WATER DISTRIBUTION MANAGEMENT IN SMALL WEST AFRICAN CANAL SYSTEMS

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ABSTRACT: The performance and progressive development of irrigation distribution and rotation methods were studied in two government-sponsored systems of Niger, West Africa. Systemwide water distribution was monitored intensively throughout several growing seasons and farmer surveys were conducted at both sites. Characteristics of farmer-managed rotation among tertiary canals and among parcels were examined in relation to farmer response to physical and organizational system constraints. A method for indexing the orderliness of irrigation rotation was developed. Where water deliveries were limited, organizational efforts on behalf of the farmers resulted in functional, orderly rotation and distribution among parcels. Farmers exhibit less incentive to organize efficient and orderly rotation among parcels where access to water is less limited. Several organizational and design factors influence the degree to which farmers are both willing and able to organize functional water distribution among themselves. Also, farmers may circumvent design intentions or management strategies imposed on them by irrigation authorities in order to establish their own more effective water management methods, which tend to better accommodate local labor and production constraints. Technical and organizational considerations related to water distribution and management derived from the study results may serve to facilitate the design and operation of small-holder systems in the Sahel.

INTRODUCTION

The West African Sahel is a dry and agriculturally marginal region, occupying the transitional zone between the Sahara desert to the north and the Sudanic and Tropical climatic zones to the south. Niger Republic is one of several underdeveloped and landlocked Sahelian countries, which together represent some of the world's poorest in terms of per capita gross national product, human development, and natural resources [United Nations Development Program (UNDP) 1994]. Over the past 5 decades, irrigation development has been treated as an important component of national and regional programs to attain economic and nutritional sustainability. Most major irrigation development investments in the Sahel have been for large-scale (>500 ha), government-sponsored systems that are shared by multiple users.

Performance records indicate that most of the large-scale systems have fallen severely short of their anticipated benefit levels (Kortenhorst et al. 1989; Moris and Thom 1990; Alam 1991). Poor management, primarily arising from the inability of large numbers of farmers to organize within a single, large system, often has been the cause of failure. The region's successful irrigation developments tend to be small- to medium-scale systems (i.e., up to 500 ha), in which farmers play a major role in system management (Diemer and van der Laan 1987; Norman and Walter 1993). In many of the world's developing regions, including the Sahel, it is well documented that the social and cultural factors are often more important to successful system management than the design of the system's physical infrastructure (Seckler et al. 1991; Ton and De Jong 1991; Levine et al. 1998). A better understanding of the interface between irrigation technologies and social factors of farmer organization in system management should serve to provide useful lessons for the development of new systems and the rehabilitation of existing ones.

Most detailed water management studies of small systems addressing the farmer-system interface have been drawn from experience in Asia [e.g., Wensley and Walter (1985), Yoder and Martin (1990), and Vermillion (1998)]. Irrigation performance studies of farmer management from Sahelian Africa are limited, often qualitative in nature, and focused on economics, social science, and policy concerns of irrigation development [e.g., Diemer and van der Laan (1987), and Kortenhorst et al. (1989). Despite the Sahel's poor irrigation development record, many of these studies indicate that participatory farmer organization is relatively well developed in some of the region's smaller systems [e.g., Bloch (1986) and Sikkens (1987)]. Unlike most large-scale systems in the Sahel, a few of the small-scale systems also have produced sustained user benefits for 25 years or more and thus warrant closer examination (Sikkens 1987; Norman and Walter 1993).

This paper provides an examination of irrigation management within small, community systems of the Sahel. The objectives of this study are (1) to examine the performance and development of farmer-managed irrigation distribution and rotation methods; and (2) to develop a better understanding of the interface between ''technical aspects of irrigation system development'' and ''organizational aspects of system management by local farmers.''

Two small irrigation systems were studied in the Republic of Niger. The systems are administered by the government and are shared by farmers holding small parcels within each. System management is handled jointly by the state and the farmer community.

STUDY SITES

Physical and Organizational Setting

Two surface catchment reservoir systems in south-central Niger were selected for study. Table 1 provides a summary of the physical and organizational characteristics of the two systems. The annual rainfall is highly variable, 250–550 mm/year, and the mean annual temperature is 25°–30°C. The climate is characterized by a dry season from November to April,

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TABLE 1. Physical and Organizational Characteristics of Study Sites

Characteristic (1)	System A (2)	System B (3)
First year of operation	1967	1983
Design command area (ha)	65	250
Water delivery flow rate (L/s/ha)	5.0	2.5
Canal construction	Stone and mortar	Concrete
Field turnout type	Inverted siphons	Portable siphons
Number of farmers	110	854
Farmers/ha	1.7	3.5
Number of farmer management units	4	25
Number of villages represented	4	8

in which there is no rainfall, and a wet season from July to October. Millet and sorghum, the mainstay of the sedentary population, are the principal rain-fed crops. Sorghum, millet, and cotton are supplementally irrigated during the wet season. Wheat, onions, and maize are then cultivated under irrigation during the dry season. In most years the sorghum, millet, and cotton yields are about 2.5 t/ha and wheat, onions, and maize are about 3.5, 2.0, and 1.5 t/ha, respectively. The systems depend on storage of surface runoff from the short wet season, although there are often limited reserves remaining after wet season supplemental irrigation. Thus, the area irrigated in the dry season may be considerably less than the total cultivable system area. Water from the reservoir is delivered by gravity through an open, lined canal network. Furrow or level-basin irrigation is employed in the fields, depending on crop type. Crop water requirements among system parcels are assumed to be similar because uniform cropping (or crop mixtures) within each parcel is prescribed before each growing season by Niger governmental officials. Soils are well-drained sandy-clay loams and loams. Farmers use animal traction to till their parcels. Field channels, furrows, and basins are prepared manually.

As with most of the Sahel's irrigated systems, the study systems were constructed with foreign financing and designed by expatriate or foreign-trained engineers. Their introduction added management dimensions not common to the region's indigenous systems (i.e., a shared, single water source) (Norman 1995a,b). Most local, traditional experience is with single-source, single-user systems, in which the farmer is the sole user of his water source.

Office National des Aménagements Hydro-Agricoles [National Office for Hydro-Agricultural Management (ONAHA)], located in Niamy,is the irrigation parastatal agency charged with the development and admission of Niger's irrigated systems. Irrigated systems are jointly managed by the state, ONAHA, and by a management committee composed of participant farmers. ONAHA provides a director for each system (and a field technician if the system size exceeds 100 ha). The directors reside on-site and serve in monitoring and policing roles, overseeing system operations. Their responsibilities include collaboration with the farmer management committee to assure timely agricultural operations, such as flow regulation of the reservoir outlet and major gated outlets during irrigation days.

Farmers holding irrigated parcels in a system are divided among farmer management usings (FMU) that correspond with a system's physical units. A physical unit (unit) is an area composed of 30–40 parcels usually served by one secondary delivery canal. Each FMU typically consists of about 30 farmers. Among most ''old'' systems, attempts were made during system implementation to establish unit divisions according to the proximity of farmers to their residence; e.g., farmers in a unit in the northern portion of the system would likely be from a geographically nearby village. When parcel ownership changes, attempts are generally made to maintain unit continuity by reassigning parcels to members of the same family or village.

The farmer management committee is comprised of one elected representative from each FMU in a system. This is the primary body that collaborates with the system director to manage operations. An important function of each FMU representative (i.e., management committee member) is to notify the farmers in his unit about irrigation schedules and to see that proper turnout rotation is maintained along the unit's secondary canal.

Farmers within government-administered systems must pay a seasonal tax based on their parcel size. The tax is recalculated after each season based on collective maintenance and operating costs of the system and part of ONAHA's operating costs. No charges are directly levied against water use, partly because there are no accurate means to measure flow rates.

System A

Irrigation System A, near the village of Moullela, was selected for study because it is Niger's oldest surface reservoir system and one of Niger's oldest, continually functioning systems. Thus it has a farmer community with some of the longest, continuous system management experience. System A is primarily constructed of local material. The system was constructed to fit the layout of the land with minimal land leveling during construction. Parcels are laid out in irregular sizes with a mean area of about 0.5 ha. The resulting pattern of the canal delivery system is dendritic, with three major primary canal divisions near the head of the system (Fig. 1). These divisions each supply several secondary canals from which turnouts supply water to individual parcels. Concrete inverted siphons, permanently fixed to the base of the canal, serve as turnouts for water delivery to field parcels. The design discharge for the siphons is 6 L/s, but rocks or other obstructions are frequently placed in the secondary canal to increase turnout delivery head. The system was originally designed so that approximately half the turnouts along each secondary operate simultaneously but, at present, water is delivered along each secondary on a rotation basis with fewer turnouts opened at a time and higher flows per turnout. Supplemental, wet season irrigation usually takes place every 6–10 days during periods with sufficient rainfall. One complete irrigation of the command area, if not interrupted by rainfall, usually takes four 8-h days. Dry season irrigations take place every 8–10 days,

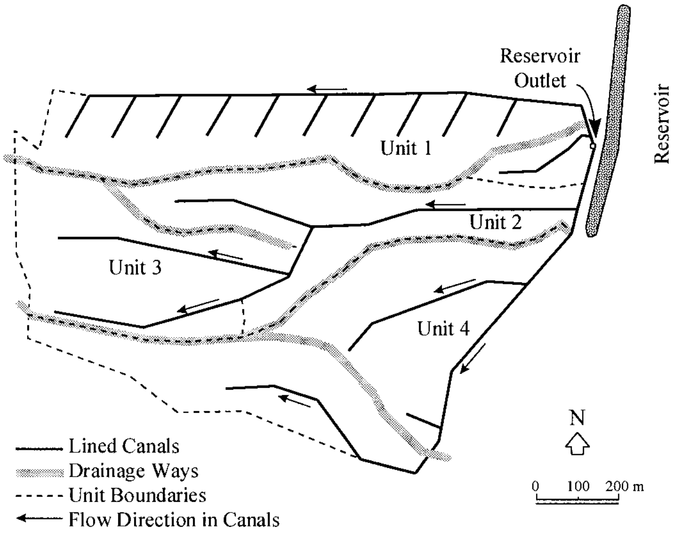


FIG. 1. System A Layout

with 1–3 days needed for completion, depending on the area and crops irrigated. In most years water storage for irrigation is limited due to sediment accumulation in the reservoir. By the late 1980s, systemwide irrigation efficiencies based on actual crop water demand were typically 65%, with dry season efficiencies usually 10% higher than the wet season's (Norman and Walter 1988).

System B

Irrigation System B, near the village of Galmi, is located 5 km from System A. It was selected because its proximity to System A facilitated concurrent monitoring of both systems and because it is one of Niger's newest systems, with a farmer community still in the early stages of adapting to the system. It also represents a very different design and construction method from System A. The system is laid out in a long narrow pattern, stretching 6 km from the base of the reservoir to the end of the primary canal and having an average width of approximately 0.5 km (Fig. 2). Twenty-five secondaries receive water from the primary canal, their flows regulated by gated orifice outlets. These secondaries define physical divisions among the system's 25 FMUs. The primary and secondary canals are constructed of poured concrete, and all tertiary canals are made of compacted heavy soils. Secondaries serve 4–15 tertiaries, and tertiaries serve an average of six 0.25-ha parcels (Fig. 2). The secondaries are equipped with gated outlets that supply water to the tertiary canals. Siphons are used to deliver water from the tertiaries to individual field parcels. The system was designed for a flow of 700 L/s at the head of the primary canal so that all 25 management units could concurrently receive 2.5 L/s/ha with an estimated canal seepage loss of 75 L/s. At the secondary level, usually one to four tertiaries are opened at a time, with usually no more than four parcels simultaneously irrigated along the same tertiary. Each unit possesses a set number of siphons (rated at 1 L/s each) directly correlating to the design flow of its respective secondary canal. These siphons are then rotated among farmers with a prescribed five siphons per parcel. The original system design called for a parcel delivery of 5 L/s, although this is often not adhered to. As long as adequate water is available at the field parcel level, parcel irrigations are normally completed in 1 day. Systemwide efficiencies based on actual crop water use are about 50–55%, with dry season values slightly higher than the wet season (Norman and Walter 1988).

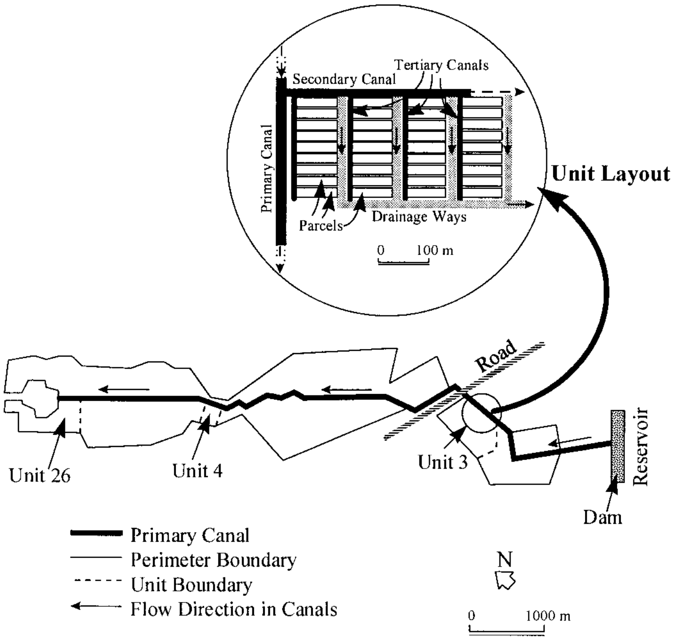


FIG. 2. System B Layout

METHODOLOGY

Field Data Acquisition

A full-time field researcher, placed at each site throughout each growing season, monitored all system and farmer activities on a daily basis. During the study period, 1985–1992, dry season irrigation was monitored during three separate growing seasons and will henceforth be referred to as DS-I, DS-II, and DS-III. Wet season irrigation was monitored during two growing seasons, referred to as WS-I and WS-II.

At System A, during WS-I and DS-I, all water releases into the head and tail-end FMUs, Units 1 and 3, respectively, were recorded. Measurements were made using broad-crested weirs in the channels and orifices at parcel turnouts. Initial and regular calibrations utilized a portable flow meter. Changes in water releases during the course of the day were recorded, and all diversion and control points were checked twice each day. Irrigation delivery at the field parcel level was monitored for selected parcels during this period. During WS-I, WS-II, and DS-I, the irrigation rotation to parcel turnouts was monitored twice daily along the single canal of Unit 1 and along the larger of Unit 3's two secondaries.

At System B, flows were measured daily (using weirs or a flow meter) during DS-I, DS-II, DS-III, and WS-II. Although measurements were made from several FMUs, Units 3, 14, and 26 were representative of the system's head, middle, and tail units. To monitor rotation among tertiary canal groups, the tertiary gated outlets along each length of each unit secondary canal were checked daily and recorded as open or closed. For each open tertiary the total number of farmers irrigating was noted.

Insights into organizational aspects of irrigation rotation among farmers at both systems were obtained through (1) discussions and interviews with farmers, management committee members, and system directors; and (2) through daily monitoring of turnout schedules along secondaries of selected management units. A survey addressing irrigation scheduling and information flow was conducted at both systems. The survey at System A included 23 randomly selected farmers (10% of the farmers) and slightly less than 10% at System B.

For comparison with the collected data, system records were reviewed at both sites to assess performance levels and operational characteristics of the systems during their early years of operation.

Irrigation Rotation Order Analysis

As stated earlier, irrigation was monitored in five FMUs, two units in System A and three in B, for a total of 15 unit-seasons of data. Of the information presented in these data, irrigation rotation order is the most important for the purposes of this study. Arguably orderliness may be difficult to detect if the scheduling rubic is not obvious, but the prescribed unit-level irrigation rotation for both the study systems progressed from tail to head parcels (Fig. 3). When irrigation rotation data are presented graphically, as in Figs. 3–5, the relative order is visually observable, both within (Fig. 4) and among units (Fig. 5). However, prior to this study, no unbiased techniques have been developed to quantify irrigation rotation orderliness. An irrigation rotation order index (IRO) was developed for this study as the primary means of quantifying relative orderliness of irrigation rotations. To evaluate orderliness, comparisons are made between a theoretical, ideally orderly system and an observed system (Fig. 3). The IRO is a measure of the degree of correlation r^2 between the observed timing and position of open turnouts and those of an ideally orderly system. The deviation of the observed time of turnout opening from the ideal also provides a means of assessing orderliness (Fig. 3).

In an orderly rotation, gate openings propagate down the canal with time similar to the way wave fronts propagate with time. Therefore the wave equation is useful to define the ideal system in this study

$$\frac{\partial^2 i}{\partial x^2} = c^2 \frac{\partial^2 i}{\partial t^2} \tag{1}$$

where i = irrigation status for gate x at time t (e.g., gate open for $i = 1$ and gate fully closed for $i = 0$); t = time (days); x = turnout number; and c = rate at which irrigation rotation progresses (number of turnouts per time period). Fig. 3 diagrams the model and parameters for this ideally orderly system; the n_i in Fig. 3 is an integer designating different rotation sequences. Eq. (1) can be solved such that irrigation rotation progresses upstream (large x to small x) starting at a gate x_0

$$i = \sin\left(\frac{2\pi}{\lambda}(x + ct - x_0)\right) \tag{2}$$

where λ = average number of turnouts between open turnouts. Because the turnout data in this study are discrete (i.e., turnouts are either opened or closed), a discrete version of the continuous function $i(x, t)$ is needed. If the duration each gate remains open is e, (2) can be simplified by solving for open gates $x_{\text{open}}(t)$

$$x_{\text{open}} = x \geq x_0 - ct + n\lambda \tag{3a}$$

$$x_{\text{open}} = x < x_0 - c(t + e) + n\lambda \tag{3b}$$

The rotation sequence is defined by n (Fig. 3) (n = 0, 1, 2, . . . , N); and N = total number of sequences. The variables x_0, c, e, and λ are determined by best fitting (3) to the data. The best fit is the combination of these three fitting parameters that minimizes the total disagreement. A disagreement is any (turnout number, time) point where the ideal system and the data give opposing gate states; i.e., one indicates a turnout is opened and the other that it is closed. The total disagreement is the sum of all disagreements. For this study it is implicitly assumed that c is constant throughout the system; i.e., the rate at which turnouts are opened and closed does not speed up or slow down between the tail and head of the system. The rate also is assumed constant between canal closings, typically 1–2 weeks, but may vary throughout the season (e.g., Fig. 5). It also is assumed that when more than one sequence of irrigation rotation are occurring simultaneously, the spacing λ among sequences (siphons) are equivalent and regular (Fig. 3).

It is easiest to define the IRO as the correlation coefficient r^2 between the times of observed and ideal turnout openings. A high IRO (r^2) indicates a very orderly system. For this study it was assumed that gates in the ideal system were open for only an instant; thus, (3) is written as the following expression:

$$x_{\text{open}} = x_0 - ct + n\lambda \tag{4}$$

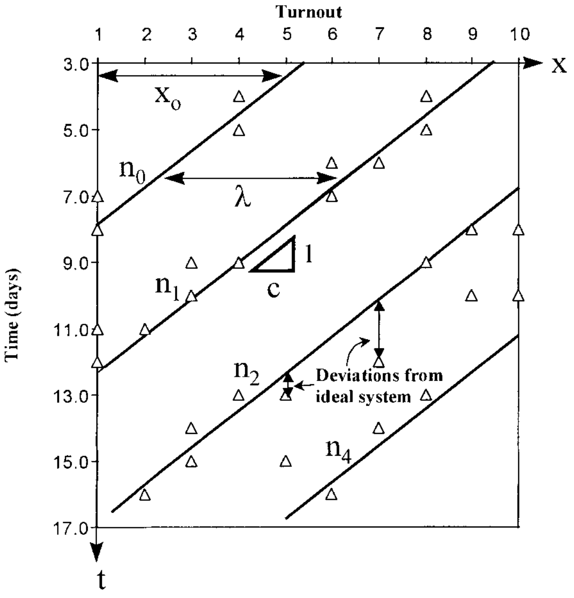


FIG. 3. Example of Ideally Orderly System Example Applied to System B, Unit 26, DS-I, Days 3–17 [Triangles Are Observed Data (Open Gates); Solid Lines Are Ideally Orderly System, $i(x, t)$]

RESULTS AND DISCUSSION

The IRO index values for monitored seasons are given in Table 2 and examples of rotation order data are presented graphically for selected seasons in Figs. 4 and 5. Irrigation order at System A is characterized by an average IRO of approximately 0.6, which means 60% of the variability in the data is attributed to orderly rotation. System B was generally more orderly with an average IRO of about 0.85.

Once daily, for 27 consecutive days, primary canal flow rates were measured at seven points along the length of the primary canal in System B. The average flow rates per unit area for this period are presented in Table 3, together with the corresponding coefficient of variation of flows at each point. Flow data at the three study units, 3, 14, and 26 are in Table 4.

System A experienced several incidents of open, unattended turnouts through which water was flowing (+ symbol in Fig. 4). There was no attempt to eliminate these data when deter-

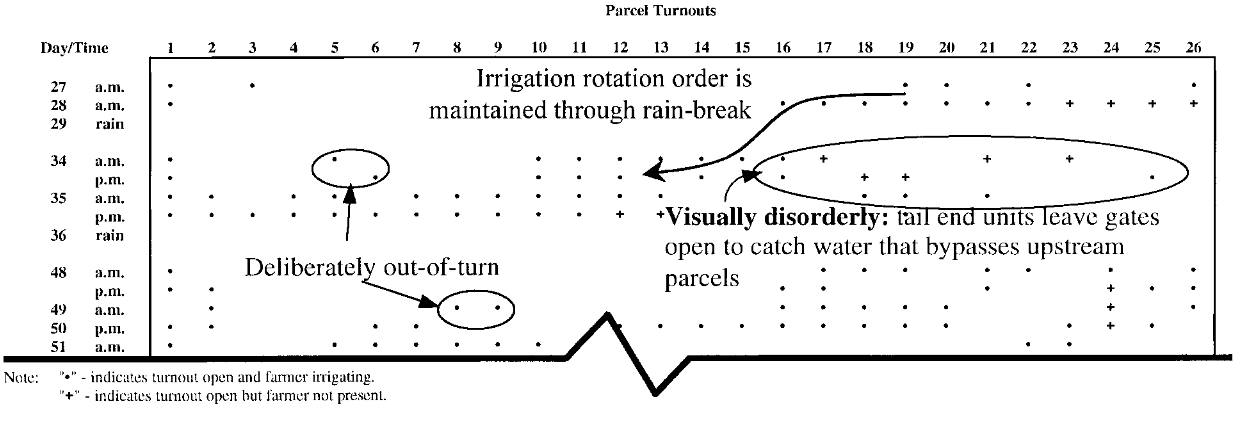
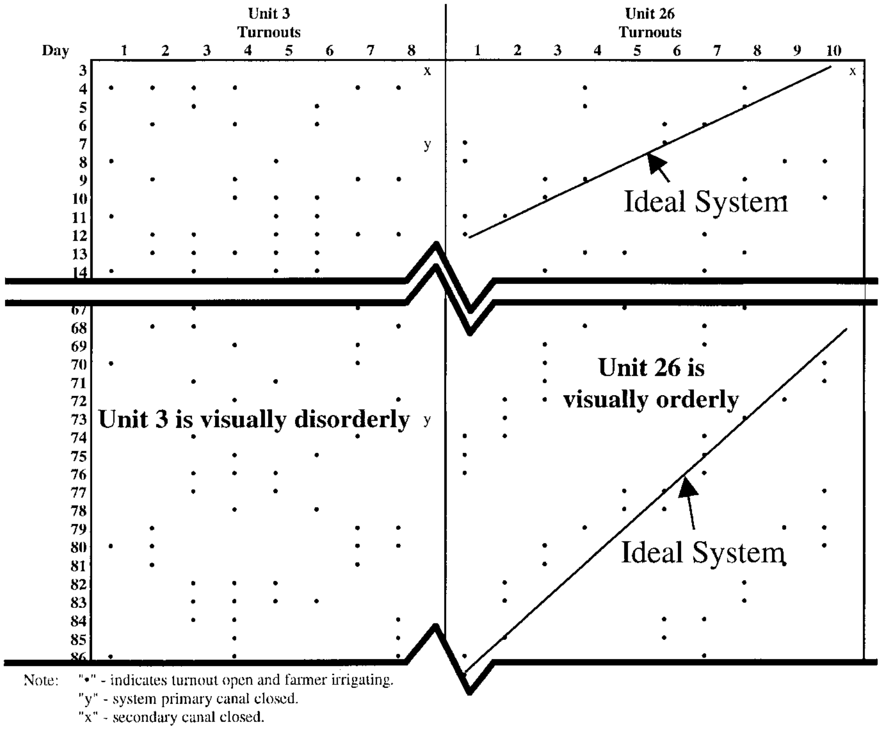


FIG. 4. Unit 1 Irrigation Rotation in System A, Wet Season (WS-I); Growing Season Is 130 Days



Note: "•" - indicates turnout open and farmer irrigating.
"y" - system primary canal closed.
"x" - secondary canal closed.

FIG. 5. Units 3 and 26 Irrigation Rotation in System B, Dry Season (DS-I); Growing Season Is 120 Days

TABLE 2. Irrigation IROs[a] for Management Units in Systems A and B

	System A			System B			
Growing season (1)	Year of system operation (2)	Unit 1 IRO (3)	Unit 3 IRO (4)	Year of system operation (5)	Unit 3 IRO (6)	Unit 14 IRO (7)	Unit 26 IRO (8)
WS-I	19	0.58	0.49	—	—	—	—
DS-I	20	—	0.69[b]	3	0.66	0.82	0.86
DS-II	—	—	—	7	0.73	0.94	0.84
WS-II	24	0.51	0.79	8	0.95	0.98	0.86
DS-III	—	—	—	8	0.55[b]	—	—

[a] $P > 0.01$ for all IROs.
[b] Unit parcels subdivided and shared among system farmers.

TABLE 3. Flow Variation at Points along Primary Canal in System B

Point of measurement (1)	Cumulative downstream area served (ha) (2)	Mean flow (L/s/ha) (3)	Coefficient of variation (%) (4)
1	249	2.6	17
2	209	2.6	17
3	168	2.5	17
4	130	2.5	19
5	103	2.4	21
6	80	2.4	23
7	42	2.3	42

mining the IRO. Unattended, open gates occur most commonly in two cases. First, on the morning of the first day of irrigation some turnouts were left open from the previous irrigation so that residual canal water could drain into fields. Usually, by the afternoon of the first day, these gates are located and closed by other farmers or the director. Second, and more commonly, farmers downstream of the rotation group may leave their turnouts open to allow excess, residual water to drain into their parcels rather than lose it to the drainage ways (Fig. 4). Because water is commonly scarce in the dry season, unattended, open gates are not often observed.

Four major, interrelated conclusions emerge from this study: (1) Effective intrasystem communication incorporates strong farmer self-management characteristics, especially at the unit level; (2) water availability strongly influences irrigation rotation orderliness; (3) farmers show good operational adaptability to organizational and infrastructural constraints; and (4) the physical layout of the system influences rotation orderliness.

Intrasystem Communication

System A

Survey results from System A indicate that most farmers (74%) have little problem with water availability; field visits with farmers generally confirmed this. Of those dissatisfied with water availability (26%), slightly more than half identified organizational problems with rotation and the rest cited infrastructural problems.

At System A, the decision to start an irrigation is made by the system director who then notifies the farmer management committee president. The president then notifies each management unit head, usually within a half-day after being notified by the director. Unit heads then notify members of their units, particularly those who will be irrigating first in the rotation schedule. Those having parcels at the tail end of each secondary canal usually irrigate first. This information is frequently transferred at evening prayer at the village mosque. Farmers further up the rotation schedule (i.e., on the second, third, or fourth days) are generally notified by fellow farmers. Because the wet season process is routine, most farmers can predict when the rotation schedule will reach them.

Farmers indicate that information transfer regarding upcoming irrigation periods is satisfactory. According to the random sample survey of parcel holders, 92% of respondents were informed regularly of upcoming irrigation schedules by their respective unit heads. Most tail-end farmers find that unit heads are fulfilling their duties in this respect. Although farm-

TABLE 4. Seasonal Delivery and Irrigational Intervals in Units 3, 14, and 26 of System B

Parameters (1)	Unit 3 (13.5 ha)		Unit 14 (4.8 ha)		Unit 26 (16.7 ha)	
	Average flow (L/s/ha) (2)	Irrigation interval (days) (3)	Average flow (L/s/ha) (4)	Irrigation interval (days) (5)	Average flow (L/s/ha) (6)	Irrigation interval (days) (7)
Design (fully open)	2.2	—	4.2	—	2.4	—
Observed	2.6	4.6	3.5	5.2	2.3	7.1
Coefficient of variation (%)	22	76	38	38	26	40

ers are usually aware several days in advance of the need for irrigation, the director rarely announces the first day of irrigation more than 24 h in advance. This short notice is partly due to the director juggling multiple concerns, such as farmers' demands for water, personal field assessments for crop water needs, anticipated rainfall (in the wet season), constant need to conserve limited water reserves, market days, Muslim days of prayer (Fridays), farmer labor demands external to the system, and canal cleaning. Farmers complain that they do not have adequate time to efficiently schedule their scarce labor on short notice. However, they find the director willing to make minor adjustments of a day or two if the management committee presents him with good reason.

After an irrigation period has begun, responsibilities in overseeing water distribution and delivery in the system are divided between the director and the four unit heads. The director takes responsibility for water delivery in primary canals and gated outlets to secondaries, and the unit heads are charged with overseeing parcel turnout rotations along secondaries within their respective units. Unit heads appear to know their responsibilities well and resolve disputes in the field regarding the rotation schedule, particularly on days when the unit heads are irrigating their own parcels. However, routinization of the rotation due to years of experience among unit members results in relatively smooth unit operation and allows the unit head to be absent for external labor demands (sometimes for several days at a time). When the situation necessitates, the system director often assumes the unit head's responsibilities in the field during his absence. As a result, unit heads occasionally become lethargic about their responsibilities.

System B

As at System A, unit heads at System B are charged with overseeing irrigation rotation along their respective secondary canals. They are also responsible for overseeing the distribution of siphons. Because all System B's units are divided among tertiaries, many unit heads have informally designated individual farmers as canal heads of their respective tertiaries. Their role is to oversee irrigation rotation among parcels of the tertiary canal, whereas unit heads concern themselves with rotation among the tertiaries served by their management unit's secondary canal. Selection of the unit head is not greatly influenced by the farmer's social or economic status. Usually the unit head is selected for his ability to maintain records for seed and fertilizer allocations and system taxes, and for his rapport with the farmers of his unit. Each unit functions independently of the others and specific, functional characteristics of each vary greatly. This variation is influenced by the makeup of each unit's constituency, the personality or management style of its unit head, and the unit's size (4.8–17.6 ha, 15–60 farmers).

Many farmers in the system have previous irrigation experience with small, individually managed, and privately owned traditional systems (Keller et al. 1987; Norman and Gandah 1990). As farmers within the relatively new system, they must contend with the unfamiliarity of a shared, single water source system that necessitates managing higher flows at the field level and cooperating among themselves. They have less experience in corporate and participatory activities than do farmers in the region's older irrigation systems (e.g., System A), particularly in terms of system management. However, there is good unit level organization as indicated by the relatively high IRO values (Table 2) and by reports from the first 4 years of operation (Arnould 1986; Keller et al. 1987).

Attempts have been made to maintain some degree of homogeneity within each management unit as to village and ethnic background. In the few units where this has not been maintained, efforts at participatory management within the unit have been strained.

A survey addressing unit level irrigation rotation scheduling was targeted at farmers in tail-end units of both their respective secondaries and tertiaries. The survey was conducted during peak demand periods in the dry season when the system was under near-continuous irrigation. All respondents were able to cite their irrigation day. Few farmers indicated never having been informed of their irrigation time. Only one respondent was informed of his irrigation day by his unit head; the others indicated the canal head and other farmers as the usual sources of information. This differs considerably from System A where the information is usually obtained from the unit head. Two major recurrent complaints from farmers were (1) the failure on the part of ONAHA personnel, unit heads, and canal heads to adequately police the secondaries and tertiaries to ensure proper rotation; and (2) farmers who repeatedly irrigated out of turn.

A water guard, designated by the farmer management committee and under the supervision of the system director, is charged with the daily opening and closing of the reservoir outlet and with overseeing the distribution of water among units along the length of the primary canal. However, observations and discussions with farmers indicate that significant disparities exist in system-level water delivery and distribution to units within the system. The lack of effective system-level monitoring by irrigation managers is particularly critical in shared systems when water is in short supply, as is often the case among the region's systems. Merrey (1990) and Vermillion and Murray-Rust (1994) showed similar problems in Asia. Any such variances or uncertainties of water deliveries to secondaries consequently affects how water is managed among farmers within their respective units, as discussed in the water availability section.

Water Availability

System A

Water availability is a factor in rotation orderliness. The IRO during the dry season was 0.69, which is higher than all but one of the monitored wet seasons' IROs (Table 2); i.e., irrigating out of turn is less common in the dry season, when water is limited, than in the wet. The few disorderly portions of the dry season irrigation rotation are isolated and intentional. For example, no rotation schedule is maintained during the first irrigation period of each dry season because this is the planting period; thus, irrigation rotation appears very disorderly during this period. The IRO index at Unit 3 for days 1–4 was 0.56, less than the season average value of 0.69 and less than any other irrigation sequence in that season (data not shown). Irrigation disorderliness in wet season planting is irrelevant because planting follows rainfall and the first irrigation of the season occurs subsequent to planting.

The effect of water limitations on irrigation orderliness is apparent when comparing System A's wet seasons. Limited water deliveries in WS-II relative to WS-I may explain the markedly higher IRO value at Unit 3 for the former season; however, Unit 1 experienced a slight decrease in orderliness (IRO difference <0.1) from WS-I to WS-II (Table 2). Temporal rainfall distribution was poor in WS-I, and supplemental irrigations were therefore frequent and regular throughout the season. In WS-II, rainfall was more abundant and only three dry periods required supplemental irrigations. When water releases from the reservoir are limited and infrequent (uncertain), farmers generally manage water more carefully—a tendency also observed at System B.

Although water scarcity increases irrigation rotation orderliness, abundant water may decrease rotation orderliness. Often, if farmers do not show up during their turns and there is sufficient water, upstream farmers along the same secondary canal will take advantage of the opportunity and use the water until the others arrive. When farmers deliberately irrigate out of turn and are caught, they are usually required to shut their turnout until the appropriate rotation time. Examples can be seen in Fig. 4 at Turnouts 5 and 6 on Day 34 and Turnouts 8 and 9 on Day 49.

Perhaps the most direct example of water availability influencing rotation orderliness can be seen by comparing Units 1 and 3. For the wet seasons, the average IRO for Unit 3 (0.64) was higher than for Unit 1 (0.55) in part because the water delivery rate to Unit 3 (35 L/s) was nearly 1/4 the amount to Unit 1 (130 L/s). A 10–12 L/s drop in flow due to an out-of-turn upstream irrigation is more readily noticed in a 35-L/s flow rate than in 130 L/s.

Rainfall disrupts the rotation. Along each unit's secondary, the rotation is implemented independently, usually beginning at the tail end and working its way toward the head as an irrigation period progresses. When irrigation is interrupted by rain, the next irrigation period continues from the last parcels irrigated. An example of this can be seen from Days 29–34 in Fig. 4. However, if an irrigation period is interrupted by a large rainfall (>15–20 mm), irrigation will often be suspended for at least 10 days and the following irrigation period will begin with the tail-end parcels. There is a total of six irrigations for sorghum during WS-I, and many parcels at the head end of secondaries only irrigated two or three times. There were no significant yield losses in these cases, and farmers did not complain.

System B

At System B, evidence correlating decreased water availability with increased rotation orderliness is seen in the orderliness of downstream Units 14 and 26 with average IROs of 0.91 and 0.85, respectively, relative to head Unit 3 with an average IRO of 0.70. As in System A, the greater ease of access to water among the system's head units allows for a greater individual control over parcel irrigation timing and thus relatively lower orderliness. This comparison is strongest for DS-I and DS-II. DS-III is an exception because there was only sufficient dry season water reserves to irrigate Units 1–5 and, as in DS-I at System A, parcels in these units were temporarily subdivided among all system users.

Observations among the three units suggest that higher variability (or uncertainty) of water delivery enhances rotational order among parcels to ensure adequate delivery to everyone. Table 4 shows high variability in flow to Units 14 and 26 relative to Unit 3, and Table 2 shows consistently higher IRO for Units 14 and 26 than for Unit 3. The trend is stronger for the dry seasons, when water is the most limited, than the wet. A similar comparison can be made between Units 14 and 26.

Additionally, as the availability and ease of access to water decrease, there is less secondary gate adjusting (i.e., it is left fully open most of the time) and operational losses within the unit are less. Daily monitoring revealed operational losses in Unit 3 were nearly a daily occurrence, whereas they were only occasional in Unit 14 and never observed in Unit 26. The only exception is the residual drainage from the canal network, which drains through Units 25 and 26, after system shut down. Nevertheless, farmers frequently captured this water even long after dark.

As the dry season advances and crop water demands peak, the sequential rotation rate increases (i.e., the irrigation interval decreases). For DS-I, this can be seen in the increasing slope of the Unit 26 data throughout the season in Fig. 5. The corresponding ideal system had an irrigation rotation rate, c in (1)–(4), of 0.42 turnouts/day for Days 17–24, 0.70 turnouts/day for days 59–93, and nearly 1 turnout/day for the remainder of the season. Furthermore, the outlet to unit 26 is never closed, whereas occasional closure is common for Units 3 and 14 (Fig. 5). Although the ease of water access and the dependability of delivery were poorer at Unit 26 than Unit 3, cumulative seasonal delivery is nearly the same as Unit 3. Given these constraints, farmers in Unit 26 were able to organize themselves into a functional rotation schedule, provide the necessary increase in labor, and minimize operational losses to assure adequate delivery to every parcel. These efforts were not necessary in Unit 3.

Farmer Operational Adaptability

System A

System A's original design assumed concurrent irrigation of approximately half the parcels in each unit. Each turnout was to deliver 6 L/s to a field parcel and six furrows, 80–100-m long, were to be irrigated concurrently. Thus, an average field, 0.5 ha, would require two 8-h days to fully irrigate. Half of the system was to receive water in the first 2 days, and the second half was irrigated in the following 2 days. Most local farmers do not have the mechanical means to develop long furrows capable of performing at acceptable application efficiencies (Keller et al. 1987). Nor are the farmers willing (or able) to invest the time (2 days) and labor required for originally prescribed field irrigations. During the wet season, private rain-fed holdings for staple crops, external to the system, were usually given priority in the allocation of limited household labor. Early use of the system saw relatively poor production levels and insufficient water applications. In the first 13 years of operation the ratio of irrigation supply to demand was on the order of 0.6–0.8, and yields were generally 80% lower than they have been in recent years (Norman and Walter 1993).

System A's farmers adapted to the system by reducing furrow lengths to about 10–15 m and nearly doubling operational flow rates at the parcel level. The present furrows essentially function as level impoundment furrows (or level basins); they are flooded and dyked on both ends. This new field irrigation method required the implementation of the rotation system, still practiced today, which allows fewer farmers to irrigate concurrently but with higher individual flow rates and uniformities. By the mid-1980s, mean field turnout flow rates were 12 and 9 L/s for the wet and dry seasons, respectively, as compared to the design flow of 6 L/s. Irrigation of individ-

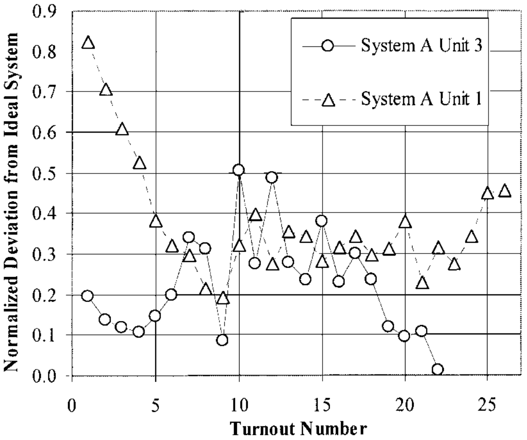


FIG. 6. Normalized Deviation of Time of Turnout Opening from Ideally Orderly System for Units 1 (Triangles/Dotted Lines) and 3 (Circles/Solid Lines) in System A

ual parcels is usually completed in 1 day, and 18–30% of parcel turnouts along each secondary canal receive water concurrently, which represents the approximate size of a rotation group. By 1978–1979, this adopted rotation system became the official water distribution method at System A. These changes are similar to those found by Sikkens (1987) in a 51-ha reservoir system at Goinré, Burkina Faso.

One profound incident of effective farmer adaptability was during DS-I, which saw limited water reserves, when all System A's farmers were relocated to Units 2 and 3. Farmers shared subdivided parcels in these units, with two or three farmers to a parcel. Thus, there were three times as many farmers operating in the dry season than in the wet and twice as many farmers as turnouts (approximately 45 farmers with 18 turnouts). Most of these farmers held parcels in other units and were temporarily assigned plots in Unit 3. Nevertheless, with both increased numbers and a mixture of farmers not normally familiar with rotating among themselves, orderly rotation is relatively well maintained (Table 2). Furthermore, rotation orderliness was relatively uniform throughout the unit; the head turnouts, 1–5, typically deviated from the ideal system by 0.42 days, and the tail turnouts, 15–20, deviated by 0.45 days. Although this phenomenon may be linked to water scarcity and increased labor availability, farmers from different units exhibited the organizational capacity to work together within subdivided parcels of a single unit and maintain relatively orderly and equitable water delivery and distribution among themselves.

System B

In System B, farmer adaptability is demonstrated by farmer responses to flow variability throughout the system. Table 3 shows a 10% decrease in flow from the head to the tail of the primary canal. Secondaries toward the system's tail end frequently had to adjust to upstream fluctuations in canal deliveries that resulted from changes in upstream gate openings. Table 4 shows the average observed flows and average irrigation intervals for Units 3, 14, and 26. Differences in mean observed flows indicate inequities in supply to each unit, and mean values for the irrigation interval for each parcel reflect adaptation to inequities. Farmers in Unit 26, for example, space out the period between each individual's irrigation to accommodate everyone. The variability of delivery rates also contributes to this problem. Although Unit 26 does not have the lowest coefficient of variation for flow among the three units (Table 4), delivery in the primary canal to tail-end units exhibits the highest flow variation (Table 3). Being a very small unit with great ease of access to water, farmers of Unit 14 frequently make individual adjustments to their secondary gate, resulting in high flow variability.

Physical System Layout

System A

System A's small size facilitates good system-level management. Because it is small, on most irrigation days the director walks the operating canal network, making necessary adjustments in major gated outlets to meet delivery needs. For example, after the last official day of an irrigation period in dry seasons, the director often extends flow from the reservoir, at a reduced rate, to assure that water reaches the last farmers to irrigate (head end). Also due to the system's small size, he is able to monitor parcel turnout rotations and make adjustments that help his assessments of water delivery needs. The centralized location of major canal divisions near the head of the dendritic canal network serves to facilitate the director's system-level management responsibilities (Fig. 1).

On the unit level, Unit 1 is larger and more linearly extended than Unit 3 (Fig. 1), making it more difficult for farmers to see and monitor one another's activities. The area irrigated in Unit 1 was 18 ha and in Unit 3 it was 12 and 4 ha in the wet and dry seasons, respectively. Unit 1's relative linearity is exaggerated because the canal only serves the area on the left bank, whereas unit 3's canal serves parcels on both sides of the secondary. There are 1.8 times as many parcel turnouts per unit length of delivery canal in Unit 3 than in Unit 1. Although there are no obvious, consistent differences between the unit's overall orderliness, there is more disorderly activity by head-end farmers in Unit 1 than in Unit 3. This relative disorder is apparent in Fig. 6, which shows the normalized absolute deviations between observed turnout opening times and those predicted with the ideally orderly model. In Fig. 6, the first four turnouts of Unit 1 (triangles/dotted line) have the highest relative deviations and Unit 3 (circles/solid line) shows no obvious trends. In Unit 1, farmers irrigating at the tail end of the canal are so distant from parcels at the head that it is difficult to monitor the upstream turnouts. Ostrom (1992) suggested that the temptation among irrigators sharing a common delivery canal to engage in opportunistic behavior is reduced when systems are constructed so that the actions of farmers taking water are visible to others. Hechter (1987) suggested that self-monitoring within groups can be facilitated by increasing visibility through architecture.

Part of the relatively orderly behavior during DS-I may be attributed to the centralization of water distribution at the unit level. Furrows among subdivided parcels essentially became tertiary canals, making unit level distribution similar to System B, which generally had higher IROs than A.

System B

When there is sufficient water, head-end units occasionally increase the head, and thus flow, by placing obstacles in the primary canal. This tendency for head-end users to take advantage of greater (or first) access to primary canal deliveries is evidenced in Table 3; the average flow in the primary canal was 2.6 L/s/ha at the head of the system and 2.3 L/s/ha at the tail. Even more marked, average flow into the first five parcels was 3.0 L/s/ha and it was 2.3 L/s/ha into the last five. Differences in flow variation are even more marked (Tables 3 and 4). For perspective, the average potential evapotranspiration was 2.8 L/s/ha. These data indicate that system-level monitoring is poor, largely due to the long physical distances involved (6 km) and the high variability of unit size. This problem is similar to Unit 1 in System A. The problem is enhanced by the lack of any direct water-use costs and the faulty design flow rating of many secondary gated outlets.

System B's tertiary canal network provides centralized water distribution on the unit level, resulting in generally good irrigation rotation orderliness. Although System A is much older than System B, units in System B are consistently more orderly than in A. This is probably largely due to the more centralized unit-level distribution system at B relative to A.

CONCLUSIONS

The recipients of irrigation development initiatives in Third World nations often operate within the environment of a subsistence-level economy and diverse household production systems. This environment usually differs greatly from the economies and farm production systems commonly found in the United States and Europe. The priorities and preferences of recipient farmer population may therefore differ significantly from the design priorities of engineers and development specialists. As a result, farmers often circumvent physical and operational design strategies imposed on them. Furthermore, when given the opportunity and necessary conditions, they are often able to adapt effectively to new technologies in spite of design and operational flaws. Systems incorporating flexibility into the physical and operational design, in the effort to accommodate local priorities and constraints, are more likely to attain projected benefit levels. Lessons from this study can serve to facilitate the design and implementation (or rehabilitation) of more sustainable irrigation systems.

Timely water delivery to FMUs can only be assured by effective system-level management. System-level management for water distribution among units must provide careful policing and monitoring of deliveries, whether the service is provided by the outside authority (e.g., a state of parastatal agency) or a local institution (e.g., the farmer management committee). Farmers have yet to fully manage the region's single-source, multiple-user system. However, allowing for farmer management at the unit level (i.e., below the secondary outlet level), while providing external management above this level (e.g., system-level management by ONAHA) has proved to be relatively successful for the systems studied.

Unrestricted access to irrigation water, both in time and volume, does not necessarily result in better management of the resource. When this condition exists, it can be detrimental to unit-level farmer organization, because there is little incentive to conserve water or establish orderly supply partitioning. Data from Systems A and B indicate that, when there are no direct costs applied to water use, water is managed more equitably and conservatively by user groups with limited or uncertain water access. Such restrictions make water more valuable, providing incentive for a group of irrigators to organize and ensure equitable, efficient air distribution.

Irrigation operations serving subsistence-level beneficiaries need to be well coordinated to fit both constant and periodic labor constraints. This was evidently a problem in the original design for Systems A and B, where the time farmers are both able and willing to commit to system parcels was overestimated. Additionally, crucial system activities may be poorly timed by system management and do not always synchronize with seasonal, off-system activities, which often receive priority in terms of farmers' labor commitment. Granting farmers the freedom to institute changes in system operation, which minimize constraints, such as labor, and maximize the use of local knowledge and capabilities, may well result in better operated systems. Farmers have demonstrated their ability for self-management at the unit level, where their organizational efforts have resulted in a functional and well-maintained rotation system that accounts for system delivery constraints and complements their own labor constraints and cultivation preferences.

The physical size of successful FMUs ranges from a few hectares to about 17 ha, whereas the optimum number of participant farmers depends more on the nature of water delivery than unit size. Units linearly extended along a secondary canal, with individuals drawing directly from the secondary (i.e., no tertiaries), appear to function best with about 20 individuals or less. Spacially compact irrigation units where farmers can easily see and thus monitor water use were found to result in less unauthorized use of irrigation water. Well-designed outlet controls on gates to units can be useful tools for system-level management. However, they cannot substitute for effective system-level (or main-system) management.

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