



Research

Robustness, vulnerability, and adaptive capacity in small-scale social-ecological systems: The Pumpa Irrigation System in Nepal

*Oguzhan Cifdaloz*¹, *Ashok Regmi*¹, *John M. Anderies*^{1,2}, and *Armando A. Rodriguez*³

ABSTRACT. Change in freshwater availability is arguably one of the most pressing issues associated with global change. Agriculture, which uses roughly 70% of the total global freshwater supply, figures prominently among sectors that may be adversely affected by global change. Of specific concern are small-scale agricultural systems that make up nearly 90% of all farming systems and generate 40% of agricultural output worldwide. These systems are experiencing a range of novel shocks, including increased variability in precipitation and competing demands for water and labor that challenge their capacity to maintain agricultural output. This paper employs a robustness-vulnerability trade-off framework to explore the capacity of these small-scale systems to cope with novel shocks and directed change. Motivated by the Pumpa Irrigation System in Nepal, we develop and analyze a simple model of rice-paddy irrigation and use it to demonstrate how institutional arrangements may, in becoming very well tuned to cope with specific shocks and manage particular human interactions associated with irrigated agriculture, generate vulnerabilities to novel shocks. This characterization of robustness-vulnerability trade-off relationships is then used to inform policy options to improve the capacity of small-scale irrigation systems to adapt to changes in freshwater availability.

Key Words: *adaptive capacity, agriculture, dynamic systems, food security, freshwater availability, global change, small-scale irrigation systems, mathematical model, Nepal, robustness, social-ecological systems, vulnerability*

INTRODUCTION

Climate change will affect where, when, and how much water is available for all uses (Karl et al. 2009). Irrigated agriculture, which consumes an estimated 70% of developed water supplies (Barker and Molle 2004) and produces 40% of global agricultural commodities from 17% of the global cropped area (Hall 1999) is thus likely to experience significant impacts from climate change. Given that 90% of farms worldwide are less than 2 hectares in size and support the majority of the world's poorest people (McIntyre et al. 2009), understanding the impact of climate change on small-scale irrigation systems is of critical importance. Against the backdrop of a number of challenges facing the agricultural sector, including competing demands for water, environmental effects on soil erosion and crop diversity, increased migration, and withdrawal of public expenditures

(Slater et al. 2007), this paper investigates the capacity of small-scale irrigation systems to adapt to increased variability in precipitation and freshwater availability related to climate change.

Although there are many points in a linked social-ecological system (SES) in which water users and irrigation departments may intervene to ensure effective and efficient use of water in response to these challenges (Meinzen-Dick 2007), experience suggests that interventions that are too narrowly focused are unlikely to improve performance. For example, massive investment by states throughout the world carried out from 1950 to 1980 to expand irrigation infrastructure have been unsustainable (World Bank Operations Evaluation Department 1985). Examples of failures, due to a variety of factors including poor system management and service provision and poor understanding of farmer

¹ASU School of Human Evolution and Social Change, ²School of Sustainability, ³Intelligent Embedded Systems Laboratory (IeSL), ASU Fulton School of Engineering

priorities (Ostrom 2002), include the Jamuna project in India (Ascher and Healy 1990), the Mahaweli in Sri Lanka (Jayawardene 1986), the Dez Pilot in Iran (Levine 1980) and many major projects across Asia (Bromley 1982). These experiences with high costs (\$8,000 to \$15,000 per ha) and underperformance have resulted in reduced investment in larger irrigation systems in recent years (Jones 1995). This places significant pressure on existing smaller-scale systems (Thompson 2001) to maintain the livelihoods of millions of people around the world and raises important questions related to identifying the productive limits of these systems, determining how they may become vulnerable as these limits are reached, and assessing their capacity to cope with global change. The associated policy challenge is to identify points of intervention to strengthen community-managed, small-scale irrigation systems and to organize larger systems to capture the strengths of the smaller ones. Addressing these questions and policy challenges is the focus of this paper.

Because irrigation systems are comprised of human agents along with physical infrastructure, social infrastructure (e.g. trust, reciprocity, structured relationships, etc.), institutional infrastructure (e.g. water and labor allocation rules, collective choice rules, etc.) and biophysical processes that interact in complex ways, this is not an easy task. For example, engineers and policy analysts have frequently not understood why farmers employ diverse rules across irrigation systems and switch between multiple rules depending on conditions. It has become increasingly clear that these phenomena are often a response to uncertainty and complex biophysical dynamics. A well-known example is Bali where efforts by engineers to change indigenous irrigation rules revealed that they solved a variety of problems (Lansing 1991). There are many other examples of systems that have endured for centuries (Baker 2005). Even today, numerous small-scale, community managed irrigation systems including in the Zanjera societies of the Philippines and indigenous systems of Northern Thailand, China, Laos, Japan, India, and Nepal serve a third or more of the total irrigated area in Asia (Barker and Molle 2004). This proportion stands at 75% in Nepal (NENCID 2007). Not only have these systems proven sustainable, they distribute water more equitably, maintain their infrastructure better, and produce higher yields than larger state funded irrigation systems with better infrastructure (Regmi 2008).

Although such studies that rely on observation of past system performance help us understand how systems may have responded to past disturbances and changes over time, their potential to address our questions regarding how small-scale irrigation systems might cope with novel shocks and unknown change in the future is limited. To address these questions, we develop a mathematical model based on observations and data from an actual historical system. The model is used to analyze the performance of different water allocation rules as environmental conditions vary and as the system experiences exogenous shocks. Our analysis suggests that in systems such as the Pampa, institutional arrangements are strongly conditioned by, and finely tuned to, the efficient functioning of physical infrastructure and allocation of labor to enable precise water delivery. The system is very robust in the sense that yields can be maintained in the face of environmental variation and shocks to infrastructure, though only up to a certain point. The price for this robustness, however, is increased vulnerability in the sense that yields might fall rapidly due to changes in technology and physical infrastructure. The failure of past efforts to boost performance by improving physical infrastructure is consistent with our analysis.

Further, our work suggests that the biophysical context may limit the general adaptive capacity of small-scale irrigation systems. In such cases, institutions may become highly optimized to coordinate activities to manage the tight coupling between the environment (timing of rain, river flows, and the agroecology of rice) and physical infrastructure (constraints on flow rates and distribution of water). At the same time, the dominance of practical constraints may reduce the challenges irrigators face regarding cooperation and collective choice. The benefits of cooperation are substantial and clear; cheating is difficult because of the spatial structure of the system and organization of activities, and conflict is reduced by pragmatic rules that dictate resource distribution in times of scarcity. Thus, institutions that support cooperation, collective choice, and conflict resolution may be underdeveloped in some irrigation systems. Again, our work is consistent with the observation that recent emphasis on decentralization of efforts by central governments to improve performance of irrigation systems also often fail; the types of institutions required to manage new resources and information coming into the system are simply not well developed. The detailed analysis

of the relationship between system performance and robustness–vulnerability trade-offs presented here contributes to the ongoing development of tools to help tailor policies to the local social and biophysical context and to move beyond policy panaceas (Ostrom et al. 2007).

APPROACH

In order to connect the Pampa case study and formal model, we employ the framework developed by Anderies et al. (2004) (Figure 1A) which highlights relationships between groups of actors and the biophysical context. Ovals indicate the social components of the system and the boxes represent physical and constructed portions of the system, which may be a combination of physical entities and institutional arrangements. Black arrows indicate relationships between these components, while red arrows indicate potential shocks to the system. Figure 1B shows a specific instance of a general SES shown in Figure 1A for an irrigation system.

The main resources in irrigation systems are soil and water. They generate direct benefits in securing food supply and income for irrigators and indirect local benefits by creating demand for supply services such as fertilizers, seeds, pesticides, and transport. The shocks that have a significant impact on the resource (red arrow, type 7, in Fig.1) are strongly related to climate change. Less predictable and more extreme variation in temperature and water availability make planning farm operations more difficult, increase the chance of crop failures and will likely threaten food security for the world's most vulnerable people. Public infrastructure in irrigation systems includes the canal system itself and flow control features. Less obvious, but equally important, is the institutional infrastructure, that is, for example, the rules that govern the use of the canal system and collective choice, and social infrastructure, that is, trust, reciprocity and power relationships, among others. The operation of this component of the system depends on the interaction of several contextual variables including political and economic conditions and climatic shocks, such as floods.

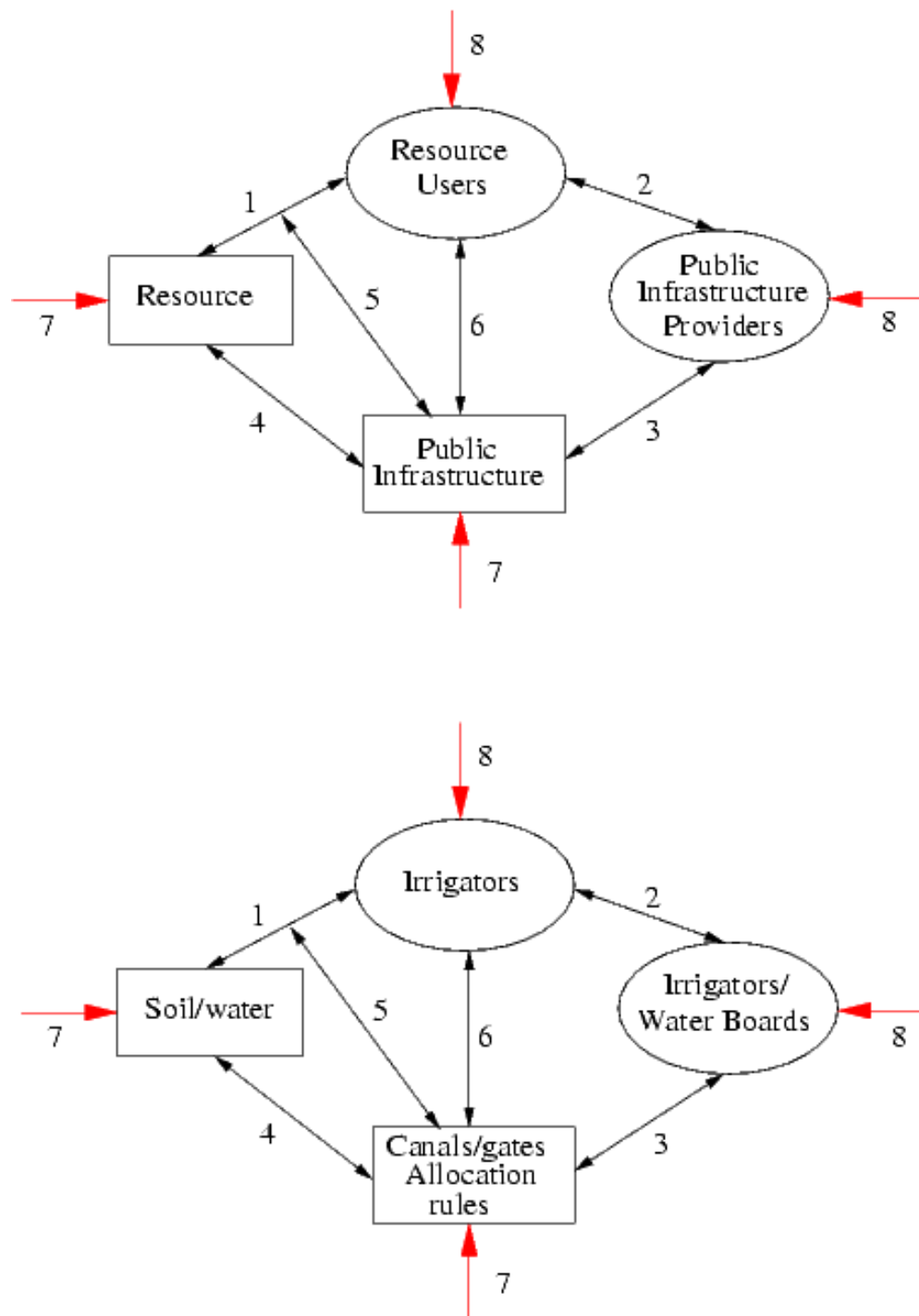
Resource users consist mainly of the irrigators themselves and their families. They are subject to a wide range of potential shocks (red arrow, type 8, in Fig.1). Industrialization, urbanization, growing populations, and environmental concerns all exert

pressure on irrigators. As multiple sectors in a rapidly expanding economy compete for scarce water, the logic of water pricing can change. Given agriculture's declining contribution to the national GDP, its consumption of 70-80% of freshwater might be increasingly difficult to justify as is the case in many South East Asian countries. A shift in agricultural labor to other sectors of the economy can also generate stress on the operation of small-scale irrigation systems.

In many small-scale irrigation systems, the resource users and public infrastructure providers are one and the same. In this case, the provision of public infrastructure, including physical, social, and institutional infrastructure, is subject to many of the same stresses that impact users. Time pressures and changing economic circumstances may reduce the willingness of irrigators to devote effort to governance activities. The extent to which public infrastructure is provided by actors other than resource users strongly influences the types of shocks the system might face. For example, political disruptions can occur through the introduction of new policies by the state. Unwillingness to recognize the legal standing of water user associations, for instance, can hinder associations in their attempts to organize. Similarly, a financial retreat by government in supporting maintenance activities can also impact infrastructure quality and, therefore, water delivery. Disruptions also occur when irrigation is politicized. Examples include the refusal of politicians to support the institution of water charges to reduce farmer costs in an effort to win rural votes, and situations when support for rehabilitation of irrigation projects is based on political influence.

Just as important to the operation and robustness of irrigation SESs as the fundamental components just described, and perhaps more so, are the feedbacks between them (links 1-6 in Fig.1). If the basic components and links are static, comparative analysis of multiple systems can provide considerable insight into how they work (Downing 1974, Meinzein-Dick 1984, Martin 1986) and identify some conditions for success (Yoder 1986, Wade 1994, Lam 1998, Dayton-Johnson 2000, Fujii et al. 2005). Unfortunately, as these feedbacks develop both in response to basic operational needs that require links between the basic components and in response to exogenous shocks, they may induce directional endogenous change in the nature of the basic components and the links themselves

Fig. 1. (A): General robustness framework (adapted from Anderies et al. 2004). (B): Specific instance of the framework for an irrigation system. The numbers on the arrows are used for reference- see text for further details.



(Anderies et al. 2007, Janssen and Anderies 2007, Janssen et al. 2007). Understanding the effect of these adaptive, endogenous dynamics on a system's capacity to cope with a changing context and new classes of disturbances is the focus of the robustness–vulnerability trade-off analysis conducted here.

Using a fleshed out version of the skeleton in Figure 1B based on the details of the Pampa system, we develop a model that captures the basic relationships among human actions, soil, water, and yield (link 1 in Fig.1) and how they are mediated by physical infrastructure, such as, timing, amounts of water flows and labor (link 5 in Fig.1). Our model falls between simple models aimed at theory development (e.g. Gordon 1954, Clark 1990) and detailed models which, in the case of irrigation systems, focus on engineering issues such as controller design (Clemmens et al. 1994, Malaterre et al. 1998, Schuurmans et al. 1999, Gómez et al. 2002, Malaterre and Khamash 2003, Litrico and Fromion 2005, Miranda et al. 2005, Litrico and Fromion 2006, Ooi and Weyer 2008), modeling and GIS for management support (Clemmens et al. 1998, Bautista and Clemmens 1999, Fortes et al. 2005, Khadra and Lamaddalena 2006, Popova et al. 2006), performance assessment (Wahlin and Clemmens 2002, Shahrokhnia and Javan 2005), or the application of systems approaches to irrigation in general (Mareels et al. 2003, 2005). We use the model to explore how spatial and temporal structuring of interactions between irrigators forced by physical infrastructure (link 6 in Fig.1) conditions the relationship between resources and irrigators (link 1 in Fig.1) and, in turn, impacts institutional infrastructure (link 5 in Fig.1). By analyzing several different institutional regimes associated with shocks to the resource and infrastructure, we explore how the system, especially links 1, 5, and 6 and the components they connect, may become well-adapted to these shocks (type 7). Finally, we use the framework to explore the implications of this particular adaption for the link between public infrastructure providers, such as government agencies, and the rest of the system (links 2 and 3 in Fig.1) and the capacity of the system as a whole to cope with novel change.

We recognize that our analysis is necessarily limited. We do not model numerous informal social processes that add flexibility to the system. This is due to practical limitations of our capacity to extract meaningful insights as model complexity increases.

We do, however, discuss how such unmodeled social processes may relate to our results. Finally, it is important to note that we are not developing a model to fit data from the Pampa case. Rather, our model is motivated by, and captures only, the key features of the Pampa case. We use the model to: (1) compare the performance of different institutional arrangements for water allocation given water needs during different growing stages and given different scenarios of water availability in the system, and (2) compare these institutional arrangements to those that the farmers actually follow in these scenarios.

THE BIOPHYSICAL AND INSTITUTIONAL CONTEXT

Information regarding the biophysical and institutional context is based on a six-week field study of farmer managed irrigation systems in Eastern Chitwan undertaken by A. Regmi in 2003 and the Nepal Irrigation Institution and Systems (NIIS) database maintained by the Workshop in Political Theory and Policy Analysis at Indiana University. The Pampa is one of 125 farmer managed irrigation systems (FMIS) located in Chitwan, one of 75 districts in Nepal. The economy of Chitwan, 150 km south of Kathmandu and covering 2218 square kilometers, is predominantly agricultural and engages 75% of the economically active population. Prior to 1950, Chitwan valley was covered with dense forest growth and was infested with malaria. Only indigenous inhabitants who had acquired some immunity to malaria lived in the valley. Only after the eradication of malaria did the population begin to multiply, increasing from 36,000 in 1950 to a little over half a million in 2006. Irrigation systems that are 50 years or older are, therefore, associated with the indigenous Tharu and Darai communities and the newer ones with the migrant “Pahadia” (people from the hills) communities. Pampa is a relatively new irrigation system that was initiated by migrant communities in 1968.

Among many possible characteristics of irrigation systems, two particularly important ones in Chitwan impose distinct biophysical constraints and management structure: the direction of flow of the rivers they utilize (north-south or east-west) and whether they are agency or farmer managed irrigation system (AMIS or FMIS). The Pampa river flows north-south and the associated irrigation

system, located on the foothills of the Mahabharata mountain range, is farmer managed. Systems of this type are characterized by steep gradients, seasonal flows, changing river courses, low discharge volumes, longer idle canal lengths, narrow cross sections, landslide zones and frequent flash floods. Unlike AMIS that are designed, constructed, and operated by government agencies with command areas greater than 4000 hectares, FMIS are constructed, operated, and maintained entirely through the resources and efforts of resource users, and typically service command areas of less than 150 hectares. The Pumpa is located in Birendranagar village and serves 140 households who own 70 hectares of agricultural land. Seventy-five percent of households own between 0.33-0.67 hectares of land and landholdings range from 0.2-3 hectares. Nearly 90% of the households are owner operators and the remainder are sharecroppers.

To divert water to cultivated areas, systems make use of headworks, canals, and water allocation devices. The headwork consists of a diversion structure, an intake canal, and a control gate. At Pumpa, the diversion is a gabion stone structure interspersed with brushwood (Figure 2A); the intake canal is a concrete structure, and the control gate is a stone and cement structure with a head regulator made of wood (Figure 2B). There are four major branches in the canal system. The main canal A, defined as the longest canal in the system, is 3500 m long and the three branches B, C and D are 500, 1000, and 1000 meters long, respectively (Figure 3). To minimize seepage and conveyance losses, about 2000 meters of the main canal is cement lined. The rest are earthen canals. Check gates and water division boxes are also placed at strategic points in the canals to help manage water distribution. Other physical infrastructure includes cross drainage, overpass structures, and retaining walls which help maintain the integrity of the canals by helping prevent soil erosion and landslides (Figure 2C).

The command area is divided into six sectors, each covering approximately 12 hectares (Figure 3) and each with equal rights to the available water. Since the Pumpa is a seasonal river, dry season flows are greatly reduced and the system can access adequate water only for nine months of the year.

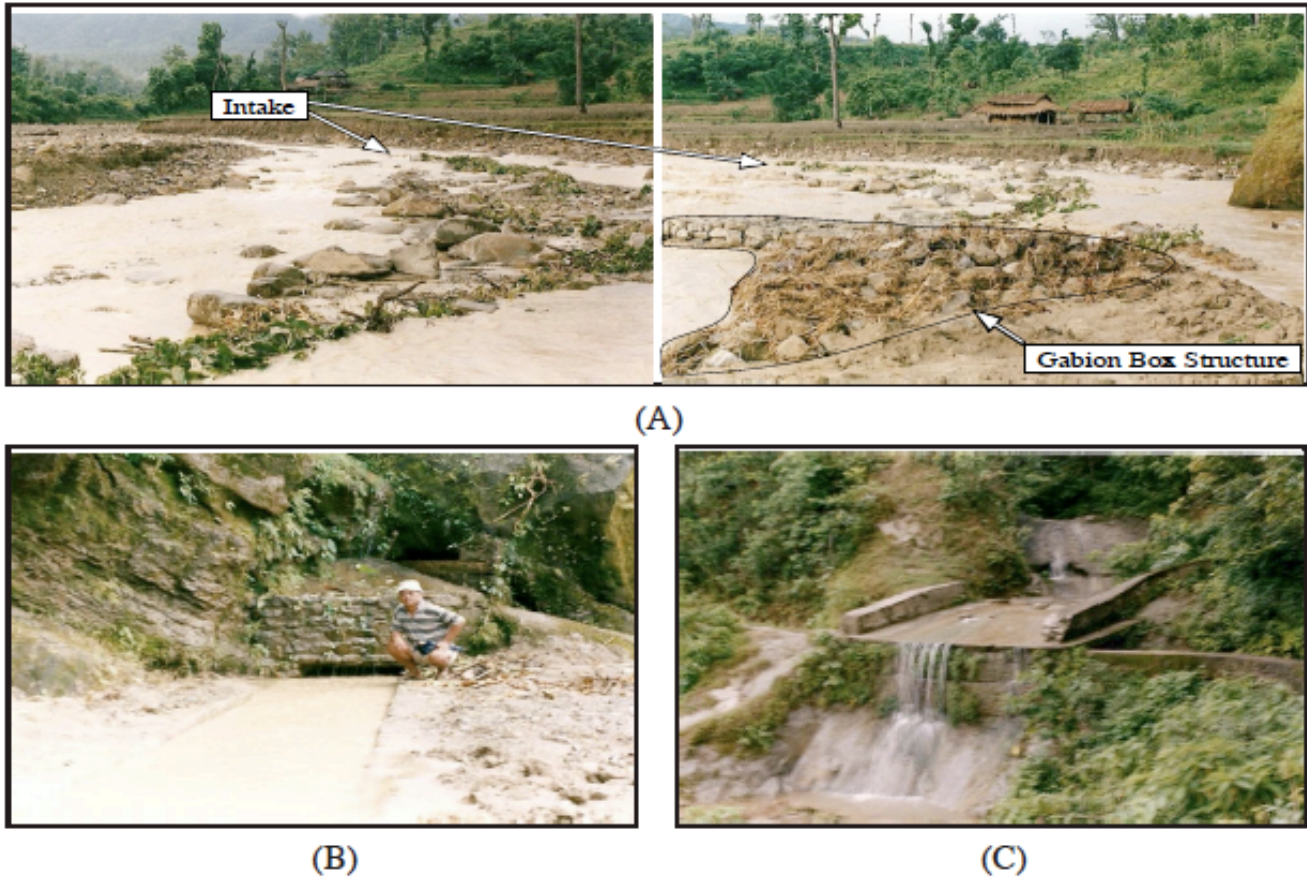
Paddy cultivation and water demand

The two most important crops in Chitwan are paddy rice and maize. Areas that have access to year-round irrigation cultivate three crops: spring paddy rice, monsoon paddy rice and one winter crop (maize/wheat/mustard or lentil), while water deficit systems such as Pumpa cultivate two: monsoon paddy rice and either maize or wheat in winter. We focus on monsoon paddy as it is the most important crop. The beginning of the cropping calendar for monsoon paddy falls between May 15 and June 23. The cropping cycle for paddy is usually 4-5 months and ends with harvesting by October.

The process of paddy cultivation begins by preparing a nursery seed bed 5-10% of the size of the area that will be planted. The soil is repeatedly pulverized by dry ploughing, after which the nursery plot is flooded and puddled for a few days and allowed to set with a thin layer of water before sowing the seeds. Seeds are sown sometime between May 15 and June 23 and become ready for transplantation about a month later when they have four to five leaves. The standing water requirement during this period is on average 20 mm (Figure 4).

Preparation of the fields requires three to four weeks for flooding, ploughing, puddling, and leveling the soil before rice can be transplanted. This process requires about 200 mm of standing water. After the seedlings are transplanted, the standing water level is maintained at 100 mm. During the latter part of the vegetative stage, the water level is reduced to 20-50 mm and then increased again during the mid season stage. This entire cultivation process thus comprises four stages: nursery, vegetative, mid season (reproductive stage), and late season (ripening stage). The most sensitive and least sensitive stages to water shortages are the mid season and late season, respectively. During the month-long mid season, stem elongation and flowering occurs. If the plant does not receive adequate water during this stage, it affects rice yields significantly. During the late season when rice is reaching maturity, its water needs are at a minimum and water is actually cut off to the fields 10-15 days before the harvest. Water demand for paddy cultivation is summarized in Figure 4.

Fig. 2. Pumpa irrigation infrastructure. (A): Canal intake showing gabion block structure. Arrows showing intake indicate common reference point in the photos. (B): diverted water entering concrete intake and flow control gate. (C): Example of overpass structures and retaining walls.



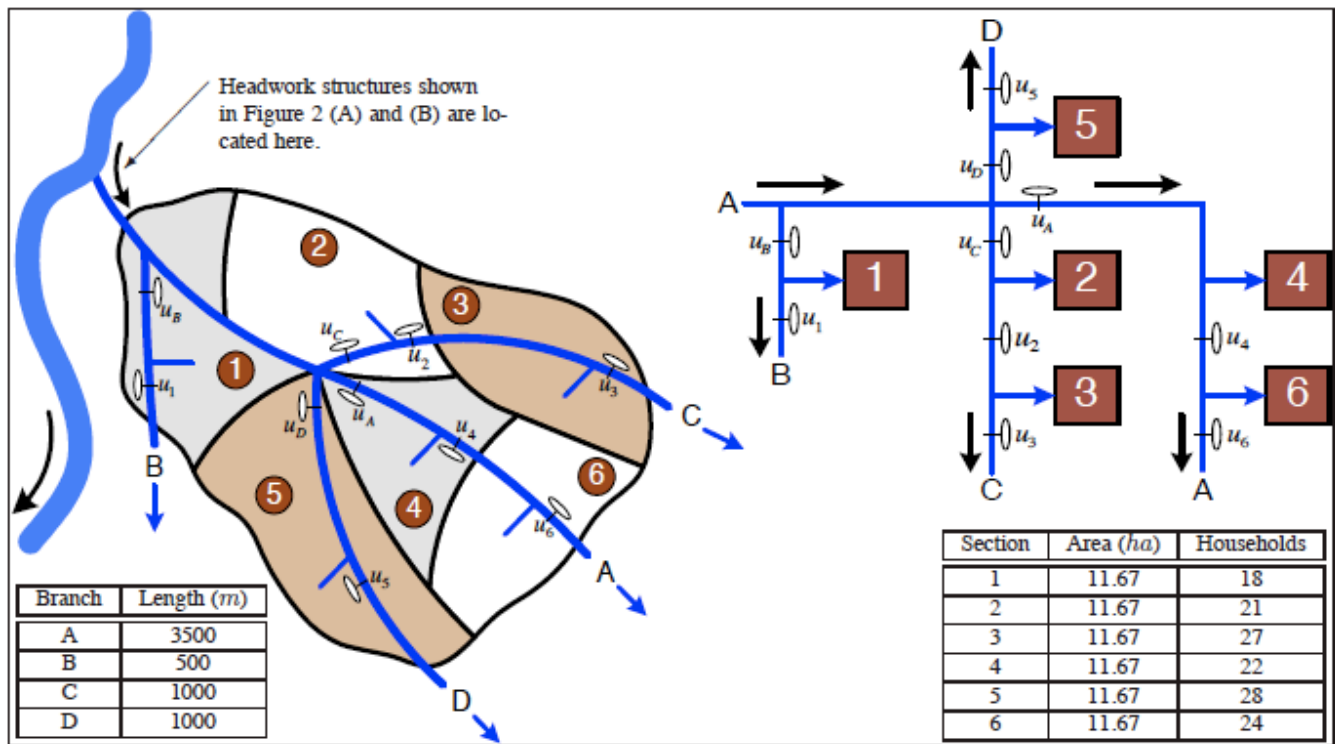
The river regime and water supply

Paddy cultivation activities are closely timed with the monsoon cycle. June through August are the monsoon months during which time the area receives most of its annual rainfall. Available water in the river closely follows the rainfall with about a one-month lag. Mean monthly discharge ranges from 0.75 m³/s in the driest month of April to 15.44 m³/s in the wettest month of August and can vary widely from year to year (the maximum and minimum recorded discharge in April and August in the Pumpa are 0.2 m³/s and 35 m³/s, respectively (Nippon Koei Company Ltd. 1986). Figure 4A shows the river flow regime and rainfall (water supply) overlain on the demand profile shown in Figure 4B.

Water allocation and distribution rules

There are at least six irrigation systems drawing water from the Pumpa. The intake points of three of these systems are in close proximity. The intake of the Jiudi/Chipteti system is located 1 km upstream of Pumpa and the Kyampa system is located 30 m downstream. The general rules governing water diversion stipulate that upstream irrigators have prior use rights over downstream irrigators and they can divert as much water as they need as long as permanent concrete diversion structures are not used. Allocation of water within a system reflects entitlements. The principle on which water is shared is decided by the irrigator community and can take a number of forms. The most common principle in practice in Chitwan, followed by Pumpa, is dividing

Fig. 3. Pumpa irrigation command area: schematic (left), block diagram (right).



water in proportion to the land owned by the farmer. When water is plentiful, it is distributed on a continuous flow basis. During periods of scarcity, there are two distinct allocation schemes: one for the transplantation phase and one for the mid season. During scarce periods in the transplantation phase, water is supplied sequentially to the sectors: all of the flow is diverted to sector 1, then to sector 2, and so on. Within sectors, water is supplied on a timed rotation from head to tail. During the mid season, Pumpa recognizes two levels of scarcity: moderate and severe. Under moderate scarcity, each sector is supplied water only for 12 hours, which translates into taking turns to irrigate every three days. However, when water is extremely scarce, each sector receives water for 24 hours every seventh day.

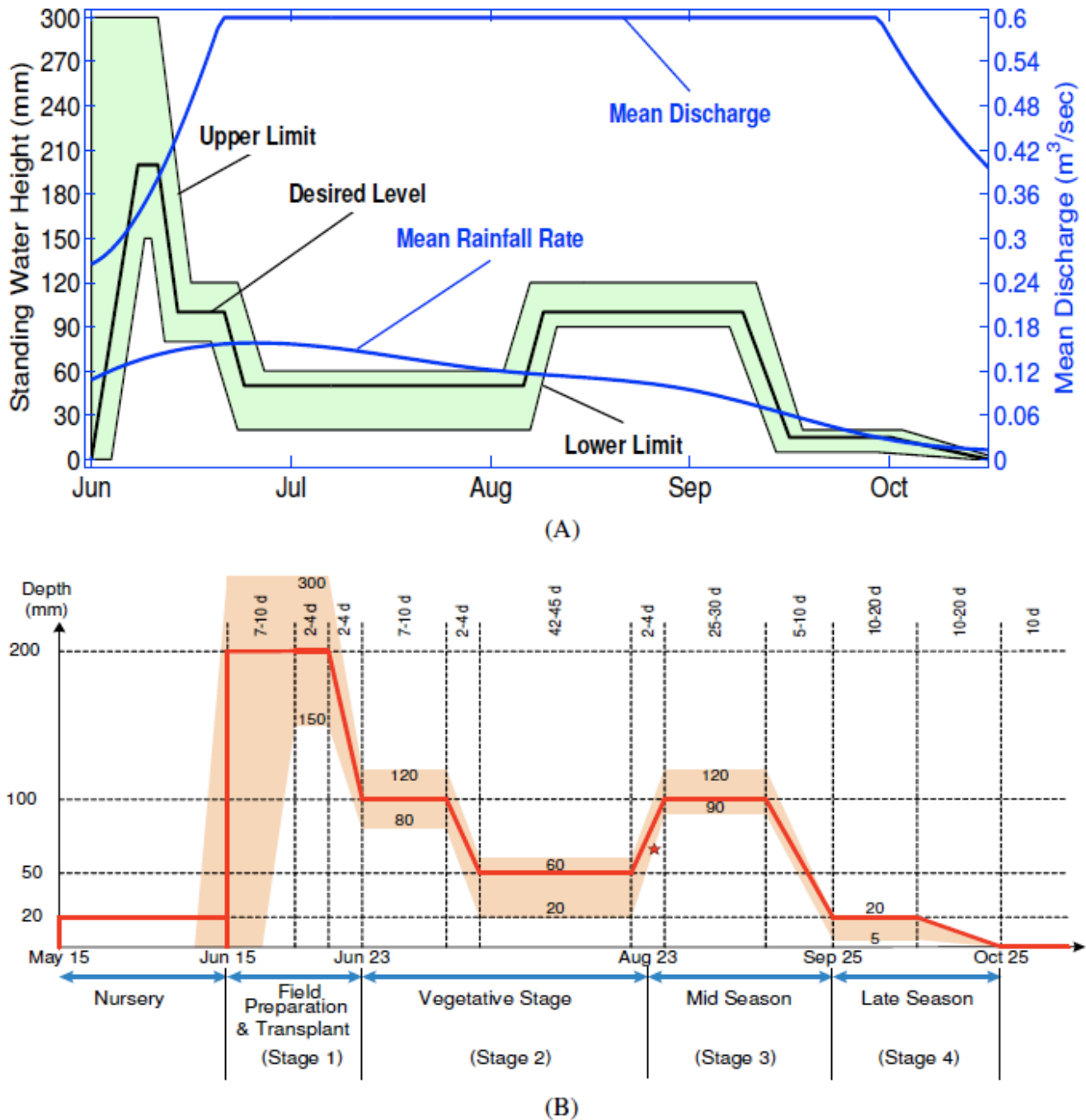
Water supply procedures adopted by the farmers are simple to understand and operate. All gates except for the sector that is being supplied are closed. The sector leader then draws up time schedules to coordinate water supply. For example, during

extreme scarcity after sector 1 receives its 24-hour supply, it is divided among 18 households on a 2 hour/hectare basis. After 24 hours, all check gates except those supplying the next sector, sector 2, are closed and so on. Farmers irrigate their fields during their scheduled time slots. Given the complete characterization of the system, we now turn to the development of the formal model.

THE FORMAL MODEL

The formal model consists of basic representations for water flows in the canals, the hydrological dynamics of water on fields, the connection between institutional arrangements and flow rates in canals, and the relationship between yield and water levels in each sector. Because of the relatively small scale of the irrigation system, we need not employ a full representation of fluid dynamics in open canals, such as the St. Venant equations with energy considerations, and simply employ mass balance

Fig. 4. (A): Water supply (river regime and rainfall) and (B): desired water level (i.e. demand). Data used to construct figures based on Department of Hydrology and Meterology, Nepal (2002) (rainfall), Nippon Koei Company, Ltd (1986) (riverflow), Brouwer and Heibloem (1986) (water requirements for paddy rice), and Shukla et al. (1993) (paddy planting cycle in Chitwan).



relationships. The most challenging component of the model is capturing the relationship between yields and water depth over time. We turn now to the description of each component of the model.

Hydrological dynamics

Because rice paddy yields correlate strongly with surface water depth at time t , we neglect other factors such as soil moisture and groundwater issues. In this case, the model reduces to a volume balance of surface water. This enables the surface water level to be modeled by first order differential equations given by:

$$dy_n/dt=(U_n-\phi_n y_n)/A_n \quad (1)$$

where $n \in \{1,2,..,6\}$ represents the sector number, y_n represents the standing water height (m) in sector n , U_n represents the combination of check gates (i.e. $U_1=u_B-u_1$) and the amount of water used per time (m^3/s) to irrigate a section, A_n represents the area of a sector (m^2), and the coefficient ϕ_n represents evapotranspiration/leakage/seepage (m^2/s) which, in general, can be time dependent. Given the size of the command area, this coefficient will be assumed equal for all sectors and represented by ϕ .

Irrigation network topology

The sectors are essentially nodes in a flow network linked by the check gates and canals. Linking the depth equations for individual sectors (Eq. 1) based on the physical configuration of gates shown in Figure 3 (block diagram) yields a system or network of differential equations:

$$dy_1/dt=(u_B-u_1-\phi y_1)/A_1 \quad (\text{Eq.1})$$

$$dy_2/dt=(u_C-u_2-\phi y_2)/A_2 \quad (\text{Eq.2})$$

$$dy_3/dt=(u_2-u_3-\phi y_3)/A_3 \quad (\text{Eq.3})$$

$$dy_4/dt=(u_A-u_4-\phi y_4)/A_4 \quad (\text{Eq.4})$$

$$dy_5/dt=(u_D-u_5-\phi y_5)/A_5 \quad (\text{Eq.5})$$

$$dy_6/dt=(u_4-u_6-\phi y_6)/A_6 \quad (\text{Eq.6})$$

where $u_A,..,D$ represent water flow rates through the check points as labeled in Figure 3 (block diagram). Note that the physical structure of the irrigation network is reflected in the nature of the coupling in the equations provided (e.g. the flow into sector 2 depends on the flow in the canal controlled by gate u_C and the flow through the sector 2 control gate u_2) and by the fact that flow rates must satisfy mass balance constraints and maximum flows permitted by each gate (comparing the equations with the block diagram in Figure 3 will reveal that they are just accounting rules for water entering and leaving each node):

$$\begin{aligned} 0 \leq u_A \leq w-(u_B+u_C+u_D), & \quad 0 \leq u_1 \leq u_B, \quad 0 \leq u_4 \leq u_A \\ 0 \leq u_B \leq w, & \quad 0 \leq u_2 \leq u_C, \quad 0 \leq u_C \leq w-(u_A+u_C+u_D) \\ 0 \leq u_5 \leq u_D, & \quad 0 \leq u_3 \leq u_C-u_2, \quad 0 \leq u_6 \leq u_A-u_4 \\ 0 \leq u_D \leq w-(u_A+u_B+u_C). & \end{aligned}$$

Institutional structure and policy implementation

The institutional characteristics of the system play out in the values of u_n and $u_A,..,D$. For the open flow regime, $u_A,..,D$ are always open and irrigators open u_n without restriction and all gates may be open at the same time. For policies other than open flow, the sector-gate relationships are shown in Table 1. The social interactions among farmers, conditioned by their irrigation institutions, determine the order of the opening and closing of these gate combinations which, in turn, determines the performance of the system. Based on river discharge, the water users committee determines how water is released from the main canal to the branch canals following the set of general rules described in the Biophysical and Institutional Context section, "Water allocation and distribution rules" sub-section. The resulting policy dictates gate activity and thus determines water flow into the Pumpa command area. Our final task lies in defining a performance measure for the system.

Table 1. Relationships between gate openings and sectors receiving water.

Irrigated Sector	Open Gates	Irrigated Sector	Open Gates	Irrigated Sector	Open Gates
1	u_B and u_1	2	u_C and u_2	3	u_C and u_3
4	u_A and u_4	5	u_D and u_5	6	u_A and u_6

Water dynamics and agricultural yield

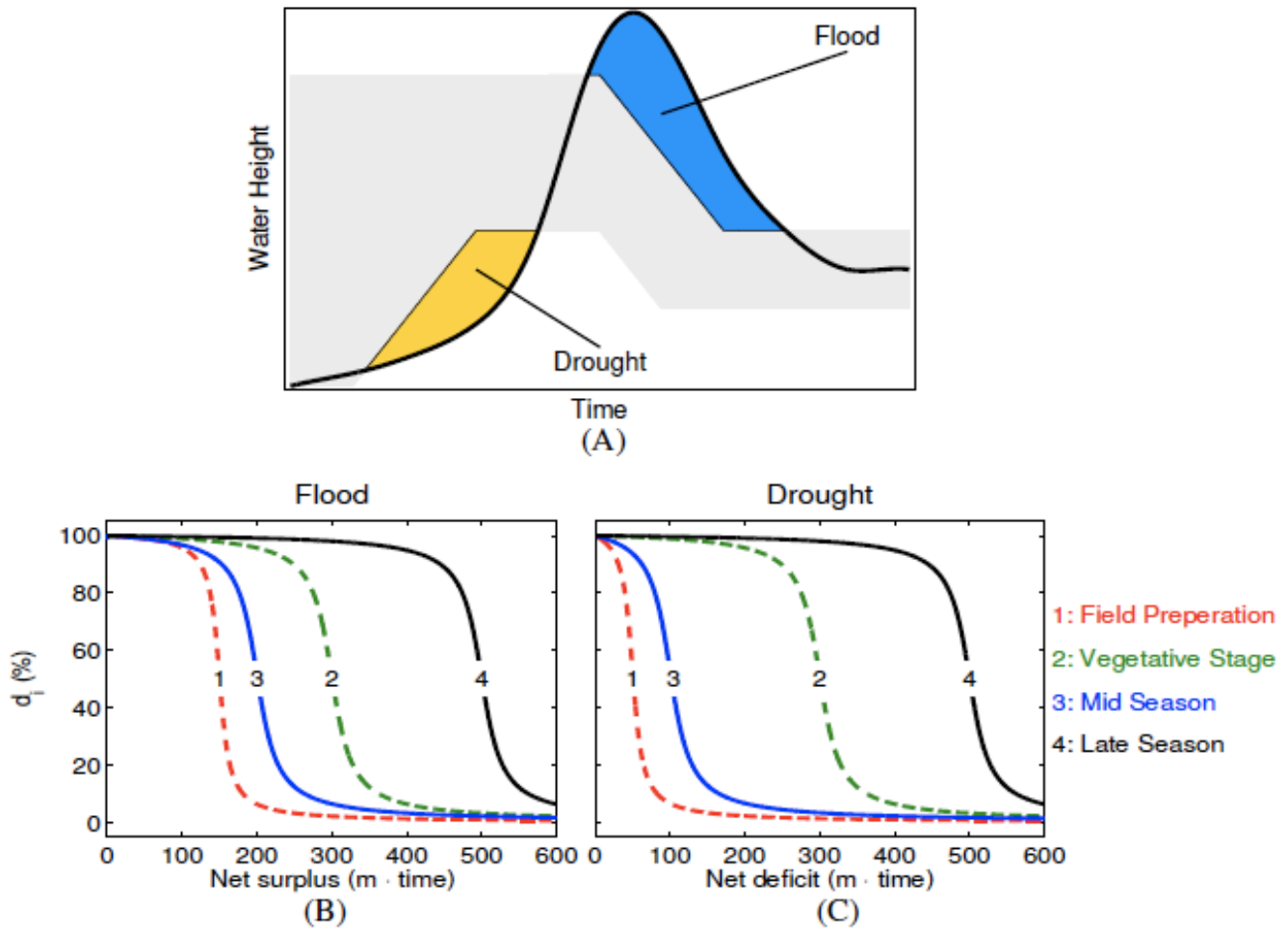
The performance of irrigation systems obviously depends on many factors. Given our focus on water, we base our performance measure on a 100% yield concept. We hold all other conditions, which are beyond the scope of this paper, constant and define a 100% yield for sufficient water. By sufficient water, we mean that the water level remains within the bounds shown in Figure 4. The impact of a drought or flooding on the monsoon paddy yield differs depending on the stage of the growth cycle. When drought or flood conditions occur, it may not be possible to keep the water level within the desirable band needed for a crop shown in Figure 4. When this occurs, the actual water level will fall outside the desired band as shown in Figure 5A. The longer the drought or flood, the longer the actual water level will remain outside the band. We compute the cumulative water stress as the area between the actual and the desired water height (yellow and blue areas in Figure 5A). The yields are then penalized depending on the cumulative water stress using the functions in Figures 5B and 5C. The shapes of these functions are based on field data gathered from personal interviews with the chairman of the Pumpa water users committee, Mr. Prem P. Kharel, and many farmers in that area who were asked questions of the nature: “How much water do you require during each stage? If you receive only 75% of your need in this stage, then how will it affect the crop/yield? If you receive only 50%, then?” The impact on the yield due to reduced water is based on the estimates provided by Mr. Kharel.

The functions shown in Figures 5B-C are used to obtain two numbers which quantify the performance for each stage: $0 \leq d_{if} \leq 1$ for the flooding effect (area

of blue region), and $0 \leq d_{id} \leq 1$ for the drought effect (area of yellow region). The shape of the functions depends on the biophysical considerations for each stage. Field preparation and mid season stages are relatively more critical than the vegetative stage and the late season. One main reason for this is the fact that during field transplantation and mid season, standing water heights must be increased. This is especially true for the field preparation and transplantation stage during which time this increase is very large (see Figure 4). These considerations underlie the shape of the functions in Figures 5B-C.

Because the field preparation stage is most vulnerable, function 1 has been constructed so that its value drops quickly, in this case even more quickly when there is a drought. Alternatively, the late season is very robust to water deficiencies or floods. Hence, function 4 has been constructed so that its value does not drop as quickly until the flood or drought becomes very intense. The yield percentage for the i^{th} stage, d_i , is simply their product, i.e., $d_i = d_{if} d_{id}$. For example, suppose the yellow area and blue area for stage 1 are 50 and 150, respectively. From Figure 5C we see that $d_{1d} \approx 0.5$ and from Figure 5B we see that $d_{1f} \approx 0.5$ thus $d_1 = d_{1f} d_{1d} \approx 0.5 \cdot 0.5 = 0.25$. The overall efficiency of the irrigation system, d , is the product of the efficiencies of all four stages: $d = d_1 d_2 d_3 d_4$. This multiplicative structure captures a key aspect of crop dynamics: history matters. Not only do farmers need the correct volume of water, they need it at specific points in time. Thus, problems during any stage carry through subsequent phases. Finally, the actual yield with respect to the foreseen maximum yield, Y_{max} is simply $Y = Y_{max} d$.

Fig. 5. (A): Illustration of computation of cumulative drought (yellow area) and flood (blue area) events. (B-C): Performance measure coefficient functions for floods (B) and droughts (C).



ANALYSIS

Given our interest in how physical and social infrastructure influence the capacity of small social–ecological systems to cope with variability and change, our analysis concentrates on the sensitivity of yield to water scarcity. Figure 4 makes it clear that water supply far exceeds demand in all but the field preparation and transplantation stage, and analysis of the model confirms it. We thus concentrate on this stage given that it offers the greatest potential for conflict between supply and demand. There is one interesting exception in stage

three as we shall see. Sensitivity, in our case, is a measure of how much yield decreases when water availability deviates from nominal conditions. By nominal conditions, we mean that the water availability (i.e. the mean discharge of the Pampa River) is as expected, i.e., conforms to that shown in Figure 4. Our analysis focuses on four related questions:

1. Do farmers actually choose efficient institutional arrangements given the conditions they face?

2. How sensitive is yield to variations in rain and river flow regimes given what farmers actually do - i.e., under institutional arrangements actually in use?
3. To what extent can farmers increase robustness, i.e., reduce the sensitivity, of their system to variations in rain and river flow regimes by adopting alternative institutional arrangements?
4. What new vulnerabilities may arise as a result of efforts by farmers to increase robustness, i.e., reduce the sensitivity, of their system to variations in rain and river flow regimes?

We explore these questions in the context of three different potential shocks to the system related to climate change: reduced discharge in the rivers (we ignore the case when there is increased discharge because the Pampa command area is not vulnerable to flooding, since the main diversion gate can be closed), shifts in the seasonal nature of river flows and rainfall (i.e. the monsoon season arrives late), and shocks to water diversion infrastructure during the mid season. For each, we examine the performance of four water allocation regimes observed in the field: open flow, sequential, 12-hour rotation, and 24-hour rotation.

Under nominal conditions, the free, open flow policy is applied. In the open flow regime, all gates are open and water flows freely to all sectors, such that farmers can take water whenever they wish. Given that the sectors are of equal areas, each will have the same irrigation profiles under this policy. Likewise, under the sequential regime, water is delivered to sectors 1 through 6 in order. In its turn, sector 1 receives water until its needs are met, at which point water is diverted to sector 2, and so on. Under the rotation regimes, in its turn, sector 1 takes water for 12 or 24 hours and then water is diverted to sector 2 for 12 or 24 hours, and so on. We present a detailed analysis of each of these four policies for each of the three shock types.

Variation in river discharge

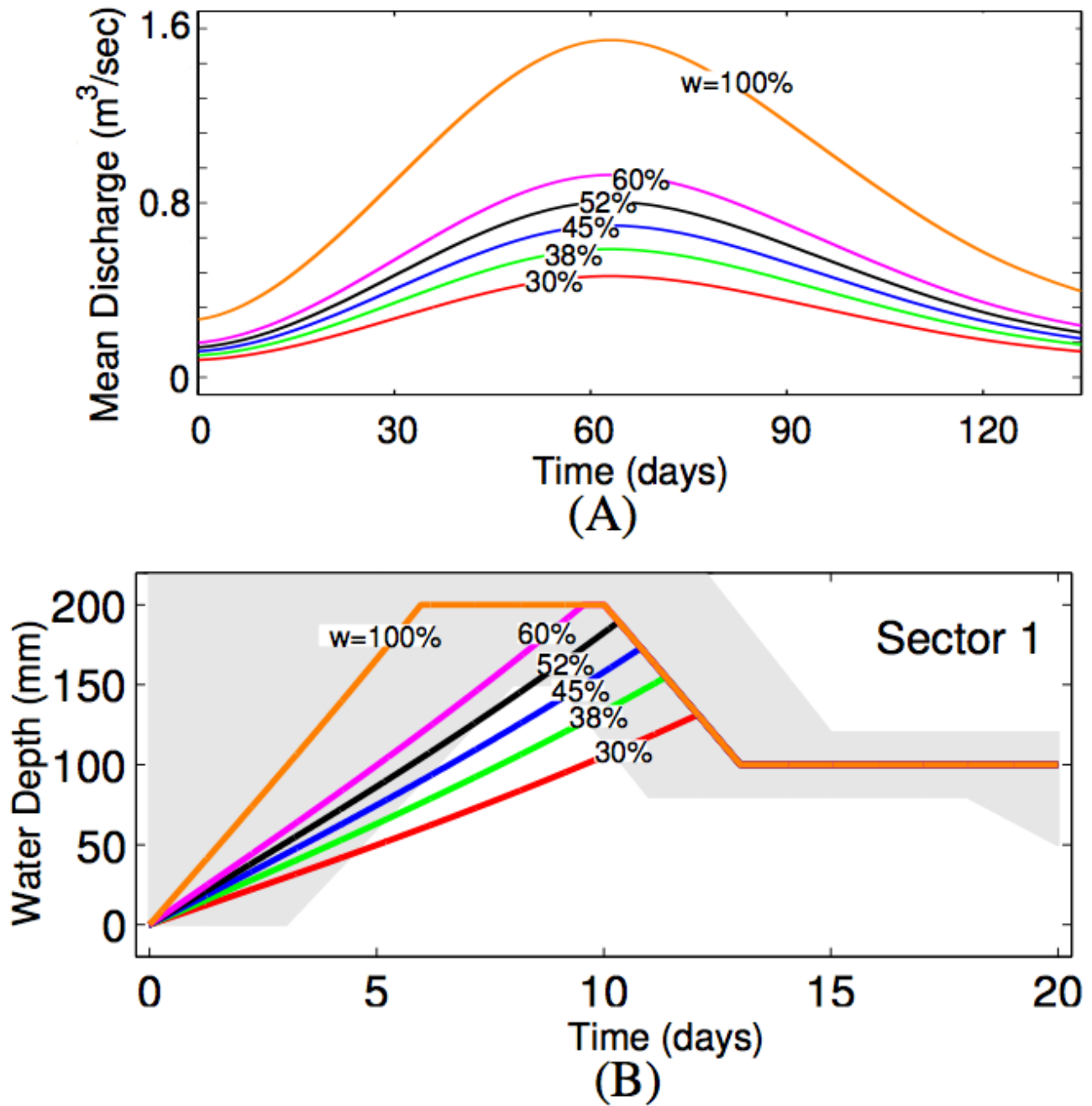
One of the key issues potentially faced by small farmers in many areas of the world is reduced mean rainfall during monsoons, resulting in lower river

flows. Several such scenarios are shown in Figure 6A. The top curve labeled "100%" represents the existing situation, our nominal case. The curves below it represent scenarios with the same temporal signature but with a percentage of the nominal flow as labeled. Figure 6B shows the resulting color-coordinated depth profile in the rice paddy during stage 1 (see Figure 4B). In the open flow scenario, all sectors are identical so we only show Sector 1. As the mean flow decreases, the rate at which fields can be filled (slope of lines in Figure 6B) decreases. At some point, the water level falls outside the acceptable band (gray shaded area), which in this case occurs when the mean river flow is less than 52% of nominal. Beyond this point, yield deteriorates rapidly.

The main limitation is flow rate. When the flow rate is too low, the time required to achieve the required water depth is greater than that necessary to remain in the acceptable band. Referring back to Figure 1B, reduced flow rate in the river is a shock to the resource in terms of increased water scarcity. The key challenge faced by irrigators is how to distribute this scarcity as, except under extremely rare conditions, at least some farmers would be able to grow a full crop. Two possible responses to such scarcity are altering the resource characteristics or utilizing infrastructure. An example of the former might be to plant a different crop, which is not really an option in rice paddy irrigation. Farmers, left with infrastructure as their only tool to respond, have a choice between using physical infrastructure, that is, changing the dynamics of water movement in the system, or social infrastructure, i.e., institutions enabling exchange of resources.

There are two basic mechanisms by which infrastructure can ensure that farmers remain in the acceptable water depth band. One approach would require every farmer to reduce their cultivated area proportionately to the reduced flow rate. Thus, if the river flow is 50% of nominal, each farmer would simply reduce their land under cultivation by 50%. Although this approach evenly distributes scarcity among the farmers, it would require that each farmer build additional dikes, at considerable cost in terms of effort, within their fields to reduce the area to be filled with water; farmers cannot simply decide to cultivate less rice paddy as doing so requires investment in infrastructure. A second approach is to increase the flow rate in the canal system by reducing the total canal area in use at any point in time. All of the rotational schemes that open only a

Fig. 6. (A): River discharge volume scenarios. (B): Associated irrigation water supply profiles (color coded) superimposed on desired supply level range (gray shaded area).



small proportion of the canal system at any given time accomplish just this. Figure 7A illustrates the performance of the sequential rotation scheme. The first thing to note is that yield in Sectors 1 and 2 is completely insensitive to up to a 70% reduction of nominal flow, while such a reduction under the open flow regime would result in zero yield in all sectors (Figure 8B). Thus, institutional arrangements for water distribution can increase the robustness of the system to variation in river discharge volume, at least for some farmers.

It is interesting to note that water rights are a reflection of settlement history in which earlier settlers own more productive land and also have prior water rights. Thus, increased robustness generated by water allocation institutions alone may disproportionately benefit headenders. However, other social infrastructure such as informal reciprocal exchange relationships may have the potential to increase robustness of most farmers to periods of low river flow. An example might be a case in which water allocation institutions were accompanied by other social arrangements enabling irrigators in sectors 1 and 2 to employ farmers from sectors 3-6 during dry periods as labor, when they would not be able to irrigate anyway, and thereby redistribute the yields. This, unfortunately, is typically not the practice in Pampa or elsewhere across Chitwan.

In a similar vein, with a little more effort, the performance of the system can be further enhanced using what we call an “optimized sequential” rotation. The scenarios in Figure 7A are based on the assumption that sector 1 fills to the nominal demand (the red line in Figure 4B). However, it is not necessary to fill to the nominal level to obtain maximum yield. If sufficiently precise measurements can be made, farmers need only fill to the minimum required so that the water level remains in the acceptable band or falls outside the band so little that yield is not affected through stage 1. The difference can be seen by comparing depth profiles for Sector 1 in Figure 7B, in which farmers fill only to about 150 mm, to those in Figure 7A in which farmers fill to 200 mm. This more precise level control (thus the term optimized sequential) frees up additional water to be used downstream. For this rotation, Sector 3 can maintain yields even when river flow is 38% of nominal. As is always the case, this increased performance requires additional work and coordination on the part of the farmers.

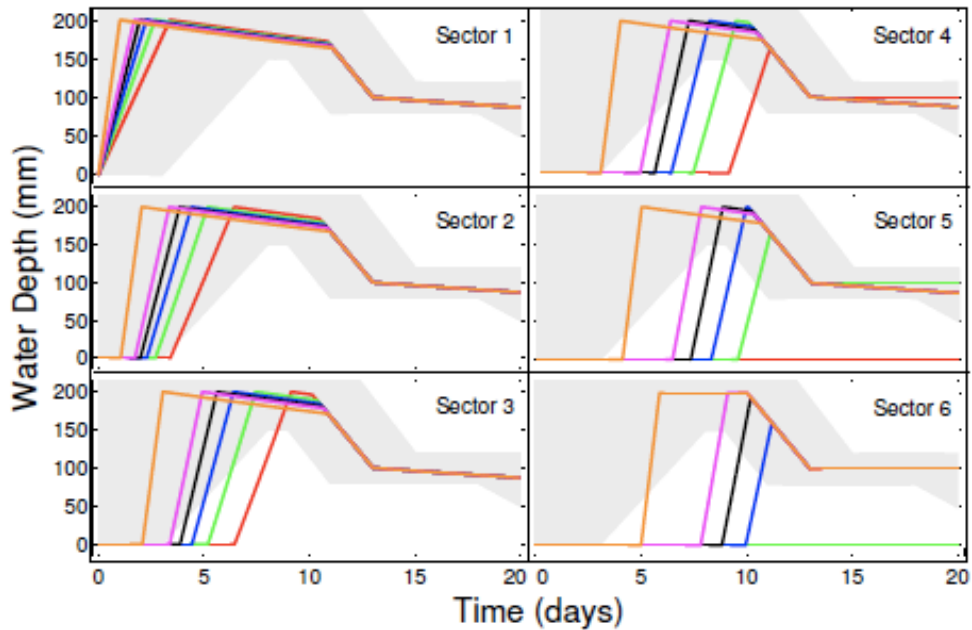
The next natural question is whether 12- or 24-hour rotation schemes can do even better than sequential schemes. Recall from the discussion above that unless there is some social infrastructure in place to redistribute the gains from cooperation, the result could be highly inequitable under the sequential rotation with sectors 1-3 receiving all the yield. The 12- or 24- hour rotation schemes may solve this problem to some extent without the need for additional social infrastructure for redistribution. The trajectories for water levels in sector 1 for 12- and 24-hour rotations are shown in Figure 8A; the other sectors are simply shifted to the right by 12 or 24 hours. It is clear that these trajectories fall somewhere in between the open flow and sequential cases. These rotations may improve equity, but the yield for a particular farmer depends strongly on their luck of the draw regarding who takes their turn first in the sequence. In order to compare all five strategies, Figure 8B shows the total yield for the entire system as a function of percentage mean river discharge for each strategy on the same graph. It is clear that if river flow is above approximately 50% of nominal, open flow is the best strategy in terms of total yield; note the Gini coefficient in this circumstance is also high. For flow below 50% of nominal, the performance of the open flow regime drops precipitously until at about 44% of nominal flow, when optimized sequential becomes the best strategy. The 12- and 24-hour rotations are always outperformed by other strategies. This is, in fact, what is observed in the field: 12- and 24-hour rotations are never used in the field preparation and transplantation stage.

The qualitative agreement between the model and field observations suggests that institutional arrangements can, indeed, increase the robustness of the system to variation in water availability and helps us understand why farmers choose the strategies they do. In this case, institutional arrangements are driven very strongly by biophysical constraints. Is there a relationship between institutional arrangements and other types of shocks?

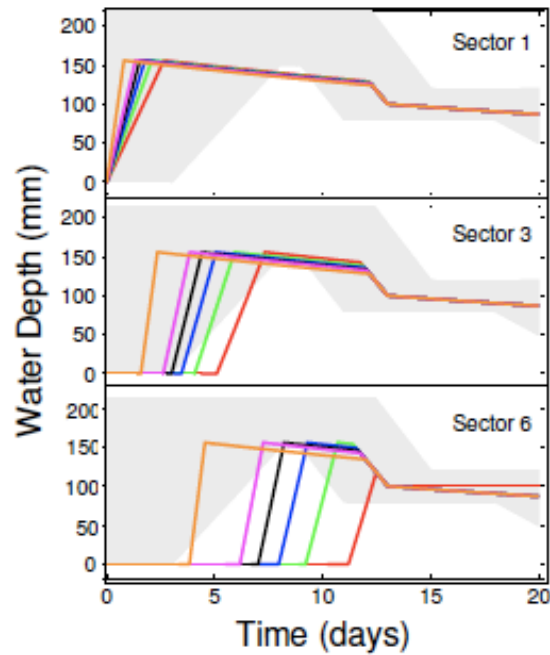
Temporal shifts in river discharge

Another impact of climate change could be temporal shifts in precipitation patterns and discharge in rivers. The effect of temporal shifts are similar to reductions in discharge under a sequential rotation for downstream users (see higher numbered sectors

Fig. 7. Irrigation water supply profiles (color coded to match discharge scenarios in Figure 6) superimposed on desired supply level range (gray shaded area). (A) and (B) show the water distribution under the sequential and optimized sequential regimes, respectively.

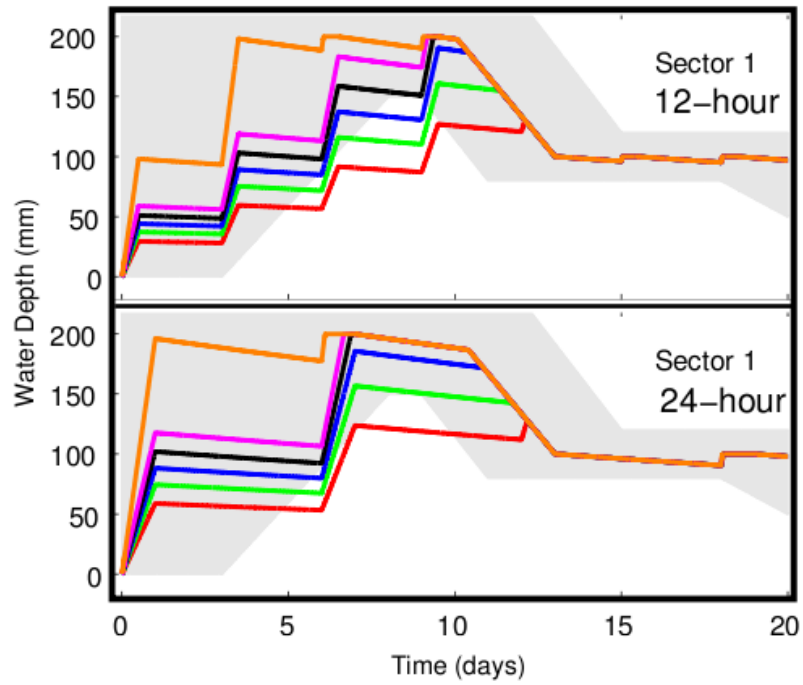


(A)

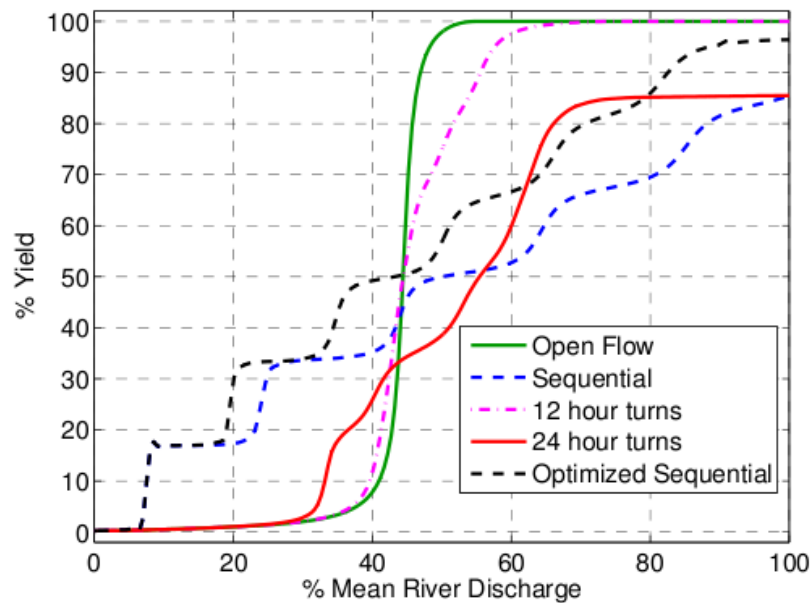


(B)

Fig. 8. (A): Supply profiles for 12- and 24-hour rotation policies superimposed on desired flow level range (gray area) under changes in mean river discharge volume. (B): Total yield as a function of percentage mean river discharge for each of the five irrigation policies.



(A)



(B)

in Figure 6A), except that all sectors are affected equally. Time-shifted river regime profiles and the corresponding percentage yield values are shown in Figures 9A and 9B, respectively. Similar to the case with river discharge, there is a sharp drop-off in yield if precipitation patterns and thus river discharge are shifted beyond a certain threshold, which is about 25 days in this case. Beyond this threshold, shifting to the optimized sequential regime can reduce the negative impacts of this shift. Thus, institutional diversity can increase the robustness of the system of climate induced shifts in precipitation patterns, but only to a point. It is interesting to note that what is crucial is the relative timing of temperature and rainfall patterns. If the growing season and the precipitation both shift, there would be no impact on yields.

Challenges to physical infrastructure

Thus far we have discovered no situation where 12- and 24-hour rotations perform better than sequential or open flow. Again, this matches the actual situation in the field. When are 12- and 24-hour rotations used in the field, not only in Pampa, but more generally? One distinguishing feature of rotation schemes, including sequential schemes, is that they reduce the canal area in use at any one time. This, in turn, can significantly reduce water losses due to leakiness of the canal infrastructure. A second feature is the way in which such schemes affect labor allocation. For example what distinguishes a rotation based on clock time (e.g. 12 hour) from one based on volume (e.g. sequential) is the predictability of when diversion structures must be opened and closed. Thus, time-based rotations may help communities more effectively coordinate labor in times of need. We explore these issues using the model by increasing the loss rate in the canals and simulating a shock to the infrastructure in the form of a complete washout of the diversion structures early in the mid season, when river flow rate is highest.

Figure 10 summarizes the impact of increasing losses from 0 to 3 liters per second per 100 meters of canal length. It is striking that 12-hour rotations begin to dominate for losses above 1 l/s/100m and mean discharge above 50%. Thus in a system with higher canal losses, we would expect to see irrigators employ 12-hour rotations under normal conditions and then shift to a sequential rotation

under conditions of very low flow. As it turns out, Pampa irrigators do not use 12-hour rotations in the field preparation stage under conditions of scarcity, but rather use a sequential rotation. One reason for this is illustrated in the bottom left graph in Figure 10 (loss = 1 l/s/100m). When the losses are moderate, as is likely the case in the Pampa system, there is only a narrow window between 50-60% mean discharge in which 12-hour rotations perform best. It is likely that it is difficult, given the nature of the river (see Figure 2), to determine river discharge with such precision. As such, it may not be worth the effort to implement the complex strategy of shifting from open flow to 12-hour rotation to sequential rotation as discharge declines. Rather, the irrigators employ the simpler policy of shifting from open flow to sequential with minimal loss in performance compared to the more complex strategy. In systems with higher loss rates (around 3 l/s/100m), however, one would expect to see 12-hour rotations in use.

To explore the performance of different strategies in response to a washout of the main diversion structure, we computed system performance for two scenarios based on field data gathered by A. Regmi (2008). Specifically, diversion structures and gates are routinely washed out during the monsoon season at Pampa. Canals are also destroyed by landslides. When this occurs, the system comes to a halt until repair work is carried out. During emergencies, all able-bodied men are expected to contribute resources, that is, labor and cash, irrespective of landholding, according to rules made by the water users committee and endorsed by a general assembly of farmers. When farmers were asked, "How many days does it generally take you to repair infrastructure that has been washed out by floods?" The response was: "Most of the times we have the system up and running within a week. When the extent of damage is larger we have been able to do it in two weeks and have not exceeded more than 20 days in recent memory". Based on this information, we present two scenarios as shown in Figure 11A: (a) by the 5th day infrastructure is sufficiently repaired to allow for a portion of the water to flow into the system (red scenario), (b) it takes 8 days for this to occur (blue scenario). As work proceeds, flow increases steadily and by the 20th day, the canal flow is restored to the nominal flow capacity (0.6 m³/s) as shown in Figure 11A.

Figure 11B shows the time responses of the water depth in the paddy for open flow (solid), 12-hour

Fig. 9. (A): Time-shifted mean river discharge scenarios. (B): Yields for different water distribution policies as a function of time shift in river discharge.

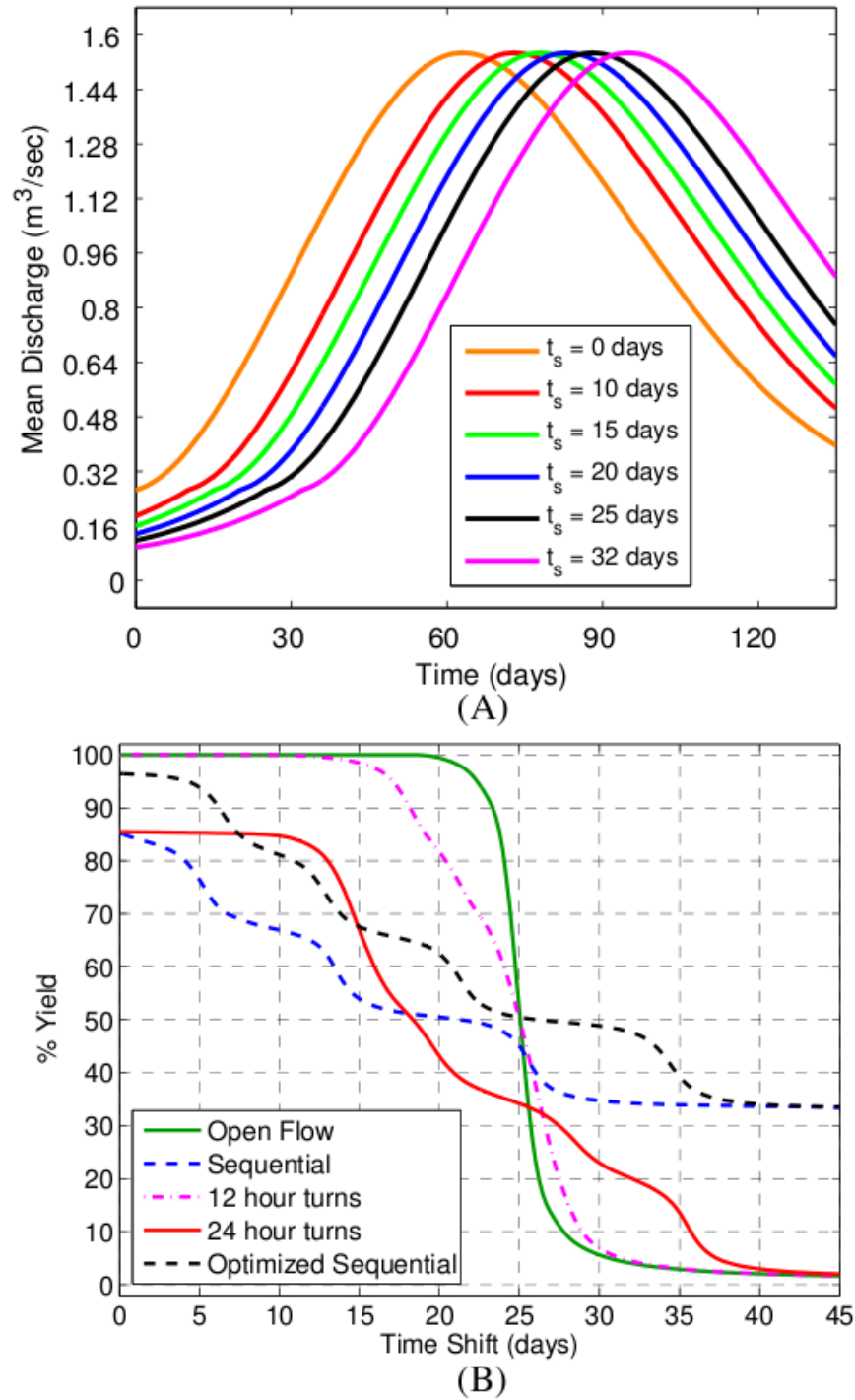
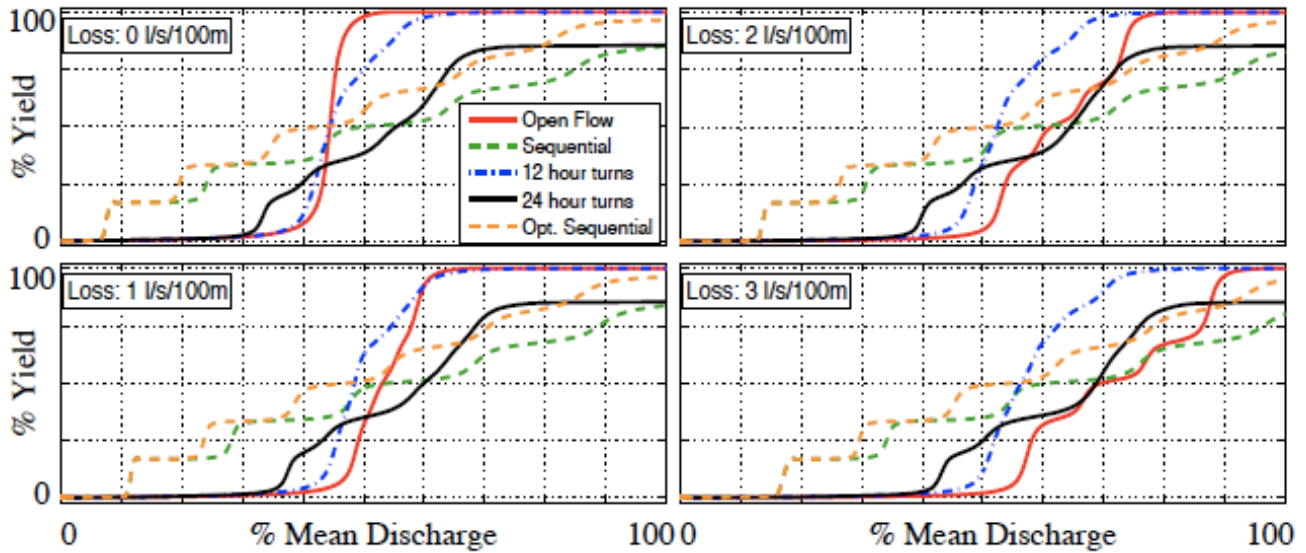


Fig. 10. The impact of canal losses on the performance of water allocation policies versus changes in mean river discharge volume.



(dashed), and 24-hour (dash-dot) policies. The first point to take away from this graph is that if repairs get water flowing more quickly (red scenario), 12-hour rotations outperform open flow and sequential (not shown in Figure 11B, but see Table 2) policies. This results from the fact that 12-hour rotations get water to farmers earlier and spread it more evenly. Table 2 shows the performance of each sector for each policy for both the red and blue scenarios. The performance of the 12-hour rotation is striking: it achieves 97.55% yield and is very equitable (Gini = 0.01, 0 best, 1 worst). If repairs take longer (blue scenario), 24-hour and sequential rotations perform best. The reason for this is clear from Figure 11B: everyone gets water too little and too late with the 12-hour rotation. With the 24-hour and sequential rotations, at least some farmers get enough water soon enough to prevent crop loss. In the sequential rotation the winners are, of course, sectors 1 and 2. With 24-hour rotation, who wins depends on when the rotation starts, often determined by drawing straws. In our simulation, the rotation starts with sector 1 and the winners are sectors 5 and 6. This is a clear example of a situation of extreme water scarcity in which a community must trade off equity (12-hour Gini = 0.08, mean yield = 15%, max yield

= 17.28%) for better performance (sequential Gini = 0.52, mean yield = 26.7%, max yield = 88.84%).

Our analysis of the performance characteristics of several different irrigation policies under three different classes of shocks, namely reduced river flow, late arrival of the monsoon, and damage to physical infrastructure, enable us to get at the questions posed at the beginning of the *Analysis* section. First, yield is quite insensitive to variation in rain and river flow regimes, to a point. Once a threshold is crossed (50% mean discharge, 25-day delay in monsoon induced river flows), potential yield drops precipitously (Figures 8B and 9B). The model clearly shows that shifting institutional regimes can significantly improve the robustness of the system. Shifting from open flow to sequential rotation during the field preparation and transplanted stage can prevent loss of the entire crop due to either reduced or late river flow. A yield loss of 50% is still substantial, but is far better than a loss of 95%. The stair-step nature of the relationship between yield and water availability is due to the brittleness of irrigated agriculture that places stringent demands on getting the right amount water to the right place at precisely the right

Fig. 11. Demand vs. supply profiles after a shock to headgate infrastructure. (A) Two scenarios of water flow as repairs to headgate are made. (B) Comparisons of open flow (solid), 12-hour rotations (dashed), and 24-hour rotations (dash-dot). The color coding is as follows: Red- by the 5th day infrastructure is sufficiently repaired to allow for a portion of the water to flow into the system. Blue- it takes 8 days until infrastructure is sufficiently repaired to allow for a portion of the water to flow into the system.

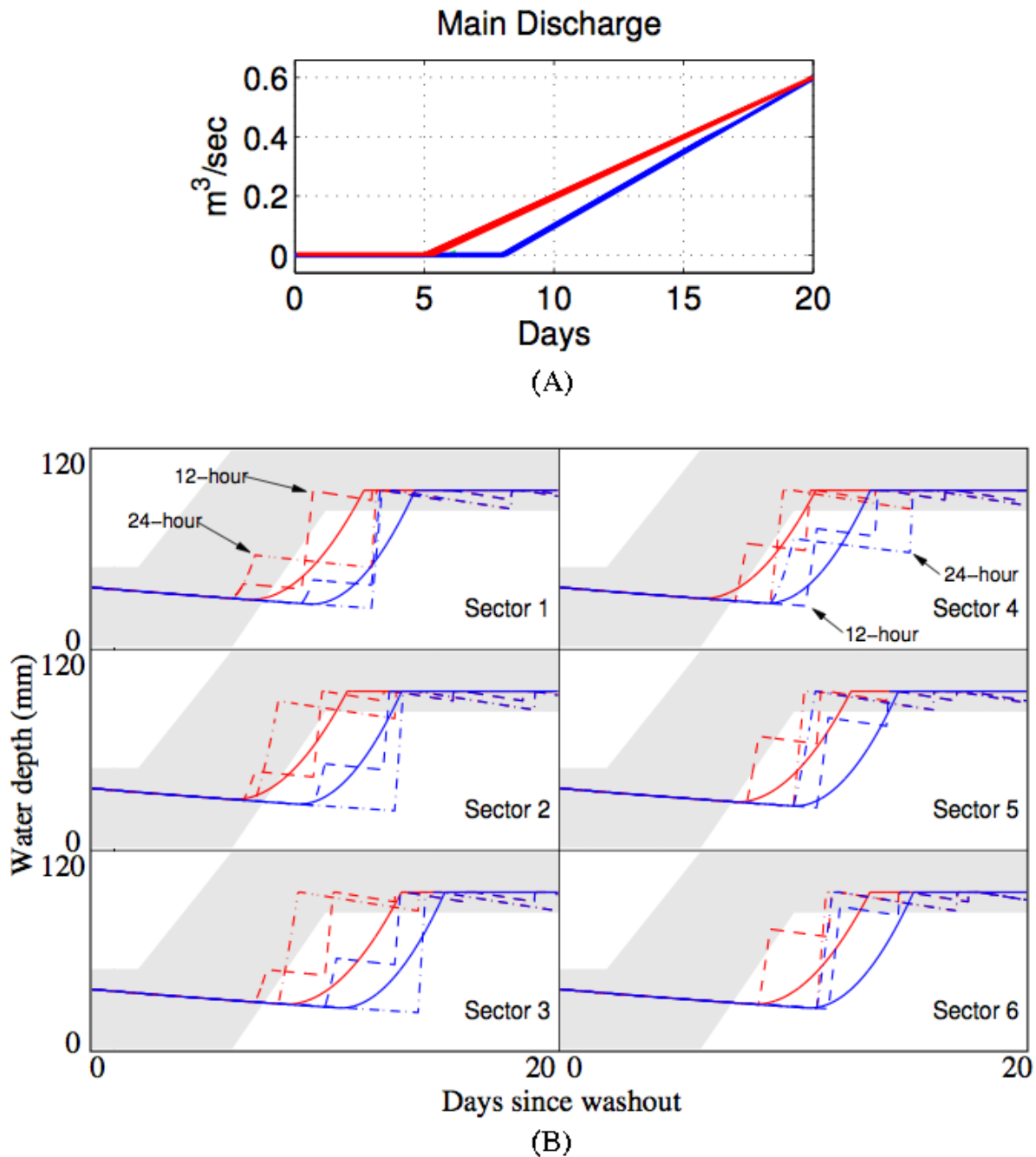


Table 2. Comparison of policy performance given a serious shock to headwork infrastructure (i.e. headworks completely washed out due to extremely high river discharge) in the midseason.

Shock	Policy	Yield, percent of maximum							Gini
		Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Mean	
Scenario	Response								Coeff.
Red	Open Flow	93.88	98.62	21.09	98.62	71.95	21.09	67.54	0.26
	Sequential	95.29	96.53	95.07	89.95	76.68	47.45	83.50	0.10
	12-hour	98.60	98.33	96.81	98.08	97.35	96.14	97.55	0.01
	24-hour	80.78	99.71	99.58	97.06	83.59	23.95	80.78	0.15
Blue	Open Flow	9.63	15.80	5.05	15.80	6.67	5.05	9.67	0.26
	Sequential	88.84	34.55	14.48	9.34	7.15	5.85	26.70	0.52
	12-hour	16.53	17.28	12.73	17.58	14.66	12.42	15.20	0.08
	24-hour	8.83	5.42	3.89	14.15	73.05	20.10	20.91	0.53

time. It is thus not surprising that changing institutional arrangements have only limited impact, given all the constraints within which they must work. Likewise, switching from open flow to 12-hour rotations can drastically reduce yield losses after a shock to diversion structures in the mid season and is more equitable than a sequential rotation.

Finally, our analysis suggests that why farmers choose the particular institutional arrangements they do is strongly determined by the brittleness of the system itself. That is, institutions are tightly coupled to practical considerations of making the system work. For each scenario we studied, there was a clear best strategy that matched what farmers actually do in the field. A striking example of this is the observed use of 12- or 24-hour rotations in the mid season. If scarcity is moderate (red scenario), 12-hour rotations are best and this is what farmers do. If water is extremely scarce, farmers shift to 24-hour rotations. Farmers likely accept the fact that if they try to distribute water equitably,

everyone will lose. Twenty-four hour rotations at least allow someone to salvage their crop, and as long as there is a mechanism that is perceived as fair to determine who the winner will be, this is the preferred strategy.

DISCUSSION

Small-scale irrigation systems are essential for food production worldwide. Understanding the potential responses of these systems to various shocks and systemic change thus plays an important role in maintaining food security for millions of people in the face of global economic and environmental change. Government agencies and NGOs alike must understand what to do and not to do when attempting to improve the performance of these systems. In this paper, we have developed and analyzed a model of irrigation activity based on the Pampa Irrigation System in Nepal in an attempt to shed light on this question. We used the model to characterize the robustness of the system and assess the adaptive

capacity of various institutional arrangements. By comparing what farmers actually do to what the model suggests they ought to do, we assessed how well tuned their actions are to the biophysical constraints they face, including labor. This, in turn, provides a sense of how much flexibility there is in the system. This institutional adaptation can be summarized as follows:

- Close to nominal river discharge conditions, open flow and 12-hour rotations are best. They both result in the same yield but open flow requires less effort and is what the farmers actually do. However, as mean river discharge decreases to about 40-50% of its nominal value, open flow and 12-hour rotations both result in a catastrophic drop in yield. Sequential policies that perform poorly near nominal conditions perform considerably better when the mean river discharge is lower than ~40%. The actual local policy of switching from open flow to sequential matches our model predictions. Note that switching between policies requires accurate measurement (Figure 8B). Incorrect measurement may result in significant losses (50% in fact), so we might expect to see substantial effort on the part of farmers to determine whether or not they should, in fact, switch to sequential, and if so, when. When there are time shifts in the mean river discharge, such as when the monsoon arrives later than usual, the story is very much the same.
- Problems with infrastructure favor fixed time rotations. With canal losses such as seepage, yield characteristics of the five policies change significantly. Because seepage is assumed to be proportional to the length of the canals that hold water during irrigation, it is not surprising that the open flow policy which maximizes the length of full canals is most impacted. As seepage increases, 12-hour rotations dominate other strategies when mean discharge is above 50%. Thus, with high levels of seepage, we would thus expect to see 12-hour rotations when conditions are near nominal and a shift to sequential policies under conditions of environmentally induced water scarcity. In the Pampa system, we estimate canal losses to be around 1 l/s/100m (Regmi, *personal communication*). In this case, there is only a small window in which 12-hour rotations perform best. Given measurement challenges, it is likely not practical to shift between open flow, 12-hour, and sequential policies for different flow conditions. Again, the model is consistent with what we observe: Pampa farmers do not use 12-hour rotations in their system under these conditions.
- In fact, the mid season is the only time that fixed time rotations are observed in the Pampa system (Regmi, *personal communication*). Because mid season coincides with the period of maximum river flow, it is unlikely that natural phenomena such as reduced discharge, or late monsoon arrival would have an impact on the yield during this stage. However, washout of the main diversion structure is more likely due to the high flow rates in the river. We know that when this occurs, the local farmers switch from open flow to the 12-hour policy which, according to our work, results in the largest yields and most equitable distribution. It is interesting to note that the 24-hour policy emerges as the best policy in only one case: after a midseason washout of the headworks, and only if fairness is a determining factor. Note, there is evidence that fairness matters. Groups of farmers from the six sectors do draw lots to determine which group will take responsibility to maintain which sectors of the irrigation system which exhibit considerable variance regarding required maintenance effort. It turns out that the 24-hour rotation rule is mainly used for winter crop (wheat) when water levels are lower in the rivers. For rice (mid season) it is considered only during an unusual year, once every 4-5 years, when a major flooding incident does severe damage to infrastructure that either takes longer than usual to repair or cannot be fully repaired, that is, a smaller fraction of the original volume is only available even after repairs. These observations suggest the existence of a threshold for minimum water volume that must be delivered to fields to be effective, related to soil wetting and infiltration.

Figure 12 summarizes the results of our study for the two cases of environmental variation: low water flow and late arrival of the monsoons. The yellow

blocks indicate the best policy and the red numbers indicate what farmers actually do, in those cases when their behavior has been observed. The policies are ranked in terms of mean performance, sensitivity (how much the performance changes as volume or time shift changes), and equity (Gini coefficient) for two scenarios. Note that we computed rankings for a third scenario in each case: 0-30% flow and a 30-45 day time shift. These are not shown in the table because they are so unlikely and the outcome is very simple: optimized sequential is best. This is very clear from Figure 8B. When flow is 60-100% of the mean flow and losses are 1 l/s/100m, open flow is best in terms of expected yield and equity and second best in terms of sensitivity. When flow is 30%-60, sequential or optimized sequential are best or second best in terms of expected yield and sensitivity. We have shown both these policies in red as we are not sure what is actually done in the field, although the prevalence of norms concerning not wasting water would suggest the optimal sequential rotation is reasonable. They are, however, not the most equitable. On the other hand, irrigators in Pampa are well aware of the prior appropriations nature of water rights and know their position in the system. Thus, the inequitable distribution of water to sectors with senior rights is perceived as fair, and the yield is partially redistributed through wage labor arrangements.

The analysis of the model enabled us to provide fairly direct answers to the first three questions posed. The answers revolve around the tight interactions among infrastructure, the agroecology of the rice paddy, and climate (precipitation and temperature) regimes. We have computed the sensitivity of four different water distribution patterns and used them to illustrate that farmers can and do significantly improve the robustness of their system through varying institutional arrangements. However, the capacity of institutional arrangements is limited by the rigidity of the infrastructure–agroecology–climate complex that defines rice paddy cultivation. When climate variables move beyond a certain threshold, yield drops precipitously, and institutional arrangements can only do so much, e.g. reducing a 95% yield loss to a 50% loss.

Our fourth question, regarding what new vulnerabilities may arise as a result of efforts by farmers to increase the robustness of their system, is more difficult to answer because it relates not only to the narrowly defined irrigation system we

actually modeled and analyzed, but to other systems with which it interacts. Further, it depends not only on the dynamics generated by the structure of the narrowly defined irrigation system but also on how the structure of the system itself responds to the dynamics of the broader system in which it is embedded. These concerns, critical to addressing the broader questions of how small-scale irrigation systems will cope with global environmental and economic change and how they should be connected to other levels of governance, are not amenable to formal modeling. We thus rely on viewing the system more qualitatively through the Robustness Framework informed by the results from the formal model (Figure 13).

The strong agreement between what the model predicts farmers should do, and what farmers actually do hints at the nature of the relationships among resource users, the resource, and public infrastructure in Figure 1. Likewise, the nature of the sensitivity relationships shown in Figures 8B and 9B hints at the nature of the relationship between infrastructure and the resource. If we use line width to represent the strength of interactions and relative importance of different driving mechanisms, these points would suggest the structure shown in Figure 13. Specifically, the interactions between resource users, the resource, and public infrastructure (links 1 and 4) are very strong. The nature of the physical component, i.e., public infrastructure, has a very strong influence on the interaction between resource users and the resource itself (link 5, upward direction). This relationship then feeds back to the institutional component of public infrastructure (link 5, downward direction), thus strongly structuring the nature of institutional arrangements. Finally, the public infrastructure has a direct impact on the resource users (link 6) because it structures the way they interact with one another in space and time. Because of the strength of these connections, institutions may become highly optimized to coordinate activities to manage links 1 and 4. This has two possible implications: (1) such systems are sensitive to changes in the nature of physical infrastructure because it has so many strong linkages, and (2) such systems are highly tuned to cope with particular types of shocks (arrows labeled 7). These, in turn imply that we should not expect these systems to be robust to climate change that exceeds the range of tolerance determined by the history of shocks represented by type 7 arrows in Figure 13. Further, we should expect the system to be very sensitive to changes in physical public

Fig. 12. Summary of irrigation policy performance. Each policy has been ranked with respect to E: Expected Value, S: Sensitivity, and G: Mean Gini. Yellow blocks indicate the best policy for a given situation, red numbers illustrate what farmers actually do in a given situation, where known. Black numbers refer to the ranking of the performance of each policy, e.g. a black "1" is the optimal policy for a given situation, etc.

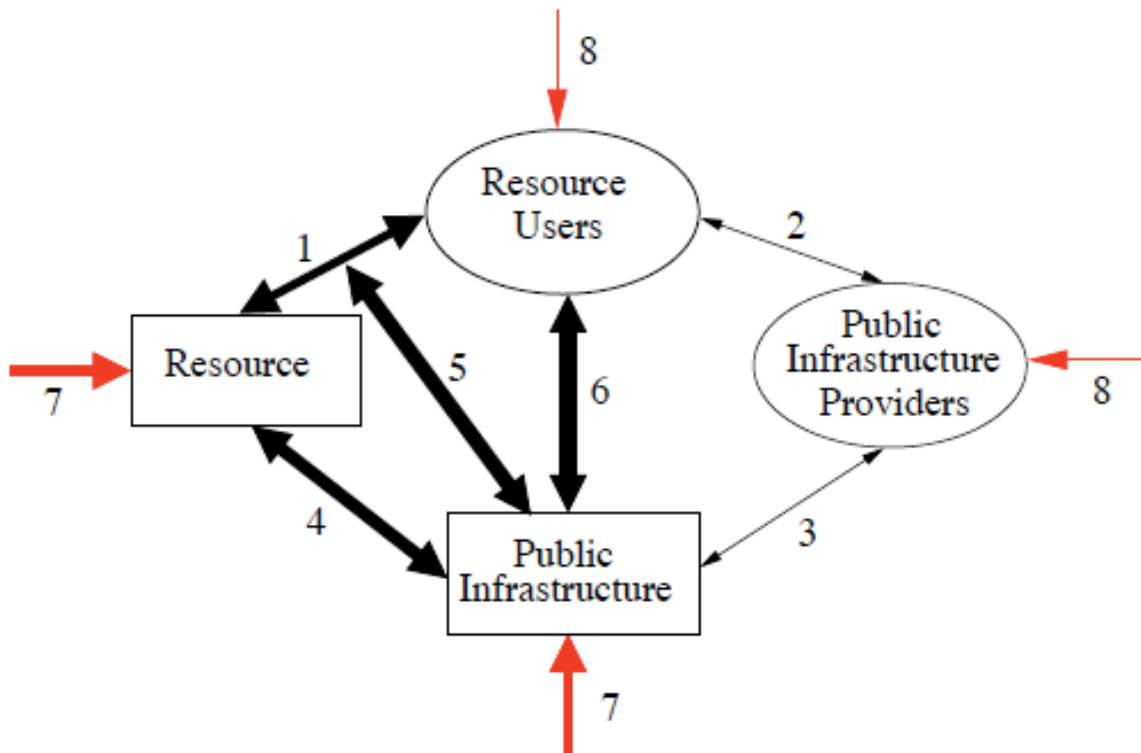
Case	Mean Discharge										Time Shift										
	60% - 100%					30% - 60%					0 - 20 days					20 - 30 days					
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4	
E	Open Flow	1	1	2	4	5	1	5	5	5	5	1	2	3	5	5	1	5	5	5	5
	12-hour	2	2	1	1	1	3	3	3	4	4	2	1	1	1	1	3	4	4	4	4
	Optimized Sequential	3	3	3	2	2	2	1	1	1	1	3	3	2	2	2	2	1	1	1	1
	24-hour	4	4	4	3	3	5	4	4	3	3	4	4	4	3	3	5	3	3	3	3
	Sequential	5	5	5	5	4	4	2	2	2	2	5	5	5	4	4	4	2	2	2	2
S	Open Flow	1	2	5	5	5	5	5	4	2	1	1	5	5	5	4	5	4	1	1	1
	12-hour	2	1	1	2	3	4	4	5	5	5	2	1	4	4	5	4	5	5	4	3
	Optimized Sequential	4	3	3	3	2	2	2	1	1	3	3	3	2	2	2	1	1	3	3	4
	24-hour	3	5	4	4	4	3	3	3	4	4	5	4	3	3	3	3	3	4	5	5
	Sequential	5	4	2	1	1	1	1	2	3	2	4	2	1	1	1	2	2	2	2	2
G	Open Flow	1	1	2	4	5	1	2	2	2	2	1	2	2	3	3	1	2	3	3	2
	12-hour	2	2	1	1	1	2	1	1	1	1	2	1	1	1	1	2	1	1	1	1
	Optimized Sequential	3	3	3	2	2	3	3	3	4	4	4	4	4	4	4	3	3	2	2	3
	24-hour	4	4	4	3	3	5	4	4	3	3	3	3	3	2	2	5	5	5	5	5
	Sequential	5	5	5	5	4	4	5	5	5	5	5	5	5	5	5	4	4	4	4	4

infrastructure or the agroecology of the resource. This is consistent with the recent history of interventions aimed at improving irrigation infrastructure or improving crop performance.

The strength of links 1, 4, 5, and 6, may, in fact, weaken links 2 and 3. That is, the relationship between irrigators and the public infrastructure is so intimate that the need for formal positions for public infrastructure provision is minimal. The strength of links 1, 4, 5, and 6 offers support for our claim that the dominance of practical constraints may reduce problems with cooperation and collective choice because for small groups of people organizing around an irrigation resource, the significant benefits of cooperation and their linkage to livelihoods are fairly clear (links 1 and 4), cheating is difficult (link 6), and conflict is reduced by pragmatic preset rules (link 5). As a result, institutions that support cooperation, collective choice, and conflict resolution may be underdeveloped in some irrigation systems. It is likely that these institutional functions are important

for general adaptive capacity. Without them, groups of small-scale farmers may not have the ability to manage new resources and information that flows into their system. The resources may be captured by local elites, misdirected, or poorly distributed because the institutional arrangements in place that focus more on effective coordination of labor and water are not well suited to solve these new problems. This is consistent with the failure of decentralization in development efforts in which resources are put under the control of local resource users with the idea that given their local knowledge, they will know best how to use them (Hira and Parfitt 2004). This may be true in terms of practical knowledge, but they may lack the institutional knowledge to manage the new set of problems associated with a new resource type in the system, e.g., cash.

Fig. 13. Robustness diagram for the Pampa irrigation system modified based on the analysis of the model. Line thickness refers to the relative importance of a given interaction. Numbers are for cross-referencing descriptions of each interaction (see text).



CONCLUSIONS

Taken together, the results of our analysis provide support for the need to avoid simple solutions, such as a focus on improving irrigation infrastructure or directing resources at systems and relying on local knowledge to maximize the impact of government resources on improving yields. Rather, recent work focused on the need to avoid policy panaceas (Ostram et al. 2007) suggests that for each system, an analysis resulting in something like Figure 13 should be conducted so that aid can be efficiently targeted. The general points that emerge from this work is that small-scale irrigation systems like the Pampa should not be expected to cope well with globalization nor should they be expected to cope with directed environmental change once certain thresholds are crossed. It seems that shifts in the

timing of monsoons on the order of 3-4 weeks may be the most critical issue as a 50% drop in river flow rates seems less likely. As such, attempts to enhance food security by improving the performance of existing systems will likely result in low returns on investment.

Given the rigidities such as those occurring in existing small-scale irrigation systems, investment directed at discovering new ways to use the resources, water and soil, which are consistent with existing institutions or which require institutional adjustments that are possible within the existing institutional context would likely be more effective. Likewise, investment carefully targeted at those institutional competencies identified as lacking as a result of the processes summarized in Figure 13 may enhance the capacity of these systems to cope

with global economic and environmental change more than continued efforts to enhance the efficiency of existing systems. Although these points are recognized by the development community in general (Shivakoti and Ostrom 2002, Shivakoti et al. 2005), the devil is in the detail. The work here attempts to fill in some of the requisite detail. Future research should focus on developing a typology of small-scale irrigation systems based on a framework such as the one used here and attempt to build evidence regarding correlations between social–ecological structure (e.g. Figure 13), interventions, and outcomes. Such detail will be necessary to face the challenge of maintaining well-functioning small-scale social–ecological systems and food security in the face of multiple sources of change.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/vol15/iss3/art39/responses/>

Acknowledgments:

The authors would like to thank Elinor Ostrom for comments on an earlier version of this manuscript. The authors gratefully acknowledge financial support for this work from National Science Foundation Grant BCS-0527744.

LITERATURE CITED

Anderies, J., A. Rodriguez, M. Janssen, and O. Cifdaloz. 2007. Panaceas, uncertainty, and the robust control framework in sustainability science. *Proceedings of The National Academy of Sciences of the United States of America* **104**(39):15194–15199.

Anderies, J., M. Janssen, and E. Ostrom. 2004. A framework to analyze the robustness of social–ecological systems from an institutional perspective. *Ecology and Society* **9**(1):18. [online] URL: <http://www.ecologyandsociety.org/vol9/iss1/art18/>

Ascher, W., and R. Healy. 1990. *Natural resource policymaking in developing countries*. Duke University Press, Durham, North Carolina, USA.

Baker, J. 2005. *The Kuhls of Kangra. Community-managed irrigation in the Western Himalaya*. University of Washington Press, Seattle, Washington, USA.

Barker, R., and F. Molle. 2004. *Evolution of irrigation in South and Southeast Asia*. Technical report. International Water Management Institute. Comprehensive Assessment Research, No:5. Sri Lanka.

Bautista, E., and Clemmens, A. J., 1999. Response of ASCE task committee test cases to open-loop control measures. *Journal of Irrigation and Drainage Engineering*, **125**(4):179–188.

Bromley, D. 1982. *Improving irrigated agriculture: Institutional reform and the small farmer*. Staff Working Paper No. 531. World Bank, Washington, D.C., USA.

Clark, C. W. 1990. *Mathematical bioeconomics: The optimal management of renewable resources*, Second edition. J. Wiley, New York, New York, USA.

Clemmens, A. J., T. F. Kacerek, B. Grawitz, and W. Schuurmans. 1998. Test cases for canal control algorithms. *Journal of Irrigation and Drainage Engineering* **124**(1):23–30.

Clemmens, A. J., G. Sloan, and J. Schuurmans. 1994. Canal-control needs: Example. *Journal of Irrigation and Drainage Engineering* **120**(6):1067–1085.

Dayton-Johnson, J. 2000. Choosing rules to govern the commons: A model with evidence from Mexico. *Journal of Economic Behavior and Organization* **42**:19–41.

Downing, T. 1974. *Irrigation's impact on society*. University of Arizona Press, Tucson, Arizona, USA.

Fortes, P. S., A. E. Platonov, and L. S. Pereira. 2005. GISAREG - A GIS based irrigation scheduling simulation model to support improved water use. *Agricultural Water Management* **77**:159-179.

- Fujiie, M., Y. Hayami, and M. Kikuchi.** 2005. The conditions of collective action for local commons management: the case of irrigation in the Philippines. *Journal of Agricultural Economics* 33 (2):179–189.
- Gómez, M., J. Rodellar, and J. A. Mantecón.** 2002. Predictive control method for decentralized operation of irrigation canals. *Applied Mathematical Modelling* 26:1036–1056.
- Gordon, H.** 1954. The economic theory of a common property resource: the fishery. *Journal of Political Economy* 62:124–142.
- Hall, A.W.** 1999. Priorities for irrigated agriculture. *Agricultural Water Management*. 40(1):25–29.
- Hira, A., and T. Parfitt.** 2004. *Development projects for a new millennium*. Praeger, Westport, Connecticut, USA.
- Janssen, M., and J. Anderies.** 2007. Robustness trade-offs in social–ecological systems. *International Journal of the Commons* 1(1):43–66.
- Janssen, M., J. Anderies, and E. Ostrom.** 2007. Robustness of social–ecological systems to spatial and temporal variability. *Society and Natural Resources* 20(4):307–322.
- Jayawardene, J.** 1986. *The training of Mahaweli Turnout Group leaders in participatory management in Sri Lanka's irrigation schemes*. International Irrigation Management Institute, Sri Lanka.
- Jones, W.** 1995. *The World Bank and irrigation: a World Bank Operational Evaluation Study*. Technical report. World Bank, Washington, D.C., USA.
- Karl, T. R., J. M. Melillo, and T. C. Peterson, editors.** 2009. *Global climate change impacts in the United States*. Cambridge University Press, Cambridge, UK.
- Khadra, R., and N. Lamaddalena.** 2006. A simulation model to generate the demand hydrographs in large-scale irrigation systems. *Biosystems Engineering* 93(3):335–346.
- Lam, W. F.** 1998. *Governing irrigation systems in Nepal: Institutions, infrastructure, and collective action*. ICS Press, Oakland, California, USA.
- Lansing, J.** 1991. *Priests and programmers: Technologies of power in the engineered landscape of Bali*. Princeton University Press, Princeton, New Jersey, USA.
- Levine, G.** 1980. The relationship of design, operation, and management. Pages 51–62. in J. E. Walter Coward, editor. *Irrigation and agriculture development in Asia: Perspectives from the social sciences*. Cornell University Press, Ithaca, New York, USA.
- Litrico, X., and V. Fromion.** 2005. Design of structured multivariable controllers for irrigation canals. Pages 1881–1886 in *Proceedings of the 44th IEEE Conference on Decision and Control, 2005 and 2005 European Control Conference (Spain, 2005)*. online [URL]: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1582434&isnumber=33412>
- Litrico, X., and V. Fromion.** 2006. H_∞ control of an irrigation canal pool with a mixed control politics. *IEEE Transactions on Control Systems Technology* 14(1):99–111.
- Malaterre, P.O., and M. Khammash.** 2003. 1 controller design for a high-order 5-pool irrigation canal system. *Journal of Dynamic Systems, Measurement, and Control* 125:639–645.
- Malaterre, P. O., D. C. Rogers, and J. Schuurmans.** 1998. Classification of canal control algorithms. *Journal of Irrigation and Drainage Engineering* 124(1):3–10.
- Mareels, I., E. Weyer, and S. K. Ooi.** 2003. Irrigation networks: A systems engineering approach. Pages 15–28 in *Proceedings of the 4th International Conference on Control and Automation (ICCA) (2003)*. online [URL]: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1595057&isnumber=33564>
- Mareels, I., E. Weyer, S. K. Ooi, M. Cantoni, Y. Li, and G. Nair.** 2005. Systems engineering for irrigation systems: Successes and challenges. *Annual Reviews in Control* 29(2):191–204.
- Martin, E.,** 1986. *Resource mobilization, water allocation, and farmer organization in hill irrigation systems in Nepal*. Dissertation. Cornell University, Ithaca, New York, USA.

- McIntyre, B. D., H. R. Herren, J. Wakhungu, and R. T. Watson, editors.** 2009. *International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD): Global Report*. IAASTD. online [URL]: <http://www.agassessment.org/>
- Meinzen-Dick, R. S.** 1984. *Local management of tank irrigation in South India: Organizations and operation*. Studies in irrigation No.3. Cornell University, Ithaca, New York, USA.
- Meinzen-Dick, R.** 2007. Beyond panaceas in irrigation institutions. *Proceedings of the National Academy of Sciences* **104**:15200–15205.
- Miranda, F., R. Yoder, J. Wilkerson, and L. Odhiambo.** 2005. An autonomous controller for site-specific management of fixed irrigation systems. *Computers and Electronics in Agriculture* **48**(3):183–197.
- Nepal National Committee of International Commission on Irrigation and Drainage (NENCID).** 2007. *Country Position Paper Nepal*. online [URL]: http://www.icid.org/v_nepal.pdf.
- Nippon Koei Company Ltd.** 1986. *Feasibility study on East Rapti Irrigation Project for the Department of Irrigation, Hydrology and Meteorology- HMG/Nepal*. TA NO. 700-NEP. Asian Development Bank, Manila, Philippines.
- Ooi, S. K., E. Weyer.** 2008. Control design for an irrigation channel from physical data. *Control Engineering Practice* **16**(9):1132–1150.
- Ostrom, E.** 2002. *The challenge of underperformance in improving irrigation governance and management in Nepal*. ICS Press, Oakland, California, USA.
- Ostrom, E., M. Janssen, and J. Anderies.** 2007. Going beyond panaceas. *Proceedings of The National Academy of Sciences of the United States of America* **104**(39):15176–15178.
- Popova, Z., S. Eneva, and L. S. Pereira.** 2006. Model validation, crop coefficients and yield response factors for maize irrigation scheduling based on long-term experiments. *Biosystems Engineering*. **95**(1):139–149.
- Regmi, A.** 2008. Self-governance in farmer-managed irrigation systems in Nepal. *Journal of Developments in Sustainable Agriculture* **3**:20–27.
- Schuermans, J., A. J. Clemmens, S. Dijkstra, A. Hof, and R. Brouwer.** 1999. Modeling of irrigation and drainage canals for controller design. *Journal of Irrigation and Drainage Engineering* **125**(6):338–344.
- Shahrokhnia, M. A., and M. Javan.** 2005. Performance assessment of Doroodzan irrigation network by steady state hydraulic modeling. *Irrigation and Drainage Systems* **19**:189–206.
- Shivakoti, G., D. Vermillion, W. F. Lam, U. Pradhan, and R. Yoder.** 2005. *Asian irrigation in transition*. Sage Publications, New Delhi, India.
- Shivakoti, G. P., and E. Ostrom, editors.** 2002. *Improving irrigation governance and management in Nepal*. ICS Press, Oakland, California, USA.
- Slater, R., L. Peskett, E. Ludi, and D. Brown.** 2007. *Climate change, agriculture policy and poverty reduction - How much do we know?* Natural Resource Perspectives 109, Overseas Development Institute, London, UK ISSN 1356-9228, available at <http://www.odi.org.uk/resources/download/1231.pdf>
- Thompson, R.** 2001. The World Bank strategy to rural development with special reference to the role of irrigation and drainage. Pages 2-17 in *1st Asian Regional Conference and Workshop on the Occasion of 52nd IEC meeting of ICID, Seoul*. International Commission on Irrigation and Drainage (ICID), New Delhi. Keynote address.
- Wade, R.** 1994. *Village republics: Economic conditions for collective action in South India*. ICS Press, Oakland, California, USA.
- Wahlin, B. T., and A. J. Clemmens.** 2002. Performance of historic downstream canal control algorithms on ASCE test canal 1. *Journal of Irrigation and Drainage Engineering* **128**(6):365–375.
- World Bank Operations Evaluation Department.** 1985. *Tenth annual review of project management*

in Sri Lanka's irrigation schemes, 1984. Technical report, International Bank for Reconstruction and Development, Washington, D.C., USA.

Yoder, R. 1986. *The performance of farmer-managed irrigation systems in the hills of Nepal.* Dissertation. Cornell University, Ithaca, New York, USA.