and M_C^*, the maximized utility functions of the corrupt bureaucrat and politician may be derived as below. Refer to B.2 for the derivation of the maximized utilities.

$$\begin{aligned} U_B(C,C) &= \sigma\Big[\overline{w} - b\Big] + \frac{\sigma^2}{8\theta} \\ U_P(C,C) &= \frac{\sigma^2}{4\theta} + \sigma[b - \overline{w}] \end{aligned}$$

4.3 Results

Before I turn to the analysis, let us recall the structure of the two contracts and utilities of the politician and the bureaucrat. The overall decision process on infrastructure provisioning is a two-stage game. In the first stage, the politician makes a strategy based on the effort the bureaucrat is applying. In the second stage, the bureaucrat chooses an effort based on the contract they are facing.

I assume that the bureaucrat will play the game only if it gives them a positive utility. That is,

$$U_B(NC,NC) \geq 0 \text{ and,}$$

$$U_B(C,C) \geq 0$$

This assumption represents the individual rationality constraint for the bureaucrat. That is, if the utility is negative, the bureaucrat can break their contract with the politician for an outside opportunity. Therefore, the politician chooses a contract that maximizes their expected utility, subject to the bureaucrat's participation constraint.

The sequential structure of the game results in a Stackelberg leader-follower equilibrium. That is, there are two possible pooling equilibria: one is they choose corrupt (C) and the other is they choose non-corrupt (NC). This is represented in the game tree in Figure 18.

If the politician chooses non-corruption (NC), they write an extensive margin contract with the bureaucrat. That is, the bureaucrat is removed from the office if they do not meet the threshold condition for infrastructure provision. Consequently, the bureaucrat chooses a corresponding level of effort. On the other hand, if the politician chooses to be corrupt (C), they withhold a portion of the bureaucrat's pay and then either punish them if the system performs poorly or "cut them slack" if the system performs well. That is, they devise a contract on the intensive margin of the bureaucrat's effort. The maximized utilities of the bureaucrat and the politician under these possible equilibria are given by:

1. Non-corrupt Bureaucrat and Non-Corrupt Politician: Using backward induction, the bureaucrat chooses the level of effort in the second stage of the game:

$$U_B(NC, NC) = \overline{w}\Big[\frac{1}{2} - \frac{T}{\beta} + \frac{\overline{w}}{2\theta\beta^2}\Big] \tag{4.7}$$

$$U_P(NC, NC) = \overline{w}\Big[\frac{1}{\theta\beta} - \frac{1}{2} + \frac{T}{\beta}\Big] - \frac{\overline{w}^2}{\theta\beta^2} \tag{4.8}$$

2. Corrupt Bureaucrat and Corrupt Politician: Using backward induction, the politician chooses the bribe in the first stage, based on the bureaucrat's performance that is determined in the second stage.

$$U_B(C, C) = \sigma\Big[\overline{w} - b\Big] + \frac{\sigma^2}{8\theta} \tag{4.9}$$

$$U_P(C, C) = \frac{\sigma^2}{4\theta} + \sigma[b - \overline{w}] \tag{4.10}$$

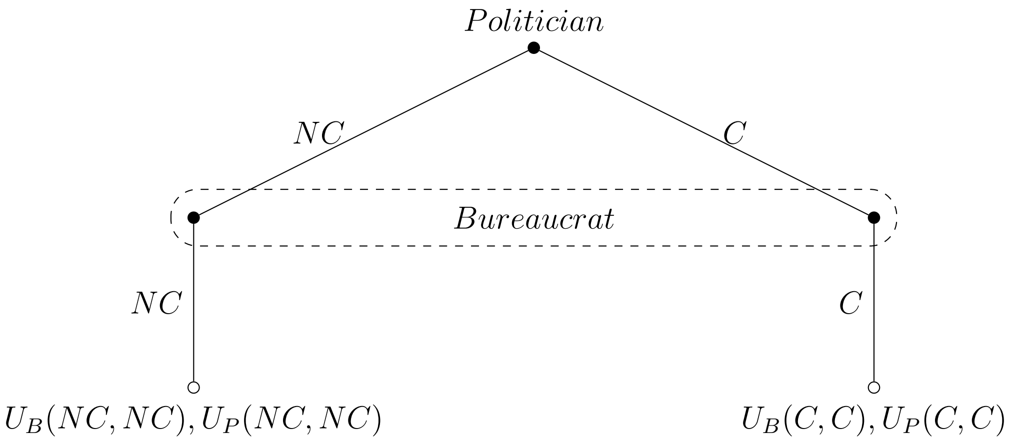

Figure 18. Extensive form of the game.

Table 2 summarizes the definitions all the model parameters. In order to examine the conditions under which the politician chooses corruption, I define I_C as the politician's incentive to be corrupt. This is simply the difference between the utility of being corrupt and the utility obtained by being non-corrupt, and is given by:

$$\begin{aligned} I_C &= U_P(C,C) - U_P(NC,NC) \\ &= \sigma\Big[\frac{\sigma}{4\theta} + b - \overline{w}\Big] - \overline{w}\Big[\frac{1}{\theta\beta} - \frac{1}{2} + \frac{T}{\beta} - \frac{\overline{w}}{\theta\beta^2}\Big] \qquad (4.11) \end{aligned}$$

Table 2. Definitions of model parameters

Symbol	Definition
$\overline{w}$	Wage of the bureaucrat
T	Infrastructure threshold
β	Climate uncertainty
θ	Marginal cost of effort to the bureaucrat
σ	Probability of corruption not being detected
b	Maximum feasible bribe

4.3.1 Comparative Statics on the Incentive to be Corrupt

I conduct the comparative statics over three parameters: climate uncertainty (β), probability of detection ($1 - \sigma$), and fixed bureaucratic wages ($\overline{w}$).

4.3.1.1 Climate Uncertainty

The change in incentive to be corrupt with respect to the climate uncertainty, β, may be shown by:

$$\frac{\partial I_C}{\partial \beta} = \frac{\overline{w}}{\theta\beta^2} + \frac{\overline{w}T}{\beta^2} - \frac{2\overline{w}^2}{\theta\beta^3} > 0 \tag{4.12}$$

Expression 4.12 shows that an increase in the climate uncertainty increases the incentive to be corrupt at the margin. However, the regime shift to corrupt equilibrium depends on the degree of climate uncertainty.

At low climate uncertainty, the infrastructure provision is higher in the non-corrupt compared to the corrupt contract because the bureaucrat must apply more effort to achieve the threshold condition with greater certainty (eq 4.4 and 4.6). Contrarily, as climate uncertainty increases, the bureaucrat's effort is higher under the corrupt regime (eq 4.6). Since the politician derives a benefit from infrastructure provision (eq 4.11), the level of bureaucrat's provision effort influences the politician's incentive to be corrupt.

I_C is negative at low climate uncertainty because of higher provision efforts under the non-corrupt regime (eq 4.11). As the climate uncertainty increases, infrastructure provision is higher in the corrupt regime, the incentive to be corrupt increases ($I_C > 0$), and the system reaches a corrupt equilibrium.

4.3.1.2 Probability of Detection

The change in incentive to be corrupt with respect to the probability of being detected may be shown by[5]:

$$\frac{\partial I_C}{\partial \sigma} = \frac{\sigma}{2\theta} + b - \overline{w} \tag{4.13}$$

Equation 4.13 shows that the politician's incentive to be corrupt depends on the value of the fixed bureaucratic wage, $\overline{w}$, relative to the probability of detection, $(1-\sigma)$, and the bureaucrat's cost of effort, θ. If $\sigma < 2\theta(\overline{w} - b)$ [6] the incentive to be corrupt decreases at the margin as the probability of detection increases. This result follows directly from the assumption about the probability of detection reducing the politician's net earnings in the corrupt contract. If $\sigma > 2\theta(\overline{w} - b)$, then the incentive to be corrupt increases at the margin and the system shifts to a corrupt equilibrium.

4.3.1.3 Bureaucratic Wage

The change in incentive to be corrupt with respect to the fixed bureaucratic wage, $\overline{w}$, may be shown by:

$$\frac{\partial I_C}{\partial \overline{w}} = \frac{2\overline{w}}{\theta\beta^2} + \frac{1}{2} - \left[\sigma + \frac{1}{\theta\beta} + \frac{T}{\beta}\right] \tag{4.14}$$

The role of bureaucratic wage in the likelihood of corruption is ambiguous and depends on the degree of climate uncertainty and probability of detection relative to the wage. That is, the incentive to be corrupt increases at the margin if $\overline{w} > \frac{\beta}{2}\left[\sigma\beta + \frac{1}{\theta} + T - \frac{\beta}{2}\right]$. Alternatively, if this condition fails, the incentive to be corrupt decreases at the margin and the system shifts to the non-corrupt equilibrium.

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[5] The probability of being caught and punished in the model is assumed to be $(1 - \sigma)$. Therefore, σ is the probability of not being detected.

[6] I assume that the bureaucrat's fixed wage is greater than the maximum bribe paid to the politician, i.e., $\overline{w} > b$

4.3.2 Comparative Statics on Infrastructure Provision Effort

4.3.2.1 Corrupt Contract

In the sequential game, the bureaucrat is responding with infrastructure provision. So, in order to understand the conditions under which infrastructure provision is higher or lower, I examine the bureaucrat's performance under the two contracts. The bureaucrat's effort levels in the corrupt contract is given by:

$$M_C^*(\sigma, \theta) = \frac{\sigma}{2\theta} \tag{4.15}$$

Expression 4.15 shows that the infrastructure provision under the corrupt regime increases as the probability of detection, $(1 - \sigma)$, and the unit cost-of-effort, (θ), decrease. This result follows directly from the assumptions in the model specification: the gains from corruption decrease as the probability of detection increases. Therefore, the bureaucrat's effort under the corrupt regime declines as the probability of detection increases.

Expression 4.15 also shows that the infrastructure provision under the corrupt contract is unaffected by climate uncertainty. This is because, due to the linear form of the corrupt contract and the risk neutrality assumption, the bureaucrat experiences only the mean uncertainty, which is assumed to be zero.

4.3.2.2 Non-Corrupt Contract

On the other hand, the infrastructure provision effort under the non-corrupt equilibrium is given by:

$$M_{NC}^*(\overline{w}, \theta, \beta) = \frac{\overline{w}}{\theta\beta} \tag{4.16}$$

Expression 4.16 shows that the infrastructure provision effort under the non-corrupt regime increases with wage of the bureaucrat. This may be explained by the fact that under the non-corrupt contract, the bureaucrat's wage is tied to their performance. Therefore, an increase in wage results in an increase in their effort level.

Expression 4.16 also shows that the infrastructure provision under the non-corrupt equilibrium is strictly decreasing in climate uncertainty (β). To recall, the infrastructure provision threshold condition is given by: $M + \epsilon > T$. For low values of β (low ϵ), the bureaucrat must apply more effort (M) in order to meet the provision threshold (T) with greater certainty. Conversely, under high climate uncertainty (high β), the non-corrupt bureaucrat applies smaller effort to achieve the infrastructure threshold.

4.3.3 Infrastructure Provision and System Outcomes

From the discussion so far, I demonstrate that the key parameters – probability of detection, bureaucratic wages, and climate uncertainty – determine whether the system shifts to the corrupt or non-corrupt regime. The discussion also highlights that these parameters affect the incentives for infrastructure provision within an equilibrium. However, the effect of corruption on infrastructure provision effort is ambiguous.

In order to compare the infrastructure provision effort under the corrupt and non-corrupt regimes, I define ΔM, which is given by the difference between the levels of infrastructure provision by the bureaucrat under the corrupt and non-corrupt regimes:

$$\begin{aligned} \Delta M &= M^*_C(\sigma, \theta) - M^*_{NC}(\overline{w}, \theta, \beta) \\ &= \frac{\sigma}{2\theta} - \frac{\overline{w}}{\theta\beta} \end{aligned} \tag{4.17}$$

The provision of infrastructure is greater under the corrupt regime if $\Delta M > 0$ and greater under the non-corrupt regime if $\Delta M < 0$.

Based on expressions for I_C in eq 4.11 and ΔM in eq 4.17, there are four possible outcomes for corruption and infrastructure provision:

1. Infrastructure Improving Corrupt Equilibrium: This equilibrium means that the system in a corrupt regime and the infrastructure provision is greater under the corrupt regime ($\Delta M > 0$, $I_C > 0$).
2. Infrastructure Degrading Corrupt Equilibrium: This equilibrium means that the system in a corrupt regime and the infrastructure provision is greater under the non-corrupt regime ($\Delta M < 0$, $I_C > 0$).
3. Infrastructure Improving Non-Corrupt Equilibrium: This equilibrium means that the system in a non-corrupt regime and the infrastructure provision is greater under the non-corrupt regime ($\Delta M < 0$, $I_C < 0$).
4. Infrastructure Degrading Non-Corrupt Equilibrium: This equilibrium means that the system in a non-corrupt regime and the infrastructure provision is greater under the corrupt regime ($\Delta M > 0$, $I_C < 0$).

Table 3 summarizes the possible outcomes for corruption and infrastructure provision effort. In the remainder of the discussion, I will focus on the conditions under which each of these four outcomes are possible. The discussion above highlights that the gains to corruption and the infrastructure provision depend on the policy controls (probability of detection and wage), and state of the world (climate uncertainty). Therefore, going forward, I will focus on these three parameters to understand when they will succeed or fail in providing greater infrastructure provision effort.

Table 3. Possible Outcomes for Corruption and Infrastructure Provision. I_C is the incentive to be corrupt. $\Delta M > 0$ implies the infrastructure provision effort is greater in the corrupt regime than the non-corrupt regime.

	Non-Corrupt	Corrupt
Infrastructure Improving	$I_C < 0$ $\Delta M > 0$	$I_C > 0$ $\Delta M > 0$
Infrastructure Degrading	$I_C < 0$ $\Delta M < 0$	$I_C > 0$ $\Delta M < 0$

4.3.4 Probability of Detection

I derive the following condition for corruption equilibrium from the expression for I_C in eq 4.11:

$$\sigma\left[\frac{\sigma}{4\theta}+b-\overline{w}\right]>\overline{w}\left[\frac{1}{\theta\beta}-\frac{1}{2}+\frac{T}{\beta}-\frac{\overline{w}}{\theta\beta^2}\right] \tag{4.18}$$

I also derive a condition for when the infrastructure provision effort is greater under the corrupt regime ($\Delta M > 0$):

$$\begin{aligned}\frac{\sigma}{2\theta}-\frac{\overline{w}}{\theta\beta}&>0\\ \implies \sigma&>\frac{2\overline{w}}{\beta}\end{aligned} \tag{4.19}$$

To examine whether the conditions in expressions 4.18 and 4.19 can be satisfied, the model mimics different climate scenarios. A high value of β reflects a state of high uncertainty and a reasonably low value of β indicates low climate uncertainty [7]

4.3.4.1 High Climate Uncertainty

Figure 19 illustrates the infrastructure provision effort, as a function of the probability of detection for high and low values of wages, in a state of high climate uncertainty. The figure also shows the shift from corrupt to non-corrupt regimes and whether that shift results in an improvement or worsening of infrastructure provision. The graph demonstrates a very intuitive point: when the climate uncertainty is high, allowing for corruption may yield greater provision of infrastructure provision (solid line). This result follows the discussion on the comparative statics of M_C^* (expression 4.15) and M_{NC}^* (expression 4.16): under high climate uncertainty, infrastructure provision effort under the corrupt regime can be greater compared to the non-corrupt regime.

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[7] I determined the high-low values based on the range of feasible values of parameters.

Figure 19 shows that at low probability of detection, conditions in expressions 4.18 and 4.19 are both satisfied, and the system is in an infrastructure improving corrupt equilibrium ($\Delta M > 0$ and $I_C > 0$). As the probability of detection increases, the gains from corruption decrease and the system shifts to the non-corrupt regime (expression 4.13). However, this may yield a worse provision of infrastructure, resulting in an infrastructure degrading non-corrupt equilibrium ($\Delta M > 0$ and $I_C < 0$). The graph also shows that low wages necessitate a higher probability of detection to push the system into the non-corrupt regime (blue line). Table 4 summarizes these results (cells I and II).

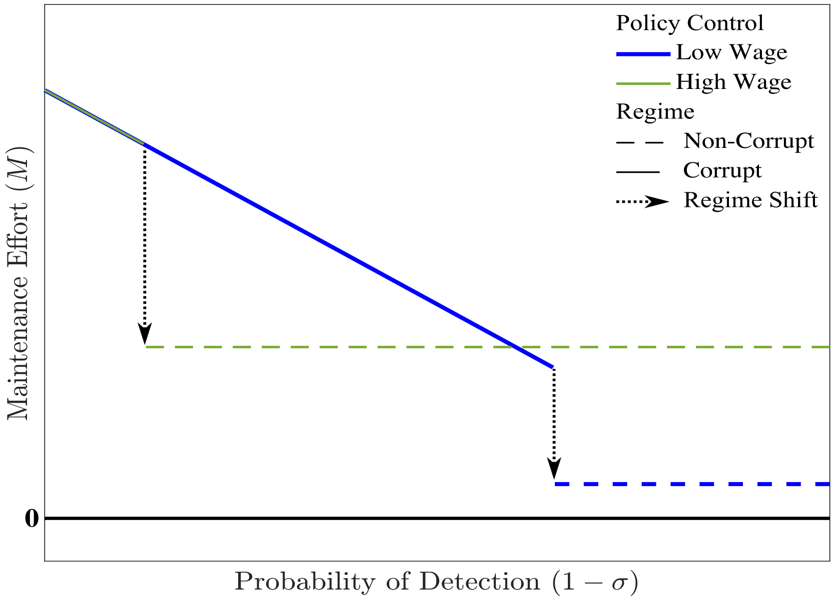

Figure 19. The infrastructure provision effort as a function of probability of detection in a state of high climate uncertainty. The solid and dotted lines represent the corrupt and non-corrupt regimes respectively. The blue line indicates low fixed bureaucratic wages and green line indicates high fixed wages.

Table 4. Conditions for the corrupt equilibrium and infrastructure provision effort in a state of high climate uncertainty. M_C is the bureaucrat's infrastructure provision effort in the corrupt regime and M_{NC} is their effort in the non-corrupt regime.

	Non-Corrupt	Corrupt
$M_C > M_{NC}$	**I.** Strong monitoring	**II.** Weak Monitoring
$M_C < M_{NC}$	**III.** Strong monitoring High wage	**IV.** Weak monitoring High wage

4.3.4.2 Low Climate Uncertainty

I examine the outcomes for ΔM and I_C in a state of low climate uncertainty. Figure 20 illustrates the infrastructure provision effort, as a function of the probability of detection for high and low wages, in a state of low climate uncertainty. A key takeaway from this graph is that increasing the probability of detection pushes the system into the non-corrupt equilibrium, but infrastructure provision effort depends on the wage.

As the probability of detection increases, a high fixed wage to the bureaucrat yields greater infrastructure provision under the non-corrupt regime compared to the corrupt regime (Figure 20 - dashed green line). This result follows the discussion on the comparative statics on M_{NC} (expression 4.16): under low uncertainty, infrastructure provision in the non-corrupt regime is higher than the corrupt regime. Also, M_C decreases as the probability of detection increases (expression 4.15).

Figure 20 shows that when the fixed wages are high, the conditions in expressions 4.18 and 4.19 are not satisfied. As the probability of detection increases, the system shifts to an infrastructure improving non-corrupt equilibrium ($\Delta M < 0$ and $I_C < 0$). Alternatively, when the fixed wages are low, increasing the probability of detection shifts the system to the non-corrupt regime (expression 4.13). However, the infrastructure provision in this state can be worse than the corrupt regime, resulting in an infrastructure degrading non-corrupt equilibrium ($\Delta M > 0$ and $I_C < 0$) (Figure 20). This result is summarized in Table 5 (cells II and III).

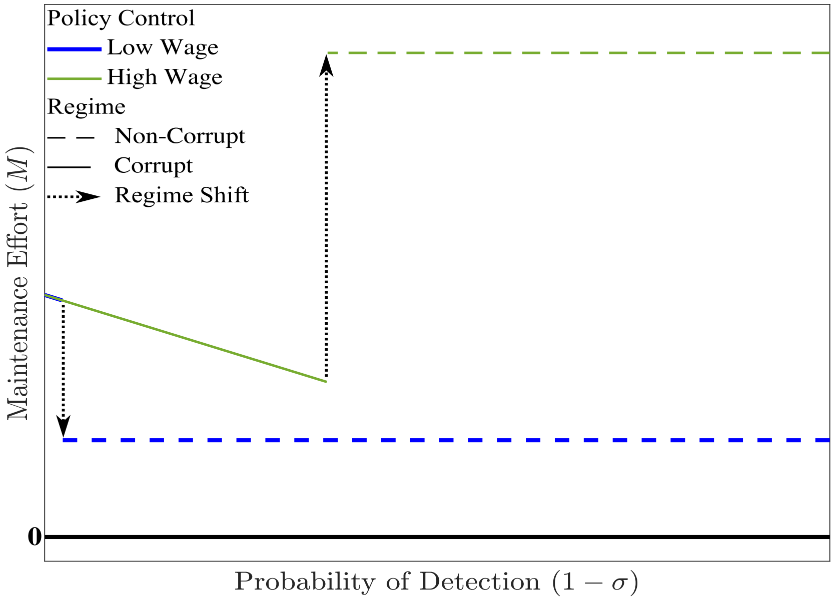

Figure 20. The provision of infrastructure as a function of probability of detection in a state of low climate uncertainty (low β). The solid and dotted lines represent the corrupt and non-corrupt regimes respectively. The blue line indicates low bureaucratic wages and green line indicates high wages.

Table 5. Conditions for the corrupt equilibrium and infrastructure provision effort in a state of low climate uncertainty. M_C is the bureaucrat's infrastructure provision effort in the corrupt regime and M_{NC} is their effort in the non-corrupt regime.

	Non-Corrupt	Corrupt
$M_C > M_{NC}$	**I.** Strong monitoring Low wage	**II.** Weak monitoring Low wage
$M_C < M_{NC}$	**III.** Strong monitoring High wage	**IV.** Weak monitoring High wage

4.3.5 Bureaucratic Wage

Recalling the condition for corruption equilibrium from the expression for I_C in eq 4.11:

$$\sigma\Big[\frac{\sigma}{4\theta}+b-\overline{w}\Big] > \overline{w}\Big[\frac{1}{\theta\beta}-\frac{1}{2}+\frac{T}{\beta}-\frac{\overline{w}}{\theta\beta^2}\Big] \tag{4.20}$$

Rewriting the condition for when the infrastructure provision effort is greater under the corrupt regime ($\Delta M > 0$) as:

$$\begin{aligned} \frac{\sigma}{2\theta} - \frac{\overline{w}}{\theta\beta} &> 0 \\ \implies \overline{w} &< \frac{\beta\sigma}{2} \end{aligned} \tag{4.21}$$

We know from expression 4.16 that as wages increase, the infrastructure provision is strictly increasing under the non-corrupt regime. However, expression 4.14 shows that the regime shift to non-corrupt equilibrium ($I_C < 0$) depends on the state of climate uncertainty.

Figure 21 illustrates the infrastructure provision effort, as a function of the fixed wage for high and low probability of detection, in a state of high climate uncertainty. The key takeaway of this graph is that the politician's incentive to be corrupt decreases as wage increases (dotted line). This is because the politician's benefit from infrastructure provision in the non-corrupt contract exceeds their benefit in the corrupt contract (expression 4.11). Once the system shifts to the non-corrupt equilibrium, the infrastructure provision is strictly increasing in wages (expression 4.16). Table 4 summarizes these results (cells III and IV).

For sufficiently high wages, it is possible that the conditions for $I_C > 0$ (expression 4.20) and $\Delta M > 0$ (expression 4.21) are not satisfied and the system is in an infrastructure improving non-corrupt equilibrium (Figure 21). The figure also shows an inverse relationship between the probability of detection and wage. That is, a high probability of detection requires a small increase in wage to shift the system into the non-corrupt regime (green line).

Figure 22 illustrates the infrastructure provision effort, as a function of the wage for high and low probability of detection, in a state of low climate uncertainty. The graph shows two regime shifts in the system. We know from expression 4.16 that the infrastructure provision effort in the non-corrupt regime strictly increases in wage. At low wages, the system shifts from corrupt to a non-corrupt regime (dotted line). This is because the politician's benefit

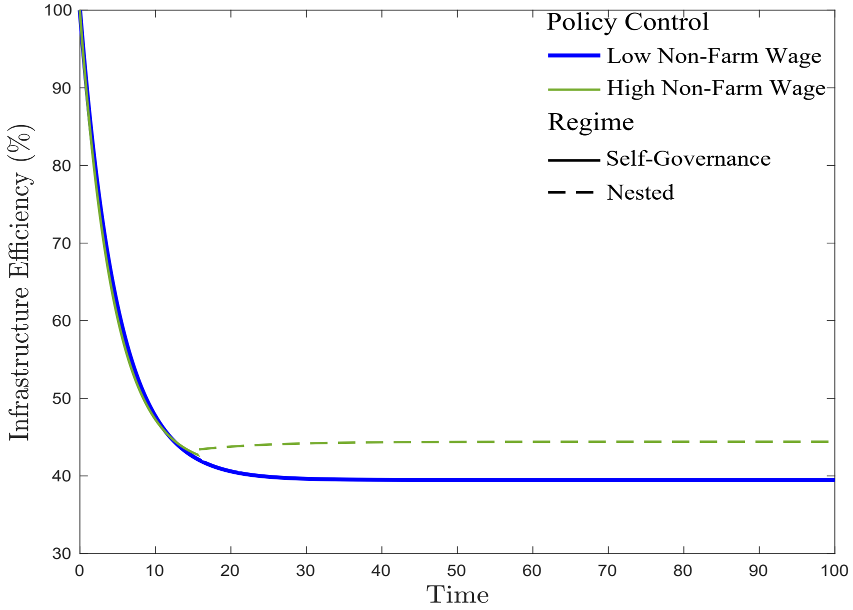

Figure 21. The provision of infrastructure as a function of wages in a state of high climate uncertainty. The solid and dotted lines represent the corrupt and non-corrupt regimes respectively. The blue line indicates weak monitoring mechanisms and green line indicates strong monitoring mechanisms.

from infrastructure provision effort in the non-corrupt regime is higher than the corrupt regime (expression 4.11). However, as the wages increase, the system shifts back to the corrupt regime with a lower level of infrastructure provision (solid line). This is because the politician's cost of paying wages to the bureaucrat far exceed their benefit from infrastructure provision in the non-corrupt regime (expression 4.11). Figure 22 shows that as wages increase, the condition in expression 4.19 fails and the system shifts to an infrastructure degrading corrupt equilibrium ($\Delta M < 0$ and $I_C > 0$). These results are summarized in Table 5 (cells III and IV).

4.3.6 Climate Uncertainty

In the final part of the analysis, I examine the effect of climate uncertainty on the corruption equilibrium and infrastructure provision effort. Rewriting the condition for when the provision

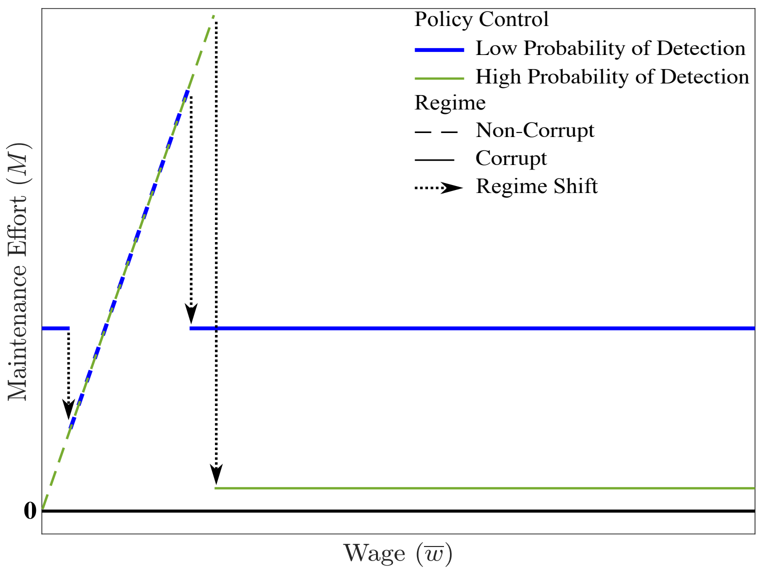

Figure 22. The provision of infrastructure as a function of wages in a state of low climate uncertainty. The solid and dotted lines represent the corrupt and non-corrupt regimes respectively. The blue line indicates weak monitoring mechanisms and green line indicates strong monitoring mechanisms.

of infrastructure is greater under the corrupt regime ($\Delta M > 0$) as:

$$\begin{aligned} \Delta M > 0 &\implies \frac{\sigma}{2} > \frac{\overline{w}}{\beta} \\ &\implies \beta > \frac{2\overline{w}}{\sigma} \end{aligned} \tag{4.22}$$

Figure 23 illustrates the infrastructure provision effort, as a function of the climate uncertainty for high and low probability of detection. The key takeaway from this figure is that corruption is more likely as the climate uncertainty increases. This result follows the discussion in the comparative statics for I_C (expression 4.12) and M_{NC} (expression 4.16). We know from expression 4.12 that at low climate uncertainty, I_C is negative even though it is increasing at the margin. This result is represented by the first regime shift in figure 23. As the climate uncertainty increases, the provision of the infrastructure is degrading under the non-corrupt regime (expression 4.16) and at relatively high uncertainty, I_C is positive. This is represented by the second regime shift in Figure 23, which shows that as climate uncertainty increases, the condition in expressions 4.22 and 4.20 are satisfied, and the system can reach an infrastructure improving corrupt equilibrium ($\Delta M > 0$ and $I_C > 0$).

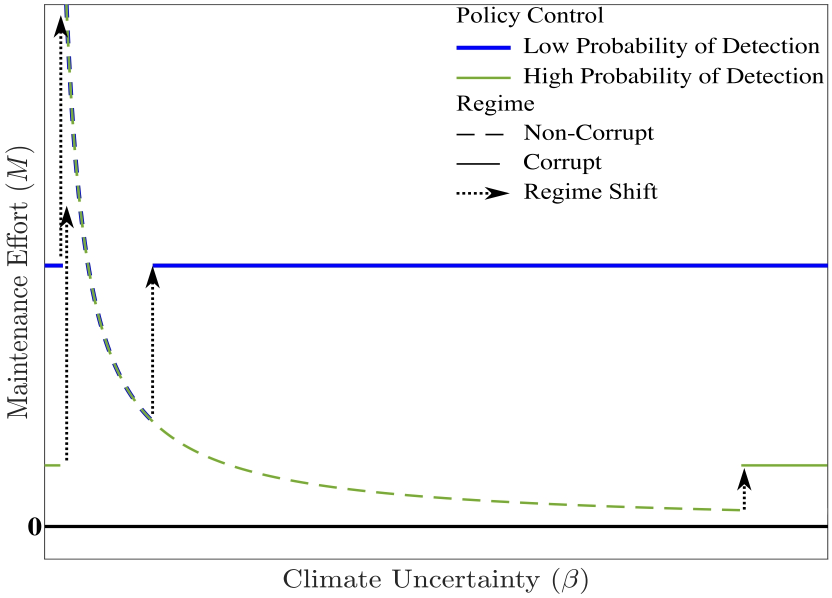

Figure 23. The provision of infrastructure as a function of climate uncertainty. The solid and dotted lines represent the corrupt and non-corrupt regimes respectively. The blue line indicates weak monitoring mechanisms and green line indicates strong monitoring mechanisms.

4.4 Discussion

Improving the efficiency of irrigation infrastructure is arguably a high priority for several developing countries. Yet, empirical evidence shows that the condition of irrigation infrastructure continues to decline in countries like India due to political and bureaucratic corruption. Casual empiricism indicates that corruption distorts the allocation of resources and reduces provision of public goods (De Soto, 1989). Wade and Chambers (1980) and Wade (1984) indicated that nearly 50 percent of the funds allocated by the government for maintenance of irrigation infrastructure was wasted in corruption. In spite of research showing the negative effects of corruption on irrigation performance in government-managed irrigation systems (Rinaudo, 2002), few studies have examined this issue.

To make matters worse, there is little to no understanding of the role of corruption in the context of climate uncertainty. In a world of increasing threats from climate uncertainty, this is an important relationship to understand. The model provides a framework for analyzing the equilibrium behavior of the politician and public good provision by the bureaucrat under different scenarios of climate uncertainty. The key predictions may be summarized as:

1. When the climate uncertainty is high, allowing for corruption may yield greater provision of infrastructure provision (Figure 19). This suggests that cracking down on corruption is beneficial only when infrastructure provision is degrading.
2. In a state of low climate uncertainty, the model predicts that cracking down on corruption pushes the system into a non-corrupt equilibrium. However, the state of infrastructure provision depends on the wages of the bureaucrat (Figure 20). This suggests a complementary role of wage increases and corruption eradication efforts.
3. As we continue to face an increased uncertainty in the climate, wages play an important role in determining if corruption may be curbed and infrastructure provision may be improved.

The first key result of the model is that in the context of government-managed irrigation systems, cracking down on corruption is beneficial only when the provision of infrastructure in the corrupt regime is worse than in the non-corrupt regime. The important policy implication of this result is that under high climate uncertainty, allowing for corruption, or a low probability of its detection, can yield greater infrastructure provision efforts (Figures 19 and 23). It is important to understand the counterfactual of this result, i.e., the effect of curbing corruption on infrastructure provision efforts in a state of high climate uncertainty.

The model predicts that while increasing the probability of detection pushes the system into a non-corrupt equilibrium, the state of infrastructure may be degrading under the non-corrupt scenario. While the notion of climate uncertainty in corruption studies is yet to be explored, the idea of allowing for corruption is not novel. This result is consistent with the extant literature, which suggests that allowing for bureaucratic corruption may, sometimes, be the optimal thing to do, particularly in the context of developing countries (Shleifer and Vishny, 1993; Acemoglu and Verdier, 1998).

The second key result of the model is the importance of bureaucratic wages. In a state of low climate uncertainty, the model shows that while cracking down on corruption pushes the system into a non-corrupt equilibrium, the state of infrastructure provision depends on the wages of the bureaucrat (Figure 20). I find that the under low climate uncertainty, in systems with high bureaucratic wages, there is a need for stronger monitoring mechanisms to curb corruption. In such cases, increasing the probability of detection in scenarios where bureaucrats have high wages may result in a higher provision of infrastructure in the non-corrupt regime (Figure 20).

The importance of adequate wages in relation to curbing corruption has been widely discussed in the corruption literature (Becker and Stigler, 1974; Shapiro and Stiglitz, 1984; Myrdal, 1972), and the conclusions are ambiguous. The model also predicts that in a state of low climate uncertainty, if the fixed wages are high, the system can be in a corrupt equilibrium with a lower state of infrastructure provision (Figure 22).

On the other hand, “shirking models” of Shapiro and Stiglitz (1984) and Becker and Stigler (1974) predict that in the presence of low probability of detection, higher wage is necessary to eliminate corruption. Interestingly, the model predicts this result in the state of high climate uncertainty (Figure 21). In such cases, infrastructure provision may improve in the non-corrupt regime only if the wages are very high.

Last, in a state of low climate uncertainty, the model predicts that even in the presence of strong monitoring and enforcement mechanisms, corruption may prevail when wages of bureaucrats are high (Figure 22). The model predicts that in such cases, the provision of infrastructure is degrading under the corrupt regime. This result is consistent with the observations of Wade (1982), which concludes that in spite of strong monitoring procedures, executive engineers, who are among the high-ranked bureaucrats in the irrigation bureau, continue to conceal their receipt and passing on of illicit funds. The fact that the exchange of illicit funds is encouraged, and is often demanded, by the politician reduces the effectiveness of these monitoring mechanisms (Wade, 1982, pg.309). Furthermore, Wade (1982) and Mollinga (2003) emphasize that in South Indian canal irrigation systems, corruption among high-ranked bureaucrats and politicians functions an informal institution and plays a major role in the poor maintenance of irrigation infrastructure.

The non-monotonic nature of the tradeoffs between corruption and infrastructure provision in the model shows that there is not a “panacea”, one-size-fits-all policy approach. Anticipating institutional responses to climate change is especially critical for managers of irrigation infrastructure. However, it is important to understand the nexus of climate uncertainty, the remuneration in non-corrupt systems, and monitoring effectiveness before making policy recommendations.

Chapter 5

CONCLUSION

The objective of this research was to better understand how institutions for provision of shared infrastructure are crafted and sustained, and the consequences they generate for resource use in diverse settings. I addressed these questions by studying irrigation systems in India. I used a combination of stylized mathematical models to examine human-environment interactions and, specifically, the incentives that motivate actors to engage in the provision of shared infrastructure. My findings demonstrate the importance of formal interventions, such as water pricing instruments, rural non-farm wage employment, and bureaucratic wages, to improve the provision of irrigation infrastructure. I also show the important role that informal institutions, such as informational interventions, may play in inducing better infrastructure provision.

In Chapter 2, I examined how the presence of shared and private infrastructure may affect the provision of shared infrastructure and system productivity. Using a stylized replicator dynamic model, I demonstrated that an integrated set of institutions, such as a fixed groundwater fee and a volumetric fee on tank users that is differentiated based on where users are located in the system, can improve system productivity and equality. I calibrated the model parameters to replicate and predict outcomes in tank irrigation systems in South India.

The next extension of my inquiry was to examine the effect of social factors on institutions. In Chapter 3, I examine the role of power asymmetries between resource users as a determinant for the political institutions that govern infrastructure provision. I developed a stylized compartmental model to track the institutional preference of elites and non-elites in an irrigation system. I use this mental model to examine the effect of policy tools, such as non-farm wage employment and informational interventions, on the persistence of two different types of political institutions in a canal irrigation system: self-governed and nested governance. My findings show that improving non-farm wage employment opportunities can shift the system to a nested institution, which typically has higher infrastructure provision. However, in order to accelerate the rate of change such that it is not too late to improve infrastructure provisions, changes to informal institutions, such as informational interventions and learning, may be required.

Last, I examine the role of political factors as determinants of infrastructure provision in Chapter 4. Using a stylized principal-agent model, I examine the effect of political and administrative corruption on infrastructure provision in a canal irrigation system. Specifically, I examined how institutional and environmental factors affect (i) the likelihood of corruption, and (ii) the provision of infrastructure. My model results suggest that in the face of increasing uncertainty in environmental shocks, a crackdown on extralegal side payments through monitoring mechanisms may result in inferior infrastructure provision. I also demonstrate that by focusing on bureaucratic wages, we can curb corruption as well as improve infrastructure provision.

Agriculture contributes to nearly 20% of India’s GDP. In spite of enormous investments by the Indian government in its management, poor irrigation infrastructure remains a critical factor for low yields and water productivity (Shah, 2009). This raises serious concerns for food security. My research is a step towards understanding the determinants of infrastructure provision and crafting policies to improve its management. Though that models I developed in this thesis are stylized, they capture key human-environment interactions that are representative of several irrigation systems in India. Moreover, the models allow us to assess the potential gains to individuals for different policy interventions. In the future, through an iterative process of model and data refinement, the models developed in this thesis can offer valuable insights to policymakers about crafting effective institutions for improving infrastructure quality and agricultural productivity. I contend that this work is in the spirit of extending Ostrom's (2007) call for moving beyond panaceas to produce actionable solutions for policymakers.

The implications of my work also extend beyond the specific case study contexts. The challenge of public infrastructure provision in human societies in not unique to irrigation systems. As world populations continue to rise, the demand for scarce resources is increasing, resulting in greater demand for the provision of existing physical infrastructures. For instance, we observe this trend in the need for better maintenance of the public electric grid as societies shift to decentralized energy systems (Castaneda *et al.*, 2017). There is also a need for building more road infrastructure as traffic congestion continues to rise (Joanis, 2011). What unifies these systems is the similarity of the political-economic factors that drive or impede the infrastructure provision. I contend that my research demonstrates how to operationalize the CIS framework and develop theory-rich models that can characterize policy recommendations for infrastructure provision in social-ecological systems.

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APPENDIX A

CHAPTER-3 APPENDIX

Table 6. Definitions of State Variables and Parameters

Symbol	Definition
Dynamical and decision variables	
I	Efficiency of the shared infrastructure
X_E	Fraction of elite farmers whose preference over governance is nested regime
X_P	Fraction of poor farmers whose preference over governance is nested regime
V	Voting outcome
$\pi_{i,S}$	Payoff of farmer in group i under self-governance regime
$\pi_{i,J}$	Payoff of farmer in group i under nested regime
t	Time
Parameters	
ν	Marginal productivity of the maintenance investment
σ	Scaling parameter
μ	Natural siltation rate of the tank
a_i	Acreage of farmer in group i
l_i	Farm labor of farmer in group i
α, β, γ	Output elasticities of acreage, labor, and water
ψ	Marginal maintenance fee under self-governance regime
θ	Marginal maintenance fee under nested regime
ρ_i	Price per unit of production input of farmer in group i
w_i	Non-farm wage to farmer in group i
ξ	Surface of the farmland
ϕ	Responsiveness of individuals to economic payoffs
Ω_i	Voting weights of farmer in group i
Γ	Voting threshold condition

APPENDIX B

CHAPTER-4 APPENDIX

This section shows the derivations of the first-order conditions and the maximized utility functions of the bureaucrat and politician for the corrupt and non-corrupt contracts.

B.1 Non-corrupt Bureaucrat and Non-corrupt Politician

The non-corrupt bureaucrat's utility function may be derived as:

$$\begin{aligned} U_B(NC,NC) &= \overline{w}Pr(M_{NC}+\epsilon > T) - \frac{\theta M_{NC}^2}{2} \\ &= \overline{w}Pr(\epsilon > T - M_{NC}) - \frac{\theta M_{NC}^2}{2} \\ &= \overline{w}(1 - Pr(\epsilon < T - M_{NC})) - \frac{\theta M_{NC}^2}{2} \\ &= \overline{w}(1 - f(T - M_{NC})) - \frac{\theta M_{NC}^2}{2} \\ \epsilon \sim U[\frac{-\beta}{2}, \frac{\beta}{2}] & \\ &= \overline{w}\Big(1 - \frac{T - M_{NC} + \frac{\beta}{2}}{\beta}\Big) - \frac{\theta M_{NC}^2}{2} \\ &= \overline{w}\Big(\frac{\frac{\beta}{2} - T + M_{NC}}{\beta}\Big) - \frac{\theta M_{NC}^2}{2} \\ &= \frac{\overline{w}}{2} - \frac{\overline{w}T}{\beta} + \frac{\overline{w}M_{NC}}{\beta} - \frac{\theta M_{NC}^2}{2} \end{aligned}$$

Knowing that $M_{NC}^* = \dfrac{\overline{w}}{\theta\beta}$, the non-corrupt politician's maximized utility may be derived as

$$\begin{aligned}
U_P(NC,NC) &= M_{NC} + \mathbb{E}[\epsilon] - \overline{w}Pr(M_{NC} + \epsilon > T) \\
&= M_{NC} + \mathbb{E}[\epsilon] - \overline{w}Pr(\epsilon > T - M_{NC}) \\
&= M_{NC} - \overline{w}(1 - Pr(\epsilon < T - M_{NC})) \\
&= M_{NC} - \overline{w}(1 - f(T - M_{NC})) \\
\epsilon \sim U[\frac{-\beta}{2}, \frac{\beta}{2}] & \\
&= M_{NC} - \overline{w}\Big(1 - \frac{T - M_{NC} + \frac{\beta}{2}}{\beta}\Big) \\
&= M_{NC} - \overline{w}\Big(\frac{\frac{\beta}{2} - T + M_{NC}}{\beta}\Big) \\
&= M_{NC} - \frac{\overline{w}}{2} - \frac{\overline{w}T}{\beta} + \frac{\overline{w}M_{NC}}{\beta} \\
\text{Substituting } M^*_{NC} = \frac{\overline{w}}{\theta\beta} : & \\
&= \frac{\overline{w}}{\theta\beta} - \frac{\overline{w}}{2} + \frac{\overline{w}T}{\beta} - \frac{\overline{w}}{\beta}.\frac{\overline{w}}{\theta\beta} \\
U_P(NC,NC) &= \overline{w}\Big[\frac{1}{\theta\beta} - \frac{1}{2} + \frac{T}{\beta}\Big] - \frac{\overline{w}^2}{\theta\beta^2}
\end{aligned}$$

B.2 Corrupt Bureaucrat and Corrupt Politician

The corrupt bureaucrat balances the increased expected marginal benefit from decreasing the probability of being caught and the marginal reduction in the net bribe paid to the politician versus the marginal cost of their effort:

$$\begin{aligned}
U_B(C,C) &= \max_{M_C} \mathbb{E}\left[\sigma\Big(\overline{w} - b + Hq\Big) - \frac{\theta M_C^2}{2}\right] \\
&= \sigma\Big(\overline{w} - b + HM_C\Big) + \sigma H\,\mathbb{E}(\epsilon) - \frac{\theta M_C^2}{2} \\
&= \sigma\Big(\overline{w} - b + HM_C\Big) - \frac{\theta M_C^2}{2} \\
FOC : \sigma H_C - \theta M_C &= 0 \\
\implies M_C &= \frac{\sigma H}{\theta} \qquad \text{(B.1)}
\end{aligned}$$

The politician's problem is to choose a bribe, H, taking as given the bureaucrat's optimal choice of M_C for a given H:

$$\begin{aligned}
U_P(C,C) &= \max_H \ \mathbb{E}\left[\sigma\Big(q + (b - Hq) - \overline{w}\Big)\right] \\
&= \sigma\Big(M_C + b - HM_C - \overline{w}\Big) + \mathbb{E}[\epsilon] - H\,\mathbb{E}[\epsilon] \\
&= \sigma\Big(M_C + b - HM_C - \overline{w}\Big)
\end{aligned}$$

Substituting $M_C = \dfrac{\sigma H}{\theta}$

$$\begin{aligned}
&= \frac{\sigma^2 H}{\theta} + \sigma b - \frac{\sigma^2 H^2}{\theta} - \sigma\overline{w} \\
FOC :& \ \frac{\sigma^2}{\theta} - \frac{2H\sigma^2}{\theta} = 0 \\
H^* &= \frac{1}{2} \implies M_C^*(\sigma,\theta) = \frac{\sigma}{2\theta}
\end{aligned}$$

Knowing the values of H^* and M_C^*, the maximized utility functions of the corrupt bureaucrat and politician may be rewritten as

$$\begin{aligned}
U_B(C,C) &= \sigma\Big[\overline{w} - b + \frac{1}{2}.\frac{\sigma}{2\theta}\Big] - \frac{\theta}{2}(\frac{\sigma}{2\theta})^2 \\
&= \sigma\Big[\overline{w} - b\Big] + \frac{\sigma^2}{4\theta} - \frac{\sigma^2}{8\theta} \\
\implies U_B(C,C) &= \sigma\Big[\overline{w} - b\Big] + \frac{\sigma^2}{8\theta} \qquad \text{(B.2)} \\
U_P(C,C) &= \frac{\sigma^2}{\theta}.\frac{1}{2} + \sigma b - \frac{\sigma^2}{\theta}.\frac{1}{4} - \sigma\overline{w} \\
&= \frac{\sigma^2}{2\theta} + \sigma b - \frac{\sigma^2}{4\theta} - \sigma\overline{w} \\
\implies U_P(C,C) &= \frac{\sigma^2}{4\theta} + \sigma[b - \overline{w}] \qquad \text{(B.3)}
\end{aligned}$$