RESEARCH REPORT

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# Fundamentals of Smallholder Irrigation: The Structured System Concept

B. Albinson and C. J. Perry

International Water Management Institute

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This paper is dedicated to the memory of Leslie Shanan,
whose earlier work inspired many of the ideas it contains.

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# Contents

# Summary

Smallholder irrigation systems—where farm sizes generally range from a fraction of a hectare to 10 hectares—pose special management problems, especially where the water available for irrigation is frequently less than the demand. The intensity of system adjustments required to meet individual farmer demands, and the administrative complexity of measuring and accounting water deliveries have generally proven excessive when attempting to meet “on demand” schedules, resulting in chaos (often characterized by illegal tampering with infrastructure, and vast differences of water use intensity at different locations in the system).

The alternative—provision of a simple service, based on proportional sharing of available supplies on the basis of landholdings—has been resilient for many years over vast areas.

The approach is based on a clear delineation between the part of the irrigation system that is actively managed (at various flow rates and water levels) and the part of the system that operates *either* at full supply level (with proportional division of water down to the level at which farmers rotate among their individual farms), *or* is completely shut.

This operational design is known as a “structured” system, and has well-defined hydraulic characteristics, simplifying operation and management, in turn allowing a clearer definition of water entitlements and the responsibilities of agency staff and farmers.

The approach is particularly suited to areas where water is scarce and discipline is needed to ration water among users. An additional benefit, which has been demonstrated in modeling studies using a well–proven model relating to water and yield, is that the productivity of water (which is more important than the more traditional productivity of land when water is scarce) is substantially increased when deficit irrigation is practiced—a widely observed and predictable response to rationed water supplies.

Structured systems are most suited where water is scarce, clear definition of water entitlements is needed, management capacity is limited, and investment resources are limited.

The approach to determining critical aspects of a structured system design is described in this report.

# *Fundamentals of Smallholder Irrigation: The Structured System Concept*

*B. Albinson and C. J. Perry*

## Introduction

This report describes what is meant by, and the principles involved in designing and operating, a correctly “structured” system. We believe it is important to provide some background as to why the proposed approach has particular merit in certain circumstances, and what these circumstances are. On this basis, we hope that designers and managers can decide whether their particular needs will be well served by a structured system.

In principle, it seems a simple matter to take a large channel of flowing water and divide it successively into smaller channels, eventually to supply individual farmers with the amount of water needed, as and when required—irrigation “on demand.” However, supplying irrigation on demand requires a system that is capable of upward communication of information and downward delivery of water—an interactive management process. There is strong evidence that the technical, political, and social environments in most developing countries create a need for an on-demand service beyond the capability of many of the responsible institutions (World Bank 1991).

The increasingly prevalent problem of water scarcity and competition greatly exacerbates the inherent complexities of providing tens of thousands of farmers with customized individual schedules—and this is the situation where the “structured” approach has particular strengths.

The approach proposed here is not entirely novel (Shanan 1992) and is essentially in place in the *warabandi* (Malhotra 1982) areas of northwest India and Pakistan. Nevertheless, as more modern infrastructure, communications, and management approaches have been developed since the “structured” approach was first implemented more than 100 years ago, many believe that more modern approaches can better serve today’s needs. To that extent, however, there is no full agreement that the structured approach should be widely followed for the design of new projects and the rehabilitation of old projects. We hope the material in this report will help to resolve the (so far) endless arguments that have arisen over the subject—though even advocates of “on demand” irrigation concede that the past several decades of effort have failed to produce a sustainable success in any smallholder system (Davids 2001).

Additional background reading on the case for structured systems includes Malhotra (1982), Shanan (1992), Jurriens et al. (1996), and Horst (1998). The case for more flexible delivery systems is well summarized by Burt and Plusquellec (1990) and Plusquellec et al. (1994). Merriam (1992) went even further, recommending that both the timing and quantity of water deliveries should be unrestricted, in anticipation of a decline in demand as confidence in system reliability improved. Success, however, was transitory, and the system proved incompatible with scarcity of water.

## Background

The modern era of smallholder irrigation that began in the nineteenth century continues to this day. Until the mid-twentieth century the majority of the development was under the aegis of various colonial powers. Water rights of individual farmers were not an issue—in Asia, the colonial powers' interests were in achieving maximum output (which generally coincided with maximum drought insurance) in order to enable the autocratic administration to enforce equitable distribution of water—although it is interesting to note that the North West India Canal and Drainage Act (1873) did provide for some fundamental water rights. Typically, the defined responsibilities of agencies and farmers focused on who constructed, paid for, and maintained which parts of the system.

The past 50 years have seen two fundamental changes in the smallholder milieu: the strengthening of at least partly democratic forces, and the ever increasing excess of demand over available supplies of water. The first makes essential the entrenchment of individual rights—and a transparent mechanism for meeting those rights. The second makes essential the rational planning of the resource allocation.

Those arguing for more modern management systems have pointed to the need to increase production to meet the needs of a growing population, and to improve farm incomes through a service that will meet the needs of more water sensitive, higher value crops such as fruits and vegetables.

Water has become a scarce commodity in many areas for one or both of the following reasons: the progressive expansion of irrigation and other water demands within basins so that supply and demand curves have intersected; and the intensification of demand within projects, which has put farmers into a situation of competition rather than cooperation in local water management. The familiar "head versus tail" problems have developed, along with far more interference in system management, ranging from attempts to influence agency officials to interventions to steal water and even destruction of control structures.

Very often the background institutional trend has been a progressive deterioration in the authority of operating agencies. The democratic forces in newly independent countries have reduced the power of the bureaucracies of colonial rule, strengthening the power of the local people—and in parallel have degraded both the officially sanctioned rewards and the social authority of the bureaucracies. In turn, the quality of the agency employees attracted to work in this less competitive (Kikuchi et al. 2000) and less respected public sector system has declined.

A common symptom of failure from the above causes is the destruction of system infrastructure by the farmers. This is not just vandalism, but can also be an expression of frustration by the farmers that the systems have been unable to fulfill the promised levels of service (Horst 1998). Typical attempts at demand operation disintegrate in the complexities of technology management; the farmers have no means of verifying fairness of delivery and there is no clarity or transparency in the operation—an invitation to corrupt practices (Wade 1982).

## What is a Structured System?

A structured system includes a regulated upper canal network feeding groups of Service Areas. Within the Service Areas (SAs) the flow is distributed proportionally to individual watercourses. Flow in the upper regulated portion is variable and canals usually run at partial capacity. Within the SA the canals always run approximately at full design discharge or are completely closed.

A key operational characteristic of a structured system is the “structured level”—the interface between the regulated variable flow of the upper part and the proportional full flow of SAs. The importance of this division is founded in the fundamentals of open channel hydraulics. Regulation of variable open channel flow while maintaining full supply command requires constant management intervention, whereas full flowing proportional systems can be designed to distribute the incoming flow without management intervention.

In present common practice, the regulated upper part and the proportional full flow SAs are responsibilities of the system managers, and the flow within the tertiary areas is farmer managed. However, the inherent simplicity of the proportional flow management within the SAs makes it an ideal subject for the next segment of farmer management.

Table 1 summarizes the hydraulic characteristics of the various levels of the structured system facilities.

The complexity of management is directly related to the structured level. Systems can be structured at any level from the dam or barrage down to the minor level. An irrigation system can, therefore, be broadly specified in terms of spatial and temporal resolution. The spatial resolution, or service area, is the smallest unit that can be individually served, and the temporal resolution can be considered as the shortest period of irrigation delivery.

The more detailed the spatial and temporal resolutions, the greater the system’s flexibility but the more difficult to manage. The resolutions should, therefore, be set at levels that meet the declared service to the farmer, and that are within the capability of the owning and operating agencies to plan, design, construct and manage.

The structured concept provides a means of classifying aspects of physical design and operation of irrigation facilities and allows for an unambiguous definition of proposed and existing standards. There is a common language and framework for describing systems. Having a common language is important; the debate about the appropriateness, relevance and feasibility of various operational plans and associated designs suffers greatly when the

TABLE 1.
Hydraulic characteristics of the various levels of the structured system facilities.

| Location | Management | Hydraulics | Responsibility |
|---|---|---|---|
| Main system | Active | Regulated | Irrigation Agency |
| *Interface* | *Active* | *Gate* | |
| Service Areas | Passive | Proportional | Irrigation Agency |
| | | | Possible take over by farmers |
| *Interface* | *Passive* | *Division structure* | |
| Watercourse Area | Active | Distributed | Farmers |

proposal is not set out so that the responsibilities, infrastructure and rules can be seen in their entirety, and interrelationships are defined.

The essential merit of the structured framework is that it forces an orderly definition of the various levels in the system, and allows examination of whether the whole package is sound, internally consistent and implementable. This, in turn, defines the legal framework required to support disciplined operation by all parties.

The approach provides for the sharing of water among the Service Areas in accordance with availability, and predefined rules—most commonly uniform amounts of water are assigned per hectare of command.

The schedule of deliveries is determined by two factors: first, the total quantity of water available (which may be precisely known, if the project is served from storage, or estimated if in-season river flows are significant); and second, the expected general schedule of demand—based on some typical, overall cropping plan. The first factor determines the number of total days in the season that the system can be run at full supply level; the second determines how those "full supply days" should be scheduled over the crop season.

The operators do not undertake obligations beyond following the proposed schedule and ensuring that the proper discharges are supplied to the head of the service area and, then, proportionally to the watercourses (within which the distribution of water is the responsibility of the farmers) during the designated irrigation periods. In practice, the schedule will be adjusted in the light of actual water availability and in response to rainfall.

When supplies fall short of expectations, the shortage is shared by rotating the supply channels in accordance with predefined priorities that ensure any shortfall in the course of the irrigation season is equally shared in all Service Areas. Most importantly, canals are run full if they are run at all, because running canals at partial discharge will always result in the same distribution of scarcity—usually the head-end service areas will take their share, while the tail enders lose out.[1]

The simpler set of obligations placed on the operators—to meet a defined uniform schedule over large areas—combined with a physical infrastructure that is designed to distribute the scheduled supplies in proportion to the land area, result in virtually automatic operation of the system. This automation further allows less scope for undetected farmer intervention and for favoritism on the part of the system operators.

Individual farmers are free to grow whatever crops they wish and are aware of the schedule when irrigation will be provided. Because of the similarity of crop water requirements for a wide range of crops (most crops except rice, bananas and sugarcane have rather similar water requirements), the farmer's choice is not significantly restricted. From the farmer's perspective, the main difference between demand irrigation and supply irrigation is that supply-based systems require farmers to select and match crops to a predefined water supply—in return offering a firm guarantee of the overall pattern of deliveries.

For the managers, in supply-based systems, the calculated crop water requirements of the design cropping plan are a planning tool to assist overall scheduling, not a management tool to meet local demand. Once the schedule is fixed, no attempt is made to force the farmers to grow any particular crop. The entire effort of management is directed towards fulfilling the promised schedule.

[1]Interestingly, when the system was first introduced in northwest India, farmers preferred to be at the tail ends. Discipline was severe and no one would interfere with the flow in the larger channels, so that all low flows and water left after a turn was complete would drain to the tails, who thus got a better service!

## The Advantages of Structured Systems

The structured approach to system design addresses several of the legal, technical, and organizational problems discussed above:

- Water entitlement is transparently and simply defined.

- Operationally, the system clearly demarcates two zones of management—one the responsibility of the agency, and the other the responsibility of the farmers.

- The operational rules are clear and control systems are simple, so that the demands on operating staff are reasonable and transparent.

The approach is well adapted to conditions of water scarcity because water is allocated based on a proportional sharing of the available supply, rather than being an attempt to match demand with the available water. As will be clarified later, this does not mean that the schedule of supply is formulated without reference to demand, but rather that the prescribed schedule approximates the demand of an aggregated cropping pattern, and the feasible cropping intensity is a matter for the farmers to decide, based on experience and general advice the agency can provide in advance about overall seasonal supply.

## Productivity of Land and Water

As a final element in justifying the structured approach, we address the issue of productivity—which would seem a likely casualty in a system where scheduling and operations are simpler, management more rigid, and infrastructure less sophisticated.

We note that as water becomes scarce, system designers and managers must focus not on crop yield per hectare, but rather on the productivity of water, or yield per cubic meter. For many systems this is a completely new objective—the original designs were based on assumptions about the cropping intensities that farmers could achieve under the prevalent conditions of labour availability per unit of land, degree of farm mechanization, and profitability of crops. Today, farms have fragmented, labor available per hectare has often increased—and often been supplemented by mechanical equipment, and crop yields per hectare have increased sharply. All these factors point to more intensive agriculture and higher demand for inputs—including water—per unit of land.

Recent research indicates that:

- returns per cubic meter of water for common field crops are little affected by the level of sophistication of the irrigation service, and

- rationing water to levels *below* that required for maximum production per unit of land sharply increases water productivity.

Sarwar et al. (2001) have applied the SWAP model calibrated for Pakistan to assess the impact on local drainage requirements of the level of water availability and different management strategies. As part of this study, yield indicators were generated in order to assess the production impacts of meeting drainage objectives. These results can be reinterpreted to provide indicators of the productivity of land and the productivity of water for different management scenarios, where water is abundant and where water is scarce.

Sarwar (2000) considered three management scenarios: the first provided irrigation “on demand” in terms of timing and quantity; the second provided irrigation with a limited amount of flexibility in timing but fixed quantities; the third provided irrigation according to a fixed time and fixed quantity schedule. The response of common field crops—wheat and cotton—was simulated over a 15-year period of actual rainfall conditions. Irrigation schedules were optimised for conditions of excess water, where the objective was to obtain maximum yield per hectare, and for conditions of water scarcity, where the objective was to maximise returns to water.

The results show that:

- where water is plentiful, the maximum returns to land were achieved with a fully responsive, on-demand system of operation,

- where water is scarce, returns to water were 30-50 percent higher when water was rationed rather than supplied to meet the full crop requirement (whether with fixed or flexible schedules), and

- returns to water for a fixed schedule were within 3 percent of returns for demand-oriented schedules.

The importance of the last conclusion is all the more significant because the initial cost of infrastructure and ongoing management costs for a structured system (which is designed to provide the simple, uniform, rationed service) are far less than the cost of a system providing on-demand, differentiated services to very small farms.

In summary:

- rationed water substantially increases the productivity of water by encouraging farmers to follow a strategy of limited under-irrigation, and

- the productivity of water, where rationing is in place, is almost identical for both simple fixed schedules and for complex “on demand” management.

These results at first glance are surprising: Why do returns to water increase as crops are under-irrigated? And why is the productive benefit of responding to crop demand so small?

On the first point, a number of authors and analyses (Vaux and Pruitt, Hargreaves, Jensen, FAO) have identified diminishing returns to water as full evapotranspirative demand is met. As with most production relationships, the initial returns are large, but the returns to increased resource use become progressively smaller.

The ability of the crop to perform as well with a rather unresponsive irrigation schedule is related to the role of the soil matrix as a store of water, carrying over unutilized excess supplies from one week to the next. This stored water corresponds to a financial “bank balance,” where income does not have to equal expenditure every day, provided the overall balance over a week or month is positive.

We now elaborate the details of how fixed schedules are established and then set out the technical approach to system design.

## Applicability of Structured Systems

The background has set out the scenarios where the introduction of a structured system is likely to be most relevant and most suitable. The parameters to consider are:

- Availability of water—structured systems are particularly appropriate to conditions of competition and scarcity.

- Need to define water entitlements—where water entitlements are undefined or disputed, a structured system provides a transparent and systematic approach to allocation.

- Management capacity—structured systems provide clear and limited demands on system operators, and well-defined responsibilities for the farmers. This makes structured systems applicable where management capacity is limited.

- Investment resources—structured systems will generally be cheaper to construct and operate than the alternatives.

The corollary of this list should also be stated. Structured systems may *not* be the best choice where:

- Water is plentiful.
- Water rights are well defined.
- Management capacity is strong.
- Investment resources are plentiful.

## The Design of Structured Systems

In outlining the general approach to designing and operating a structured system, we take the very common example of an irrigation project serving many farmers. It has a regulated but not entirely certain source of water, which is frequently inadequate to meet potential demand from the area that can be commanded from the source—that is, land is plentiful compared to water. As noted above, if water is plentiful, then a demand-based system may be the best option. If, as is common in monsoon climates, water is plentiful in one season and scarce in another, the system will have to cope with scarcity (often when water is most valuable) and as such a structured system should be considered.

As in any well-designed system, the operational plan (or irrigation service) and the physical infrastructure are intrinsically linked. We first describe the operational plan, though with unavoidable reference to aspects of the infrastructure.

The key parameters in designing the system are:

- The *system duty*, (l/s/ha) or rate of delivery of water per unit area.

- The *structured level*, or “break point” below which the system is unregulated.

- The size of the *service area* within which farmers share water.

- The modular size of watercourses.

## Determination of System Duty

To assist in describing the analysis, we set out the data for a hypothetical case below:

- Average available irrigation water: 2,000 $m^3$/ha of *command.*
- Maximum crop demand: 10 mm/day (80 $m^3$/day/ha of *crop*).
- Total crop demand: 400 mm (4,000 $m^3$/ha of *crop*).
- Duration of crop season: 100 days.
- Soil capacity: 100 mm/m (1,000 $m^3$/ha of *crop*).

From these data we see that in an average year, it will only be possible to crop 50 percent of the total command—water availability at 2,000 $m^3$/ha of command is half of demand per hectare of crop. How should this quantity of water be delivered? As a rule of thumb, we aim to deliver water on average every 10–15 days. If the irrigation frequency is much higher, it is difficult to meet peak requirements and also difficult to deliver the extra water available in a better than average year; if it is much lower, an individual irrigation may exceed available soil capacity, and in low availability years may result in excessive gaps between irrigations.

It is often convenient to deliver irrigation during a period of 1 week, because this allows each farmer to have a fixed day and time for his turn.

In this case we aim to irrigate eight times during the season, and each application will be of 250 $m^3$/ha of command, or a depth of 50 mm on the 50 percent of the command that is cropped. This corresponds to 7.1 mm/day, which we note is somewhat less than the peak demand of 10 mm/day and considerably more than the average demand for the season of 4 mm/day. The maximum demand is met by delivering water in advance of the peak, and then each week during the peak, while the lower off-peak demand is met by delivering irrigation every other week, or even every third week in periods of very low demand.

We also note that since there are 15 weeks in the season, and that we are on average irrigating in only 8 of those weeks, we have the capacity to deliver almost twice the average quantity of water if supplies are particularly good. If, on the other hand, supplies are 30 percent below normal, there will still be about five irrigation deliveries, which should be enough to allow scheduling for a smaller irrigated area.

As a hypothetical case, we have designed to provide 250 $m^3$ of water per hectare of command in each of eight irrigations in an average year. If each turn lasts 7 days, the system will deliver about 35 $m^3$/ha/day, or a system duty of 0.4 l/s/ha.

## Determination of the Service Area and Structured Level

These two parameters are related, the larger the Service Area, the higher up the system will be structured.

As defined above, the structured level is the point at which on-off control takes place—above which the canals are regulated and below which the system is unregulated, comprising a group of watercourses that receive the same, undifferentiated service.

Determination of the structured level is open to a variety of considerations; the lower the structured level, the more gates are to be operated. The higher the structured level, the less the ability of management to respond to local rainfall or other perturbations in the system—or indeed to consider specific irrigation schedules for specific areas (cotton areas as distinct from maize, for example). This decision reopens the whole issue of responsiveness versus flexibility that underlies the “on-demand” versus “supply-based” discussion earlier, and system designers should think carefully on the balance to be struck.

Some considerations that determine the appropriate structured level are: soils (sets the frequency of irrigation), response to rainfall (depends on rainfall distribution), established rights, time to fill and empty rotational units, the capability of the institution to operate and maintain, and the sociological and political environment.

*Soils:* They have a major influence on the size of the Service Area. Light soils require more frequent irrigation than clay soils, and this affects the rotational interval. A general rule is that the filling time for the service area should not be more than 10 percent of the rotational interval.

*Response to rainfall:* An assessment should be made of the spatial distribution of precipitation. A thunderstorm type distribution with highly localized distribution would require smaller Service Areas.

*Time to fill and empty:* The size of the Service Area has to be related to the operational plan. Too large a Service Area might take too long to implement the planned rotational schedule.

*Institutional capability:* The institutional capability can only be inferred by the performance in operating and maintaining existing projects. As a general rule, a good indication of operation is the amount of damage caused by frustrated farmers.

*Sociological and political environment:* A decision that affects the Service Area is whether to allow differing water duties in different blocks.

Where water is constrained the available supplies should be distributed evenly over the Culturable Command Area (CCA). But in some water constrained areas where paddy, sugarcane, bananas or other crops with higher water requirements are planned, because the soils are not suitable for other crops, water allocations may have to be localized and different water duties allowed for different blocks. If the entire block can be treated uniformly, then it can be structured as a single unit. If wide variations in supply are specified between one part of a block and another, it must be broken down and a lower level of structuring adopted. This means the regulation has to be taken to a lower level. There may be established rights, which have to be also taken into account.

*Farmers’ Rights and Obligation—Equality and Equity:* There may be established rights to certain crops, usually paddy. This may require the provision of service areas designed to serve the established right. Each farmer must have clearly defined rights and obligations. Equity is defined in the rights, and equality is established when the rules are correctly enforced. Equality in irrigation means all farmers are favored equally in periods of abundance and suffer equally in times of shortage. A correctly structured system achieves these objectives because of the inherent transparency of operation. Any farmer can afford a cheap clock, and as long as the water levels are at the standard marks he can be sure that the supply is fairly distributed.

Complete equity is difficult to achieve because the sizes of landholdings vary widely. The best we can do in the medium-term is to ensure that the supply is distributed proportionally to the areas commanded. However, if the watercourses are planned with modular areas and operated with modular flows, there is no technical or practical reason why smaller lots should not get a weighted time. The problem is that any weighting to give advantage to small lots would be arbitrary and open to misuse and has not been used in practice. However, in the warabandi system of northwest India, weightings are indeed made for distance from the irrigation outlet.

*Common allocation to Service Areas desirable:* Differential water allocations to adjacent Service Areas are quite possible to account for different agro-climatic conditions such as cropping patterns, soils or topography. However, great caution is needed to avoid the appearance of favoritism. Different allocations presuppose that the management will be able to: a) calculate and schedule water requirements for each Service Area; and b) operate the system to provide the differing water requirements in each block. In general, it is a good practice to have as little variation as possible between Service Areas. Whatever the distribution detail, it is essential that the farmers know in advance each season when and how much water will be delivered.

## Determination of Appropriate Modular Watercourse Size Range

A Service Area comprises one or more watercourses. Selecting an appropriate range of sizes for watercourse commands is essential: the smaller the watercourse, the smaller the irrigation stream to the farmers within the watercourse (given the proportional relationship between flow and area), and vice versa.

While overall system duty determines the capacity of the various channels, at the farm level the size of the irrigation stream is constrained by the on-farm technology. Typically, a farm stream of 30 l/s is manageable with a range from 20-100 l/s depending on soil characteristics, slopes, and other factors such as labor availability. The appropriate range will be a matter of determination for the local conditions (paddy will be at the higher end of the range), but continuing with the hypothetical example, we assume that 20-40 l/s should be the target range for the example. This range, together with the computed system duty of 0.4 l/s indicates that the modular watercourse area (farm stream/duty) should range from 50–100 hectares. A watercourse of 50 hectares will have an irrigation stream of 20 l/s, and a watercourse of 100 hectares will have an irrigation stream of 40 l/s.

## The Special Case of Paddy

Rice, while not an aquatic plant, is both water-tolerant and water-demanding. Paddy cultivation exploits the water tolerance that gives the plant a competitive edge over other grasses. The presence of standing water for much of the growing season also means that: (a) duties are high to provide for infiltration, evaporation and evapotranspiration, and (b) the presence of a surface reservoir provides a buffer against irregular supplies. This buffer implies that paddy is well suited to supply-based irrigation, the main technical problem being the design of proportional systems, which will handle fairly large differences in water requirement at different stages of growth.

There are vast areas of smallholder paddy in the deltas and coastal plains of the world that could be well served by correctly structured systems. Where irrigation exists it is almost invariably served by field to field irrigation. Attempts to provide a differentiated demand-based service to each farmer have been costly failures. Research (Tabal and Wickham 1981) has shown that it is much more important to provide equitable flow in the distributary canals rather than focusing on individual on-farm water supply. Correctly structured systems are a cost-effective and suitable method of fulfilling these criteria. This matter is discussed further in the Technical Annex.

## Conclusions

We have explained how, and described the circumstances in which, a well-planned supply-based system is capable of providing an irrigation service that for all practical purposes is equivalent to a demand-oriented system. The record is replete with irrigation systems that have been planned to provide a sophisticated, on-demand service but have failed to perform as designed.

There is increasing evidence that the reliability and simplicity of operation is a compelling argument for farmers and system operators alike. A recent study of the Gediz Basin in Turkey (IWMI and GDRS 2000) has revealed how, in response to drought conditions during the late 1980s, the State Hydraulics Organization (DSI) introduced a supply-based scheduling system. This replaced a crop-based system, which previously determined canal discharge by technical estimates of water deliveries necessary to avoid crop stress. The drought made it impossible to continue this system of operations as water availability was inadequate to meet crop water requirements. Estimation of water requirements for each rotation was replaced with a simple calculation of the number of irrigation deliveries, at maximum design discharge, available in the reservoir in April. Irrigation releases are now made over a shorter period of time than before. However, canals run full, or are closed, and farmers are assured of equitable access to the available resources.

In another case, in Sri Lanka, the managers of the Kirindi Oya scheme have changed operations, in consultation with farmers, from continuous variable discharge to a program of rotations at full supply discharge. This was to reduce water use and to increase equity of the distribution (Sakthivadivel et al. 2001). During the dry season (*yala*) 1999, with a severe water shortage, average paddy yield approached 4 t/ha. This contrasts with the yala, 1992 season, when water availability was broadly similar, and average yields were close to zero.

Irrigation systems designed to deliver a service matched to crop water needs have, in general, failed to perform as intended. Structured design with clear operational rules, results in irrigation infrastructure that can deliver reliable services and also allow the farmers to determine their own optimum cropping systems. The inherent simplicity of operation of hydraulic proportional distribution and the transparent monitoring systems make the infrastructure ideal for transfer to participatory management.

# Technical Annex

This part of the paper provides guidance on the special requirements of structured system design not found in the standard texts. It is not, however, intended as a comprehensive treatise on canal hydraulics.

## Hydraulic Regulation and Controls

Structured networks comprise a regulated upstream portion supplying prescheduled flows to downstream Service Areas, which distribute the flow proportionally to watercourses. In almost all cases, it proves convenient to regulate the main and sub-main canals and to use the distributary and minor canals as Service Areas. Some notes on the details of design, which are especially important to structured systems, are given below. This is not an exhaustive treatment of canal design but draws attention to the special features involved with structured systems, and should be read in conjunction with standard texts.

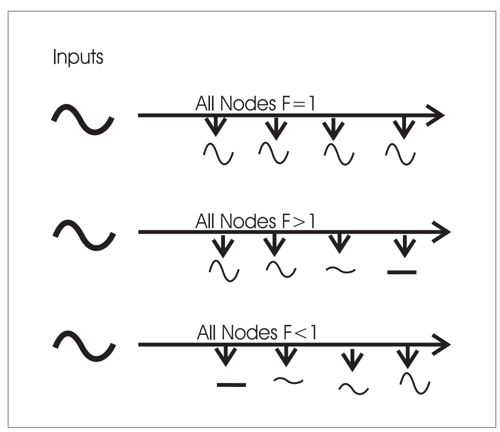
*Canal Design:* A canal has three design parameters, width, depth and slope. Only one of these combinations will produce a stable, non-scouring, non-silting or "in regime" earth canal. For earth canals, it is recommended that a section as close as possible to regime be used. The Lacey Regime f is best determined from existing similar systems on the same river which appear to have achieved some level of stability. For lined systems, it is only necessary to check for the silting potential (Lacey f above silting level) as the scour on lining will not normally be important.

## Regulation of the Conveyance System Upstream of the Service Area

*Main and Branch Canals:* This part of the network must be capable of a high degree of regulation, as it must be able to supply the distributary channels on demand. The demands will normally be predictable during the dry season, but will be subject to random variations during the rainy season as a result of the need for supplementary irrigation. To provide for varying demands there are several possible alternatives of differing degrees of sophistication and cost.

*System Response Theory:* If Q is the flow in the parent canal and q in the daughter canal, then the response at individual nodes is measured by the value of $F=(dq/q)/(dQ/Q)$ or the relative change of flow in daughter and parent canals without manual or automatic intervention. Figure 1[2] shows the nodal response with F=1, >1 and <1.

FIGURE 1.
System Response Theory.




[2]This diagram by L. Horst, 1998, is a prime example of a picture being better than a thousand words.

## Regulated Hydraulics

*With all nodes at F>1* variations at the parent canal flow are concentrated in the upper reaches and either passed into the upper branches (if they are open) or cause overtopping of the parent canal's upstream banks. Undershot regulation in the parent canal combined with overshot regulation into the daughter canal (the Indonesian Romijn gate arrangement) yields very high F values. Automatic downstream control has some of these characteristics—shortages are concentrated in the upstream reaches, but excess flows never occur because of the nature of the regulation.

*With all nodes at F<1* variations in parent canal flow are concentrated in the lower reaches, all transients are passed to the downstream ends of the parent canal, where they should be dealt with by providing additional freeboard and escapes. Long overshot weirs on the parent canal combined with undershot discharge modules to the daughter canal provide this response. Automatic upstream control yields the same results. For regulated channels, this arrangement is usually preferred because the unstable component appears at the downstream end, where excess flows can be more easily passed to the drainage system. Duckbill weirs controlling the parent canal combined with an undershot daughter off-take is a simple cheap and effective way to provide low F values for more constant flow to the daughter canals. The duckbill should be combined with undershot sluice control, the sluice passing the base flow and silt, while the duckbill handles the variable component. In this way most of the benefits of the long weir are retained at less cost. The stability of flow through the off-take can be improved by using one of several module designs available.

*With all nodes at F=1* division at each node is proportional and variations at the head are transmitted proportionally throughout the system. For proportional distribution within the structured area it is important (especially with earth canals) to provide as many critical depth control points as

TABLE 2.
Control structure combinations for proportional distribution.

| Canal Control | Off-take control | F | Comments |
|---|---|---|---|
| None, depth D | Weir with crest at 0.9 D | 1 | Usually results in impossibly narrow off-take weir |
| None, depth D | Orifice and/or pipe set at 0.3 D | 1 | Subject to earth canal stability uncertainty. Pipe entrance can be at 0.9 D to allow silt draw equity |
| Critical depth flume or weir, depth D; should match canal stage/discharge curve | Orifice and/or pipe set at 0.3 D | 1 | Recommended. Pipe entrance can be at 0.9D to allow silt draw equity |
| Critical depth flume or weir, D; should match canal stage/ discharge curve | Weir with crest at D | 1 | Usually results in an impossibly narrow off-take weir; makes a silt trap |

possible. It is the relative instability of earth canals that most seriously destroys the proportionality of free off-takes. Critical depth structures are completely stable. As shown in table 2, a pair of weirs at each off-take provide perfect proportionality, however, there are two serious problems with this solution:

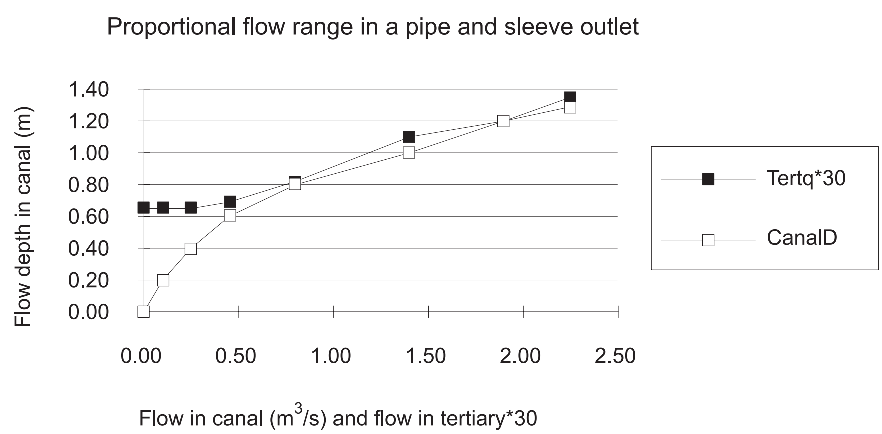
(a) the ratio of crest lengths in canal and off-take may be very large, and

(b) weirs in canals form silt traps.

However, every possible opportunity should be taken to provide critical depth conditions immediately downstream of all off-takes. Every foot crossing can be a box culvert drop providing critical conditions. Replogle[3] flumes can be used with minimum cost, and in addition to providing stability they give the chance to verify flows.

*Off-takes:* At the off-take the nodal performance should be as near F=1 as possible. A weir with crest near the canal bed achieves this but unfortunately results in weirs which are too narrow to be practical. The off-take of choice will be some form of APM[4] or pipe or a combination of the two. The APM is essentially an orifice type control. Using correct design it is possible to make an orifice or pipe (or a combination of the two) off-take proportional over a significant range of flows.[5] Figure 2 illustrates how this is achieved.

FIGURE 2.
Range of proportionality at off-take.




[3]"Flow Measuring Flumes for Open Channels"; M.G. Bos, J.Replogle, A. Clemmens; ASAE, 1991. The United States Bureau of Reclamation (USBR) in conjunction with the United States Department of Agriculture (USDA) and International Institute for Land Reclamation and Improvement (ILRI) has recently developed a full suite of Windows software for the design of Replogle flumes: WINFLUME November 1999,

[4]Adjustable Proportional Module, an orifice device which is initially adjustable with a moveable roof shoe but which is concreted in solid after the system has been tested.

[5]This is contrary to commonly accepted dogma. Although the characteristics of open channel or overshot flow are an H3/2 function and the characteristics of an orifice are a Z1/2 function, nevertheless it is possible by appropriate design to achieve a useful range of proportionality.

A computer program CFO[6] is available to assist in the design of appropriate combinations of control structures to achieve proportional division over the required operational range. The example illustrated in figure 2 is for a typical distributary channel with a design discharge Q = 2.25 $m^3/s$, Bed width B = 1.0 m, Depth of flow D = 1.25 m, and canal slope S = 0.0005. The off-take pipe has a diameter d = 0.25m, a length L = 10m with an inserted sleeve of diameter d = 0.15, and length l = 1m. The off-take pipe is set at 0.68 D with a design flow of 0.075 $m^3/s$ or ratio = 30 There is substantial range of close to proportional flow from a main canal discharge of Q = 0.9 to 2.25 $m^3/s$.

Off-takes should be set to draw an equitable portion of the wash load carried by the parent canal. This can be achieved by setting the inlets at a lower level than the outlets.

*System Tuning:* There are, inevitably, small errors in design and construction that would, if left uncorrected, result in an inequitable distribution. The practice in the warabandi areas of northwest India is to not finalize the setting of the off-take structures, most notably the adjustment of the APM off-take iron shoes, until after system construction is completed and tested under full flow conditions. When all the farmers are satisfied that the system is distributing equitably the shoes are permanently grouted in place. If pipe off-takes are used as the structure, a short sleeve can be used for adjustment and it can be permanently grouted in once an acceptable distribution is attained. The system is then very difficult to interfere with.

*Field Testing of Outlet Devices Recommended:* If some variation of the standard APM is employed using local materials, for example, a pipe with sleeves, it is strongly recommended that full scale tests of the proposed outlet characteristics be conducted. These can be quite easily and cheaply done, using a small pump and some simple V notch weirs to measure flow rates. A stage discharge curve is required to confirm the assumptions made during design.

*Arrangements for monitoring operations:* An important feature of the structured hydraulic regulation system is the simplicity of operations, either full supply or zero discharge. Monitoring the correct operation of the distribution system is also considerably simpler than with fully regulated distribution to the service area—provided the discharge entering the distributory canal is within the design limit (80-110% of FSQ) and the distribution to each outlet should be within the acceptable range. This correct functioning of the entire canal can be confirmed by a single measurement of water level at the tail of the canal, at the final off-take or tail cluster. In North India, a simple tail flume design is used, in which design water level coincides with a step in the flume walls—hence there is no requirement for a water level gauge.[7] The stepped design of the open flume structure also provides an additional degree of protection for safe passage of transient flows that may result from runoff entering the canal upstream.

## The Special Case of Paddy

*Watercourse layout for **paddy areas** in systems **structured** at the **distributary** level*

For cultivation of rice paddy, field to field irrigation rather than rotation through field channels will

[6] Canals, Flumes and Outlets (CFO), B. Albinson 1996.

[7] The warabandi and its infrastructure. S.P. Malhotra. Central Board of Irrigation and Power. Publication No. 157. New Delhi. 1982.

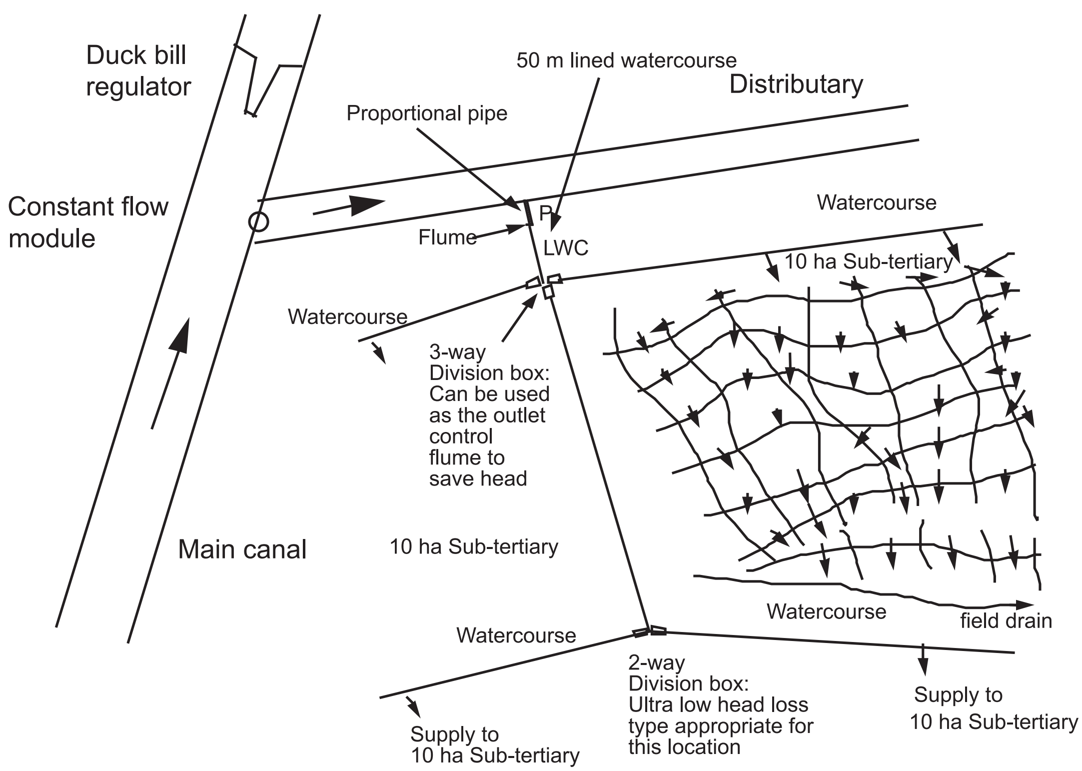
probably remain the preferred method in many areas. Tabal and Wickham (1981) showed that providing equitable and reliable flow at the head of the tertiary canal is more important than on-farm distribution. A reasonable interpretation of Wickham's data would lead to the conclusion that the number of fields crossed is not a significant factor, although the distance to the nearest farm channel should not be more than 300 m.

To satisfy these criteria, the watercourse area can be about 40 hectares, divided into four subareas. The peak duty is usually about 1.5 l/s/ha for pre-saturation and land preparation and 1.0 l/s/ha for maintenance flows during crop growth. The peak flow will be 60 l/s and this can be rotated round the four subareas in turn, starting at the highest level. When preparation is complete, the flow can be reduced to 40 l/s divided proportionally among the four subareas. The distributary system will have to supply any flow between 1.5 and 1.0 l/s/ha proportionally to all watercourses in the Service Area, with adequate command at all design flows. This is possible using correctly sized pipe outlets as illustrated in figure 2. The main canal will have to be regulated to supply the distributary channels at the flow rates necessary to meet the operational plan.

In the case of systems where paddy is grown during the wet season and upland crops are irrigated in the dry season, temporary field channels are required for the upland crops. These temporary field channels will have to be constructed each year, because they will be lost during the paddy season. With the layout described the average length of temporary field channel will not be much more than 200 m. The conceptual layout described is illustrated in figure 3.

FIGURE 3.

Conceptual layout of tertiary unit for paddy cultivation.

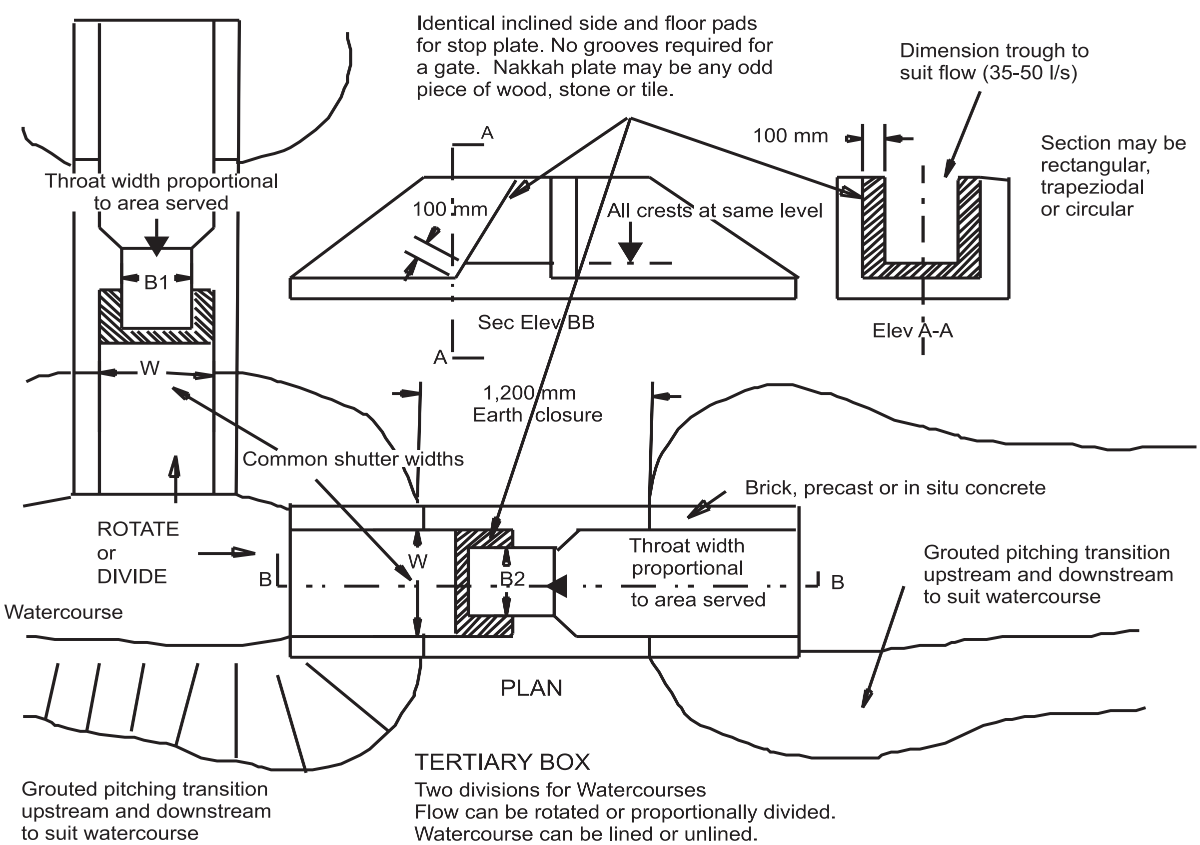


## *Tertiary Division Boxes*

Division boxes in tertiary channels often have their gates stolen. To combat this the design shown below makes a formal gate unnecessary. The key feature of this design is a relatively wide pad set at about $60^0$ to the horizontal so that no accurately formed gate is required, the shutter simply rests on the side and floor pads. Any form of shutter will do including scrap wood, roughly hewn log, woven palm leaves etc. The seal of the shutter can be improved by rubbing the shutter against the inclined pads with some coarse sand as a grinding paste. The box form provides hydraulic stability. The dimensions and design of the box are not critical, except the throat widths have to be proportional to the area served if the box is required for proportional distribution. The boxes can be precast and, for earth tertiaries, provided with grouted pitching transitions upstream and downstream to suit the soil stability. The boxes are installed at convenient locations to provide either purely flip-flop control or both flip-flop and proportional distribution depending on whether the system design is based on rotation or continuous flow.

A proposed design, suitable for either lined or unlined watercourses is shown in figure 4.

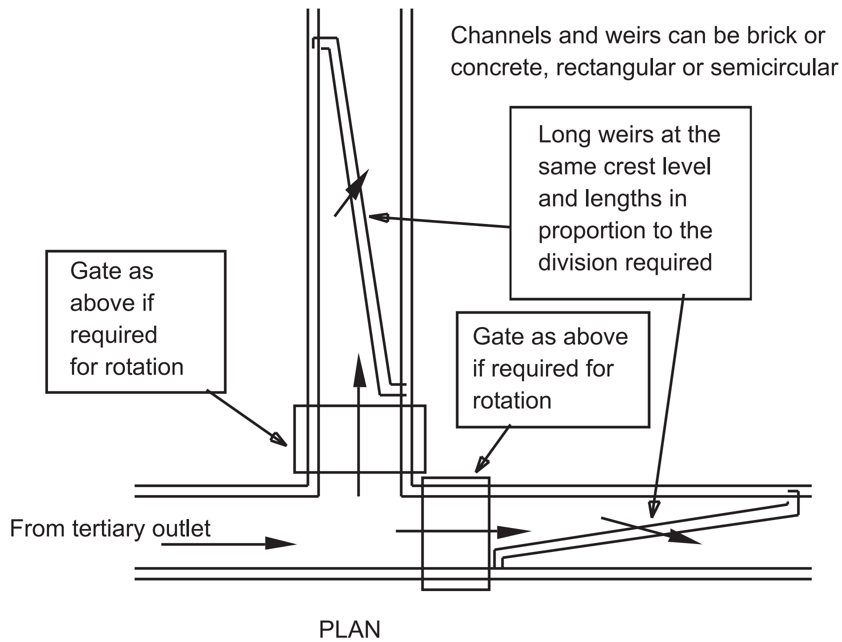
FIGURE 4.
Typical design for a tertiary division box (Not to scale).



## *Low Head Loss Division*

In the lower reaches of many irrigation systems the terrain is often very flat and there is very little head available for critical depth division boxes. The design in figure 5 is based on the notched log principle and consumes very little head.

FIGURE 5.
Typical layout for low head division.



## Literature Cited


Albinson, B. 1996. Channels, Flumes and Orifice (CFO) computer program in Visual Basic, Unpublished.

Bos, M.G.; J. Replogle; A. Clemmens. 1991. *Flow Measuring Flumes for Open Channels*. ASAE.

Burt, C.M.; and H. Plusquellec. 1990. Water Delivery Control. In *Managing Farm Irrigation Systems*, eds. G. J. Hoffman, T. A. Howell and K. H. Solomon. USA: American Society of Agricultural Engineers. 373-423.

Davids, G. 2001. Personal communication September, 2001.

Horst L. 1998. *The dilemmas of water division: Considerations and criteria for irrigation system design.* Colombo, Sri Lanka: International Water Management Institute.

IWMI and GDRS, Turkey. 2000. *Irrigation in the basin context: The Gediz Study.* Colombo, Sri Lanka: International Water Management Institute.

Jurriens, M.; P.P. Mollinga; and P. Wester. 1996. *Scarcity by Design: Protective Irrigation in India and Pakistan.* Wageningen, The Netherlands: International Institute of Land Reclamation and Improvement. (Liquid Gold 1996, paper 1).

Kikuchi M.; D. J. Merrey; and L. Dassenaike. 2000. *Compensation of irrigation professionals: A comparative study of the Philippines, Sri Lanka and Pakistan.* IWMI Discussion Paper. Colombo, Sri Lanka: International Water Management Institute.

Malhotra, S. P. 1982. *The Warabandi System and its Infrastructure*. New Delhi, India: Central Board of Irrigation and Power.

Merriam, J. L. 1992. The need on the farm for flexible water supply schedule. In *Advances in planning, design and management of irrigation systems as related to sustainable land use:* Proceedings of the International Conference held in Belgium, 14-17 September 1992.

Plusquellec, H. L.; C. M. Burt; and H. W. Wolter. 1994. *Modern Water Control in Irrigation: Concepts, Issues and Applications.* World Bank Technical Paper 246. Irrigation and Drainage Series. USA: World Bank.

Sakthivadivel, R.; R. Loeve; U. Amarasinghe; and M. Hemakumara. 2001. *Water Scarcity and Managing Seasonal Water Crisis: Lessons from Kirindi Oya Project in Sri Lanka*. Research Report (in review). Colombo: Sri Lanka. International Water Management Institute.

Sarwar, A.; W.G.M. Bastiaanssen; T.M. Boers; and J.C. Van Dam. 2001. *Evaluating drainage design parameters for the Fourth Drainage Project, Pakistan by using SWAP model: Part I—calibration.* Irrigation and Drainage Systems, 14(4):257-280.

Sarwar, A. 2000. *A transient model approach to improve on-farm irrigation and drainage in Semi-arid zones.* Ph.D. thesis, Wageningen University and Research Center.

Shanan, L. 1992. Planning and Management of Irrigation Systems in Developing Countries, *Agricultural Water Management.* 22(1 and 2).

Tabal, D. F.; and T.H. Wickham. 1981. *Effects of Location and Water Shortages in an Irrigated Area*. The Philippines: IRRI.

Wade, R. 1982. Systems of Administrative and Political Corruption: Canal Irrigation in South India, *Journal of Development Studies.*

World Bank. 1991. *Experience with Rice Irrigation in Monsoon Asia*, Washington D.C., USA: Operations Evaluation Department.

# *Research Reports*

45. *Pedaling out of Poverty: Social Impact of a Manual Irrigation Technology in South Asia.* Tushaar Shah, M. Alam, M. Dinesh Kumar, R. K. Nagar, and Mahendra Singh, 2000.

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48. *Predicting Water Availability in Irrigation Tank Cascade Systems: The CASCADE Water Balance Model.* C. J. Jayatilaka, R. Sakthivadivel, Y. Shinogi, I. W. Makin, and P. Witharana, 2000.

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58. *Fundamentals of Smallholder Irrigation: The Structured System Concept.* B. Albinson and C. J. Perry, 2002.

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