THE USU UNIT COMMAND AREA MODEL

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WMS REPORT 71

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PREFACE

This study was conducted as part of the Water Management Synthesis II Project, a program funded and assisted by the United States Agency for International Development. Utah State University, Colorado State University and Cornell University serve as co-lead universities for the project.

The key objective is to provide services in irrigated regions of the world for improving water management practices in the design and operation of existing and future irrigation projects and give guidance for USAID for selecting and implementing development options and investment strategies.

For more information about the project and any of its services, contact the Water Management Synthesis II Project.

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BACKGROUND AND METHODOLOGY

The Problem

Much money and effort are being spent on irrigation projects to improve production and rural well-being. However, without having a systematic and synthesized approach to how they are designed and managed, the results are usually disappointing.

The analysis of irrigation systems must be prepared to deal with a multitude of important linkages between the watershed catchment, storage facility (if present), main system, and individual command areas. These linkages are not generally considered in sufficient detail during the design, operation, and rehabilitation phases of an irrigation project. As a consequence, a large variety of operational weaknesses typically develop. Often the problems are attributed to the engineers and administrative agencies responsible for main delivery systems; and often they develop when the array of social and institutional forces acting within the system are not recognized or considered.

The translation of social and institutional influences into hydraulic and hydrologic impacts has yet to be made. As a result, many irrigation systems are designed and managed according to criteria which simplify and standardize the routine of the operators but constrain irrigation practices at the farm level.

Another typical reason for the shortcomings of irrigation projects is that main delivery systems are often treated as ends unto themselves. The critical perspective taken here is that main systems exist to serve the command areas. The farmers/water users are the clients without whom the rest of the irrigation system serves no purpose. Given this perspective, major improvements in the performance of irrigated agriculture can be realized through appropriate changes in the design and management of main delivery systems to enhance water use in the command areas.

The potential benefits of irrigation, however, cannot be derived unless the collection, storage, transmission, and delivery of water are coordinated with the temporal and spatial characteristics of the water demands at the farm level. A necessary input to the design, operation, and management of the main delivery system, therefore, is the behavioral needs of the area it serves.

This research addresses the twofold problem of first determining the aggregate irrigation water requirement for a command area represented by multiple landowners, cropping patterns, soil types, and community water management schemes; then, once water is delivered by the main system, of simulating the command area's response to the water supply.

This study has been undertaken as a major component of the WMS II special study topic -- Main System Design, Management, and Rehabilitation. The objectives of this special study include the development, validation, and practical application of a comprehensive multidisciplinary, simulation, and optimization model of branched irrigation networks. The overall model can be used for both: evaluating alternatives for achieving timely water deliveries; and to help determine the physical, social, and economic trade-offs associated with mitigating the gap between existing water delivery capabilities and farm water requirements. Thus, the model provides a framework for formulating guidelines for the selection and development of appropriate irrigation system technologies (101).

In the Main System Design, Management, and Rehabilitation modeling effort, irrigation systems are viewed as consisting of four linked subsystems: the watershed catchment area, the storage facility, the main delivery system and the command area. This work addresses the last of these -- the command area, where irrigation water is ultimately used to increase agricultural production.

Unit Command Area

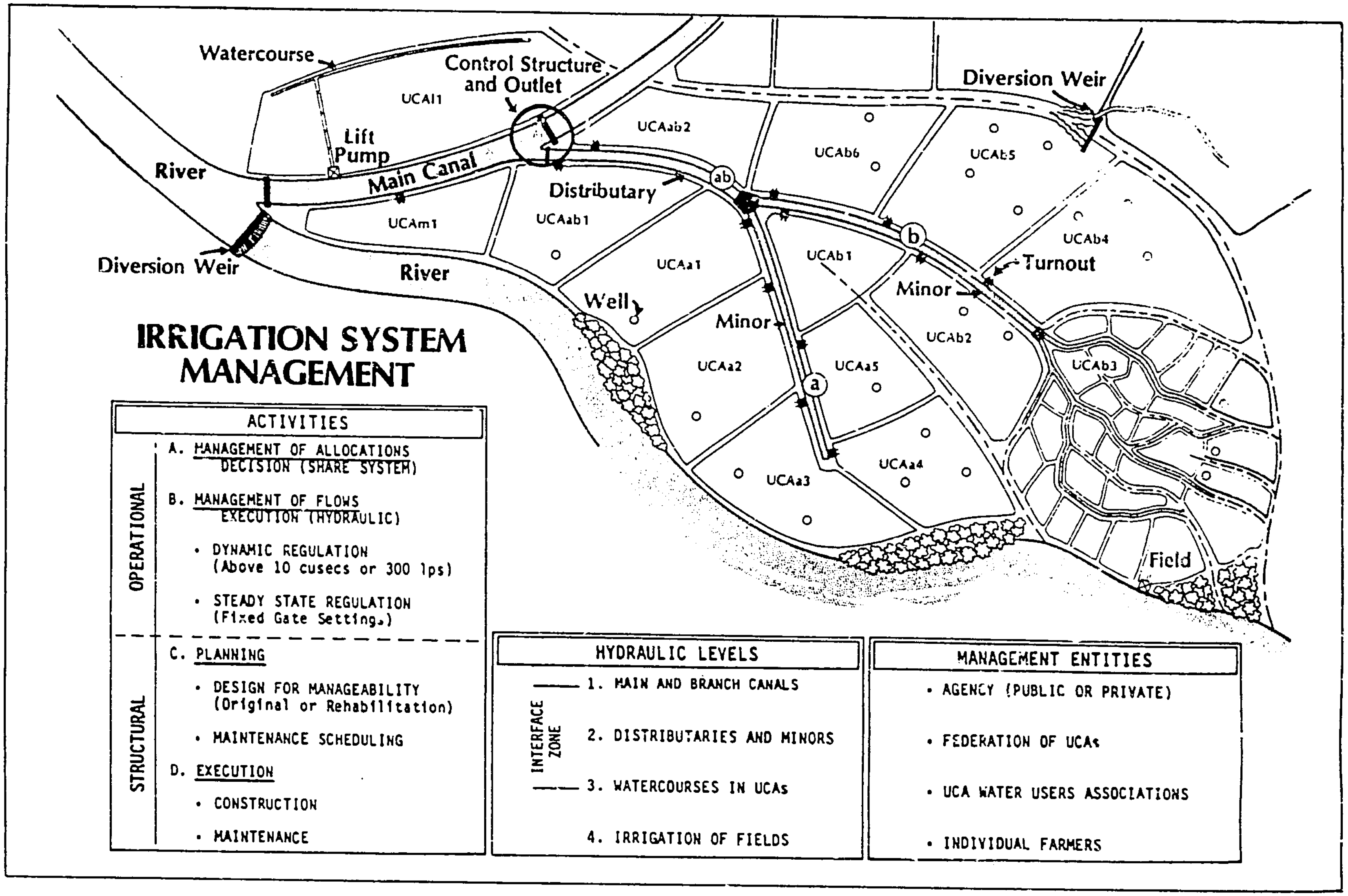
The irrigation conveyance system serves as a pathway from the water supply (diversion dam or reservoir) to the individual fields. Near the downstream end of this system, water distribution changes from allocation among groups or blocks of irrigated fields to individual field allocations. The blocks of fields where this shift in allocation occurs demarcate the main system from what are defined as the unit command areas (UCAs). These are physical points in the system and are generally at turnout or diversion structures. These points also tend to mark the places where division by flow rates end and division by time (irrigation turns) begins.

An irrigation system might be likened to a tree. The trunk denotes the main canal, the various branches represent the distributaries and minors, the leaves describe the UCAs, and the cells within the leaves symbolize the fields. The trunk and branches provide water and nutrients to the leaves without which they are only so much dead wood. Inside the leaves smaller veins, analogous to UCA watercourses and irrigation field channels, transport nourishment to the individual photosynthesizing cells. As with UCAs in an irrigation system, leaves may appear on the trunk but tend to proliferate on the smaller branches.

Figure 1 shows the layout of a hypothetical run-of-the-river irrigation system. A UCA is shown in detail at the downstream end of one of the distributaries. This same UCA is enlarged in Figure 2 and will be used throughout the text to illustrate various points and concepts. These figures evolved from the WMS II Triad Synthesis Activity with researchers from the three universities involved. They represent a consensus on irrigation system terminology, and therefore, provide a framework for reference and discussion.

Notice in Fig. 1 that UCAs can appear at any point along the main delivery system. A UCA may have a turnout directly off the main canal system or derive its water from a minor shared with other UCAs. The one distinguishing characteristic of a UCA is that, internal to the UCA, water is distributed to individual fields rather than to blocks of fields.

In Figure 2 it is apparent that the watercourses and drains within the UCA form principal field boundaries (just as canals and drains tend



IRRIGATION SYSTEM MANAGEMENT

ACTIVITIES

OPERATIONAL

A. MANAGEMENT OF ALLOCATIONS
DECISION (SHARE SYSTEM)

B. MANAGEMENT OF FLOWS
EXECUTION (HYDRAULIC)

- DYNAMIC REGULATION (Above 10 cusecs or 300 lps)
- STEADY STATE REGULATION (Fixed Gate Setting.)

STRUCTURAL

C. PLANNING

- DESIGN FOR MANAGEABILITY (Original or Rehabilitation)
- MAINTENANCE SCHEDULING

D. EXECUTION

- CONSTRUCTION
- MAINTENANCE

HYDRAULIC LEVELS

INTERFACE ZONE

1. MAIN AND BRANCH CANALS
2. DISTRIBUTARIES AND MINORS
3. WATERCOURSES IN UCAs
4. IRRIGATION OF FIELDS

MANAGEMENT ENTITIES

- AGENCY (PUBLIC OR PRIVATE)
- FEDERATION OF UCAs
- UCA WATER USERS ASSOCIATIONS
- INDIVIDUAL FARMERS

Figure 1. Example Run-of-the-River Irrigation System with Listing of Irrigation System Activities, Hydraulic Levels, and Management Entities.

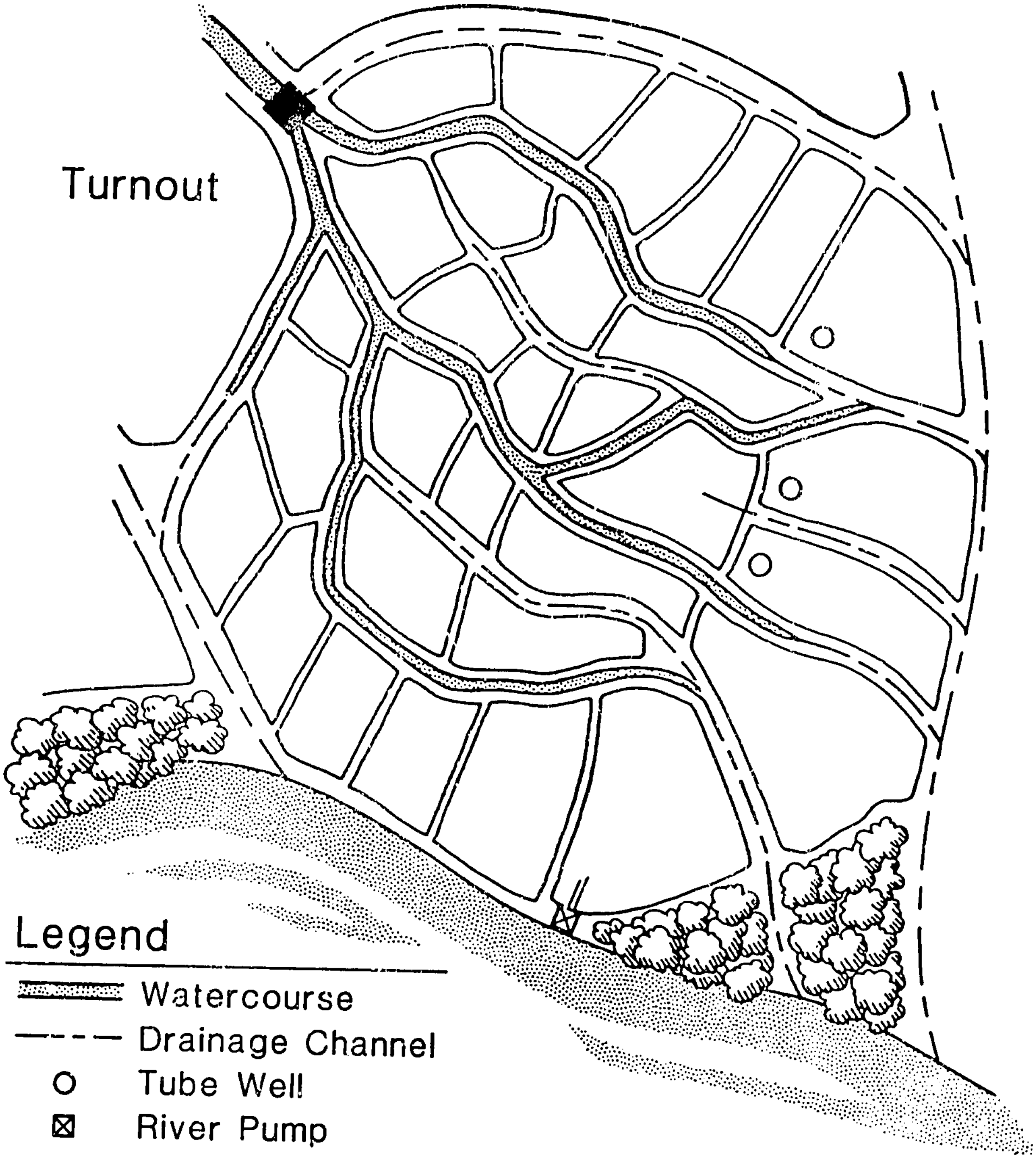


Figure 2. Example Unit Command Area Enlarged from Figure 1.

also to delineate the UCAs). This is to be expected as farmers tend to route water channels around their fields rather than through them.

Notice in the figures that most of the water supply channels end in drains. Not only does this provide a means for disposing excess water; it also provides a potential water supply for downstream users. In many irrigation systems, particularly where paddy rice is grown, it is difficult to distinguish the supply channels from the drainage channels in downstream reaches.

Irrigation System Management

While the various segments of irrigation systems are physically contiguous, the systems themselves are often administratively and operationally disjointed. Although this has become the subject of much research and deliberation, only a few points relevant to the UCA and to the irrigation system as a whole are covered here.

The turnout to a UCA is often thought of as the point dividing the public and private sectors of the irrigation economy or the governmental and private institutional levels of administration. This may be the general case, but it is not necessarily the rule. The interface between the farmers and the main system managers can occur at any point above the farm level. It is important to realize, however, that the point of interface will always be at a hydraulic node, i.e., farm outlet, UCA turnout, minor or distributary division point, or branch or main canal bifurcation. If the irrigation system is communally owned and operated, there may be no interface, as farmer control and responsibility might extend up the system all the way to the point of diversion.

It is also useful to note that the management interface between farms and the main delivery system may occur at different hydraulic levels and involve different entities depending on the management activity.

Figure 1 sketches the management activities, hydraulic levels, and management entities of an irrigation system. The management entities are placed opposite the hydraulic level at which they are most likely to occur, although, this is not to suggest that they occur only at these levels. For example, UCAs are likely to be federated at the minor or distributary level, but they can also be federated all the way up the system to the point of diversion. However, one would not expect to find a UCA with a turnout on the main canal to be federated with UCAs having turnouts along a distributary or minor, unless the federation extended all the way up the system.

Irrigation system management activities can be divided into operational and structural categories (see Figure 1). The operational activities include the management of allocations and the management of the associated flows. Managing irrigation water allocations is primarily a decision making process based on a set of rules defined by the share system. Managing flows involves the hydraulic execution procedures whereby water regulating structures are operated in an attempt to distribute the available water supply according to the allocation plan.

The structural management activities include decision (planning) and execution aspects as well. Planning involves designing for manageability (both original construction and rehabilitation) and maintenance scheduling. Execution entails the management of construction and maintenance.

Management entities may be associated with different management activities at the various hydraulic levels. For example, water user associations may be involved in water allocation decisions up through the main system level, while the public irrigation agency may be responsible for the delivery of water down to the farm turnouts.

A major obstacle to improving irrigation system performance is that the management entities and responsibilities are often too tightly associated with specific hydraulic levels. Since farmers are interested in water allocation above the UCA turnout, they should also participate in allocation decisions above the turnout. However, the UCA turnouts typically mark the points at which farmers are restricted from further participation in irrigation system management activities.

The scope of this study does not include the irrigation system activities above the UCA level in much detail. A critical assumption of this research is that main system operations are reflected in the operation of the UCAs; therefore, UCA operations can be influenced by changes in the main system. A principal objective of this work is to provide a means to estimate the response of UCAs to the water supplied by the main system. This in turn can be used as a feedback loop for identifying promising modifications in the main system which enhance the performance of UCAs.

The Unit Command Area Model

Significant advances have been made in the knowledge of irrigation processes at the field level during the past two decades. However, a general synthesis of this knowledge at the UCA level has been lacking. The UCA Model, developed here, addresses this void through the combination of two submodels. The first of these consists of a water allocation and distribution model which also totals demands and predicts responses of the fields in each UCA. The second is a state-of-the-art, on-field, crop-soil-water simulation model for the estimation of evapotranspiration, deep percolation, runoff, crop yield, etc.

For large irrigation projects, irrigation should be considered as applying water to fields rather than to crops or soils. The field is the basic subunit of every irrigation system, and is where the irrigation water must be consumed beneficially and output performance predicted. This is the premise upon which this UCA simulation model was developed.

The primary linkage between the UCA and the other components of an irrigation system is the aggregate demand for irrigation water at the UCA turnout. The aggregate demand represents the cumulative water requirements (volumetric) of the fields over the operating horizon of the system. It includes the internal distribution losses (attributable to management inefficiency and channel seepage), on-field wastage (due to deep percolation and surface runoff), as well as the farmer estimated field irrigation requirements.

The respective UCA demand represents the water supply which maximizes the collective benefits from irrigation as perceived by the farmers. Therefore, it is the optimal water supply regime when the supply and system capacity are not limiting. Possibly the best index of main system performance is the deviation between the demand for water at each UCA and the associated main system delivery summed over time.

Water supplies at the UCA turnouts often differ from UCA demands because of the supply and capacity constraints and management inefficiencies which plague most irrigation systems. Therefore, a crucial aspect in modeling demand involves simulating the UCA response to the water supply.

Modeling the irrigation water requirement or demand is very different from modeling the aggregate UCA response to the water supplied by the main system. In real time operation and management of an irrigation system, the feedback provided by response monitoring is critical to estimating future demands.

The UCA Model developed here has both a demand and response mode of operation. These modes formulate the linkage between this UCA model and the main system allocation and hydraulic model developed under the WMS II Main System Design, Management, and Rehabilitation Subproject.

When running the models in tandem the UCA Model first expresses the demands of the UCAs on the main system. The main system models then provide instructions for allocating and distributing irrigation water to the various unit command areas in accordance to their demands but subject to the available water supply and system capacity constraints. If the water delivered to a UCA is different from its demand, the UCA Model is run in the response mode to predict how this will affect the UCA. This procedure is then repeated for subsequent time intervals starting with the simulation of UCA demands.

Objectives

Unit command areas, as systems comprised of individual fields and the watercourses linking these fields to main delivery systems, have not been investigated extensively. The principal objective of this research has been to help overcome this deficiency through the development of a UCA simulation model, and to use this model to study the effects of water reliability and allocation rules at the UCA level.

The specific objectives of this research were:

1. To develop a generic computer simulation model of UCAs represented by multiple fields, soil types, and temporally and spatially varying cropping patterns. This model had to be capable of determining (on a daily basis) the aggregate irrigation demand of the fields in a UCA and to predict UCA response (in terms of crop yield, distribution of crop yield, planted area, harvested area, water use efficiency, and conjunctive water use) to the water supplied by the main system. A further goal of this physically based model was to incorporate socio-economic variables.

2. To demonstrate the application of the UCA Model using a hypothetical Indian case study called Synthabad.

3. To use the model to predict how different water management rules affect the UCA productivity, water use efficiency, etc.

4. To study how the reliability of the water supply (timing, frequency, duration, and discharge) affects water use efficiency and production within the UCA. Reliability is viewed as the certainty of having water on a timely basis with sufficient flow to operate the on-farm water application systems efficiently.

5. To develop the interface between the UCA Model and the main system water supply and allocation models.

Other aspects of UCAs need increased attention, but are not addressed in this study. Some of these include: the priority of uses within the UCA; the formal and informal arrangements for the operation and maintenance of the UCA distribution network; the effects of irrigation on household income and labor; waterlogging; water rights; and water pricing. It should be noted that the UCA Model would be a useful tool when addressing any of these issues.

CONCEPTS AND ISSUES

This section covers issues important to water management at the UCA level and to the interface between UCAs and their main systems. This is followed by a discussion of some key UCA modeling concepts. A review of relevant literature is incorporated throughout.

The distinction between concepts and issues is not important. The intent rather, is to show the value of studying and modeling UCAs, and to initiate an understanding of the simulation philosophy. The following discussion of issues is presented to set forth the contribution of UCA research to irrigation water management, while the presentation of concepts will aid in comprehending the general UCA modeling approach.

Issues

Most of the issues discussed below involve irrigation system management considerations and are discussed accordingly. In keeping with the notion of irrigation systems introduced previously, management activities are divided into two broad categories (see Figure 1). The first of these consists of the on-going, day-to-day operational requirements of the system. This includes both the management of allocation, according to the rules defined by the share system, and the management of flows (the hydraulic execution of the allocation plan). The second category entails the structural activities of design for manageability (original construction or rehabilitation) and the management of the construction and maintenance activities themselves.

The entities responsible for management may vary depending on the activity and the hydraulic level for its control. For example, water user associations may participate in allocation decisions at all levels of the system, but only be responsible for channel maintenance within the UCAs.

Size of Unit Command Areas

The discussion of UCA size is often confused with the placement of the farm/main system interface. It is not within the scope of this study to debate the proper location for the interface between the farmers and the main system management. While the interface is often coincidental with the UCA turnout, it can occur anywhere in the irrigation system and may vary with the management activity. Herein, the interface is considered to be independent of the UCA turnout position.

A UCA is a downstream section of an irrigation system where the allocation and distribution of water is among fields rather than blocks of fields. As such, the UCA may be thought of as the physical interface between the farmers' fields and the main canal system, and it can be any size.

Small UCAs require a greater public investment in structures and management of the main system than large UCAs. Thus, small UCAs result in higher administrative, operational, and maintenance costs incurred by the parties responsible for the main system. On the other hand, the main system can generally be more responsive to field irrigation requirements in small UCAs as opposed to large UCAs, and as a result, cost less to the farmers.

Figure 3 shows the irrigation system presented in Figure 1 with the many UCAs consolidated into a few large UCAs. The total area is the same in both figures, but the number of water demand nodes (UCA turnouts) and the total length of main system channel are reduced in the consolidated system. The average distance of the fields from the UCA turnouts in Figure 3 is greater than that for those in Figure 1, so one would expect this system layout to be less responsive according to the individual water users.

The analogy between an irrigation system and a tree, presented in the previous section, leads to some interesting perspectives about UCA size. The leaves of most mature healthy trees are small and numerous compared with the rest of the tree. Recalling that the leaves of a tree are analogous to the UCAs of an irrigation system, the implication is clear -- UCAs should be relatively small and abundant in order to realize the maximum common good for the system.

Reidinger's study of canal irrigation in northern India (73) supports this conclusion. He found that the stated objective of the rotation is to equitably distribute water, while minimizing seepage losses by matching the available flow to the capacity. Because the flow is often less than the capacity of the larger turnouts, farmers in smaller UCAs tend to have a more reliable water supply unless the political strength of the larger UCAs overpowers the rotation scheme.

Perhaps an even more interesting deduction from the tree model is derived when it is applied to situations of varying relative water supplies. One observes that the leaves of trees in rain forest ecosystems are immense compared with those of trees in desert ecosystems. This suggests that, where water is abundant, UCAs can afford to be large relative to the size of UCAs where water is scarce.

The actual layout of the water channels in an irrigation system varies depending on the relative size of the UCAs. It is unknown at this point whether the total channel density (total length of all channels to the total command area) changes significantly. An interesting research topic would be to address this issue to maximize the net benefits from the irrigation system as a whole.

System Priorities

The priorities of an irrigation system are distinctly different when viewed from the main system than when viewed from the farm level. This disparity arises from the difference between the collective good and individual well-being.

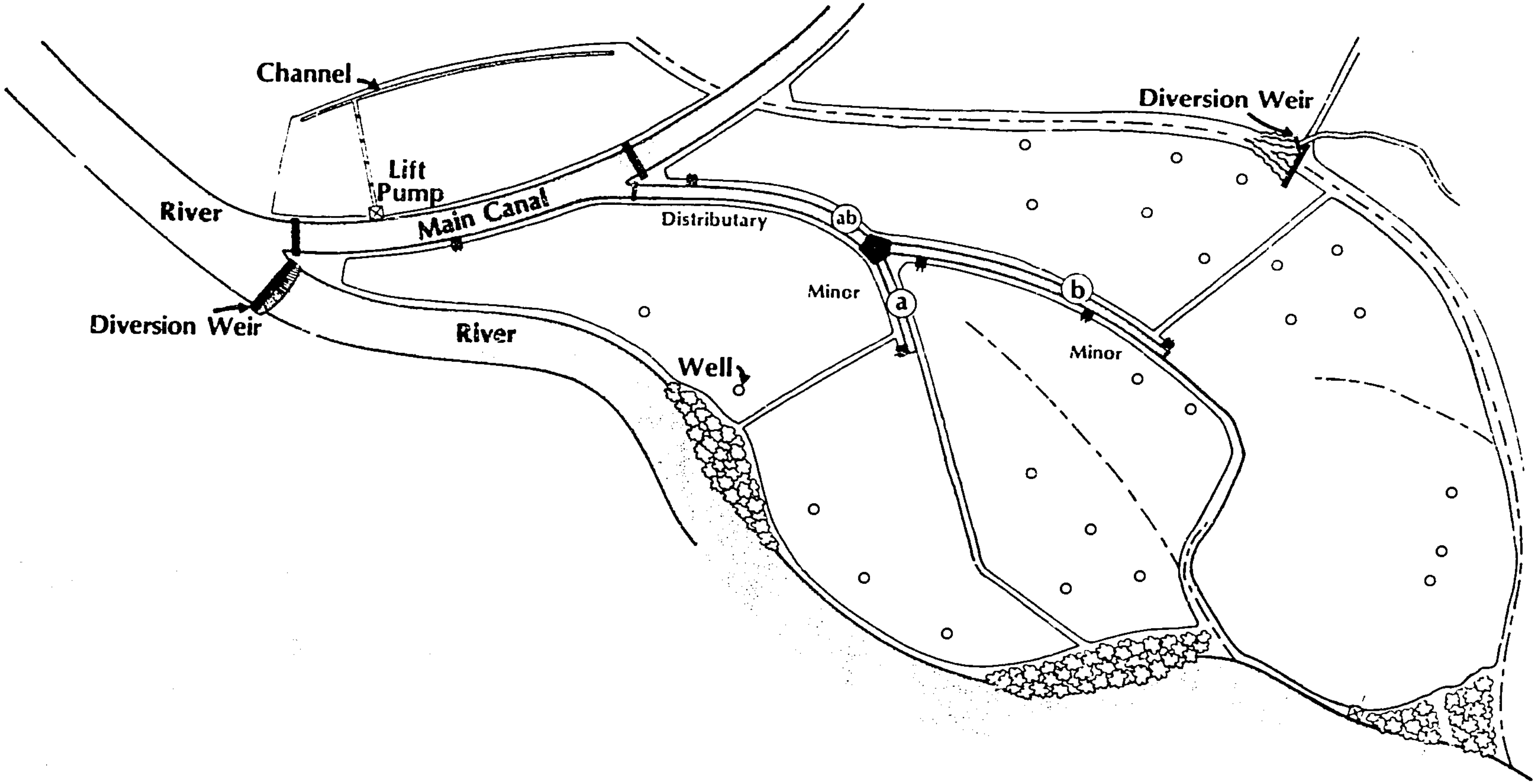


Figure 3. Example Run-of-the-River Irrigation System with Large UCAs.

At the project or societal level the emphases are on maximizing the area served and on equalizing water distribution within the system in order to provide more social equity and to encourage efficient water use. Obtaining high yields receives only secondary attention at the main system level. From the individual farmer's perspective, however, high yields and the use of extra water to save labor may be valued above all else. A major interest in the convenience and security provided by an ample water supply is also inherent at the farm level, with less concern given to the other water users served by the system (87).

One can readily anticipate some of the conflicts which arise from these different viewpoints. One conflict, which is not readily apparent, arises in the implication of the main system priorities for higher system efficiencies. Where water supplies are limited and field irrigation uniformities are low, high irrigation efficiencies directly clash with obtaining high yields. This is discussed later.

One might expect farmers to organize at the UCA level to express their common interests on the main system. Svendsen (87) argues that farmers will organize turnout-based (UCA) groups only under certain circumstances and when such groups provide a collective good <u>other than</u> more equitable water distribution or more efficient water use. He lists (87, p. 19) the following sub-goals of a group of irrigators sharing a turnout:

1. Obtaining more water for the group;
2. Retaining a volume of supply proven adequate in the past;
3. Increasing the frequency or regularity of water deliveries to the group;
4. Changing the timing of the beginning or ending of the season's irrigation deliveries;
5. Reducing the cost of water to the group; and
6. Constructing and maintaining water delivery channels and structures <u>to facilitate adequate deliveries to the group</u>.

An interesting feature of this list, as Svendsen points out, "is the absence of collective goals related to the distribution of water once obtained by the group at the turnout" (87, p. 20).

Not discussed here are the priorities for water use -- the right to use versus the best use, competing interests between agriculture and industry, and priorities within the UCA. These are macro issues beyond the scope of this study. The UCA Model does account for the priorities of water use within the UCA by ranking the queue (fields waiting for irrigation). A field's rank, relative to the rest of the fields in the UCA requesting irrigation, is a function of its relative access (political and physical) to the water supply, the value of its crop, the current level of soil water stress, and the finesse of the farmer. This is further discussed in this and the following sections.

Communication

Communication within the various reaches of an irrigation system, particularly among the farmers in a UCA, is generally efficient. However, communication up and down an irrigation system is typically poor. This may partly explain the larger discrepancies in water supply and yield often observed among UCAs as compared with those internal to UCAs.

Doorenbos and Pruitt (23) discuss the quality of management and communication as they effect water distribution efficiencies. They suggest the following multipliers for adjusting system efficiencies depending on the quality of management and communication: 1.0 for adequate, 0.85 for sufficient, 0.60 for insufficient and 0.50 for poor. For example, if the measured conveyance efficiency from the system headworks to the average field is 50 percent and the quality of system management and communication are poor, then the estimated operational efficiency of the system would be 25 percent (50 percent times 0.50). These factors were derived from a study of irrigation efficiency in some 90 irrigation projects.

The communication link between the UCAs and the main system is of particular importance to this study. The aggregate irrigation water demand of the collective sets of fields in each UCA must be communicated to the main system managers. In a like manner, the farmers profit most when provided with reliable information on the quantity and timing of water deliveries so they can best plan their activities. Furthermore, quantities delivered and the timing of deliveries should coincide as nearly as possible with crop water requirements.

Unfortunately, there is often no reliable communication link between the UCAs and the main system. Reidinger (73) presents the following case from northern India:

> "...according to the farmers, their water supply is uncertain and unpredictable with regard to timing and quantity. Each individual farmer's turn occurs for a few hours once a week (for instance, two to four a.m. Sunday morning). The farmers say they generally receive water twice a month, but they never know during which two weeks or in what amount water will be available during their turn. The interval between irrigations is often several weeks long, and they say this damages their crops, sometimes severely. At the operational level, at least, there appears to be little or no communication or cooperation between the government's agriculture and irrigation departments concerning crop water needs. Only a minimum official effort is made to inform the farmers of the seasons general water supply schedule and no estimate of the probability of receiving water on any given date in the schedule is made for the farmers" (p. 95).

In their study of farmer response to deficit water supplies in the Gal Oya Left Bank, Widanapathirana and Brewer (104, p. 14) found that "farmers adapt their practices to the expectation of water shortage based on information received from government officials." This information was not expressly delivered but rather obtained in an indirect manner. As the authors explained, the cumbersome allocation procedure use at Gal Oya for Yala (dry season) is not very useful for adapting cultivation to water supplies. Furthermore, it even makes it more difficult than need be for farmers to share water equitably and efficiently. They state (104, page 17) that, "the most important function of the allocation procedure is to provide information to the farmers about how much water is available for the system."

In pressurized pipe systems and open channel systems with downstream control, the hydraulic network can act as a communication channel (13). When a downstream demand is placed on the system a drop in pressure is registered upstream. However, the vast majority of irrigation systems do not have effective downstream regulation and, irrigation requirements must be communicated verbally or inferred.

One of the objectives of the UCA Model is to provide a predictor of irrigation demands at the canal outlets serving the UCAs. This is important unless there are other adequate means of communication between the main system and the UCAs. The model can play a very significant role, in the real time operation of systems where communication is problematic, by predicting demands and by simulating the affects of various operational scenarios which may prove useful for developing more effective management procedures.

Unit command areas seldom have formalized operating rules and the communication link with the main system, as pointed out, is often undefined. One must presuppose that the main system operations are reflected in the operation of the UCAs and that UCA operations can therefore be influenced by the changes in the main system. This is a critical assumption of the overall irrigation system modeling effort, and is used to examine how water management in the main system might be modified to enhance water use in the UCAs. This approach is supported by many researchers (15, 19, 50, 59, 60, 73, 77, 81, 101) who have suggested that repeatedly the cause of irrigation system failure can be traced to the main system, and therefore, the focus of intervention activities should be on improving the operation of the main system.

Operating Schedules

The goal of the operating schedule timing, frequency, duration, and flow rate for irrigation deliveries from the main system to the UCAs and within the UCAs to the individual fields. The operating schedule for the main system can be different from that within the UCAs as long as there is consistency between them. Without an operational plan, systems quickly degenerate into a "highority priority" situation (7).

Types of Schedules.

Irrigation systems are operated by following a continuous flow, rotation, or on-demand schedule. Continuous flow and rotation schedules are supplier oriented while on-demand schedules are user oriented.

Under continuous flow, water is constantly flowing at a discharge rate set by the available supply (run-of-the-river irrigation), system capacity, or allocation rules of the share system. The upstream portions of most irrigation systems operate on some type of continuous flow basis. Closer to the field level irrigation is often by rotation or on-demand. The paddy to paddy irrigation typical of rice systems is an example of continuous flow at the field level. Water may be rotated among blocks of paddy fields when scarce, but will flow continuously through the paddies during the rotation turn of each block.

With rotation, water is cycled among the various channels and fields in an on-again-off-again fashion. Fields receiving water during the same on period and rotating it among themselves make up a rotation block. The period when a channel, field, or group of fields has water is a rotation turn. Rotation schedules are generally of fixed frequency, duration, and discharge.

The classic rotation schedule is the warabandi system of the Punjab (northwest India and southeast Pakistan). This is a system of imposed water scarcity. Warabandi means fixation (bandi) of turns (wara). The system involves the rotation of irrigation among distributaries, among watercourses on distributaries, among farms on the watercourses, and among fields on the farms. Above the distributaries the canals run full (59). Farmers are charged for irrigation on a per acre basis depending on the crop. The farmer does not purchase water, but a period of time in the rotation.

On-demand irrigation implies the availability of water at a frequency, duration, and flow rate set by the irrigator. Pure demand systems rarely exist in practice because physical constants in system capacity, travel time, and water availability limit flexibility. Therefore, most on-demand irrigation systems are characterized by some degree of rigidity.

Replogle (74) developed a nomenclature for the operation of irrigation systems by distinguishing two categories of delivery systems -- those with rigid operation schedules and those with flexible schedules. These categories were then divided as shown in Table 1.

Most irrigation systems operate according to a combination of schedules. For example, in the western United States, many irrigation systems deliver a continuous flow to the farm turnout (54). This flow is then rotated from field to field by the farmer. Since a typical U.S. farm is approximately equal in size to one or more UCAs in a developing country, this is equivalent to continuous flow in the main system with rotation in the UCAs.

The inevitability of water loss in transit means a greater water supply at the head of a system than at the tail. Continuous flow irrigation accentuates this disparity and rotation schedules are often recommended to alleviate it. Bishop and Long (7) advocate rotation for reasons of equity, not only in the amount of water received but also when it is received (day or night).

Table 1. Nomenclature for Irrigation Operation Schedules Depending on the Degree of Flexibility Provided by the Schedule.

1. Rigid Schedules:

Fixed Rotation
Variable Frequency Rotation
Variable Rate Rotation
Variable Duration Rotation
Variable Frequency and Rate Rotation
Variable Frequency and Duration Rotation
Variable Rate and Duration Rotation

2. Flexible Schedules:

Unrestricted Demand
Limited Rate Demand
Arranged Frequency Demand
Restricted, Arranged Demand
Fixed Rate, Restricted, Arranged Demand
Fixed Duration, Restricted, Arranged Demand
Fixed Frequency Demand
Fixed Frequency, Restricted, Arranged Demand

Malhotra, et al. (59) found the warabandi rotation systems of northwest India to be operating at about 80 percent allocation effectiveness at the distributary level and around 90 percent at the chak (UCA) level. Reidinger (73), on the other hand, contends that the warabandi systems do not work well. The failings observed by Reidinger, however, may not be because of limitations inherent in rotation, but rather because of problems in the design and implementation of the irrigation schedule.

Rosegrant (77) used a simulation model for paddy irrigation in the Philippines to investigate continuous flow and rotation schedules. Ten water allocation methods were examined in 20-year simulations. The ten methods included: continuous flow without checking, with checking, and with severe checking; full rotation (9-day intervals on secondary canals, 3-day intervals on tertiary and 1-day interval for farm outlets) with continuous flow for the distribution of excess water to off-rotation canals; partial rotation where rotation is practiced at only one or two canal levels; and extended rotation where any excess water is rotated to off-rotation outlets.

Rosegrant (77) found full rotation disappointing in terms of its impact on aggregate system benefits. Given the cost of implementing rotation (primarily salaries), the potential exists for negative net benefit. Rotation was highly effective, however, at equalizing benefits among farms within a system. The equity induced by rotation resulted from increased access to water in the tail reaches, in part by reducing the water supply enjoyed in the head reaches (under continuous irrigation). Rosegrant (p. 23) concluded that, "the redistribution of income to poorer farmers within the system is the most important impact of rotational irrigation."

About the different methods of rotation, Rosegrant (77) found that over half the benefits of full rotation (compared with continuous irrigation) are generated by rotation along the main canal only. However, the gain in net income to the tail reaches from redistribution of the water supply, is less than half the gain from full rotation. Nearly 75 percent of the total benefits, and over 90 percent of the redistributive benefits, are realized from extension of the rotation through the secondary canal level. Rotation only along the tertiaries to the farm turnouts provides almost no system-wide benefits. Extended rotation (rotation of excess to off-rotation reaches) showed only a slight increase in benefits above full rotation and would not be warranted given the cost of implementing such intensive management.

Seckler (78) supports Rosegrant's conclusion that rigid irrigation schedules at the UCA level are not beneficial to paddy production. However, Seckler argues this theory from a different perspective:

> "...paddy irrigation systems have a self-regulating property that leads to a reasonably optimal allocation of water supply between farmers. Thus, in complete contrast to other irrigated crops, it is doubtful if management improvements in the form of rationing and rotation of water supply to farmers would result in cost-effective improvements over the allocation achieved by naturally functioning, laissez-faire systems.
>
> ...these conclusions regarding the allocative effectiveness of laissez-faire paddy irrigation systems should not be interpreted as denying the need for well designed, constructed, maintained and operated headworks and canal systems. However, it does appear that once water is delivered to something like a 10-15 hectare block [UCA], the net returns to terminal systems, over field-to-field irrigation, may be negative" (78, p. 3).

Several engineers (1, 14, 18, 63, 74, 87, 101) have suggested that it is not a coincidence that irrigation projects which attempt to supply water in response to irrigator demand, at a rate and duration set by the irrigator, are also ones where production and irrigation efficiency are highest. They explain that these are projects where irrigators have an interest and a participatory role in the operation of the entire project. Many other engineers have implied on-demand irrigation, or have at least assumed highly flexible irrigation schedules, by proposing optimal irrigation strategies (33, 42, 43, 52, 56, 64, 88, 89).

<u>Design of Schedules</u>. Many aspects must be considered in designing an operation schedule, most of which must also be taken into account when determining system capacity. These include:

1. The nature of the water supply and the water supply relative to the demand;

2. The effects of irrigation timing, frequency, duration, and discharge on water use efficiency and crop production;

3. Distribution system conveyance efficiency and lag times;

4. Potential changes in the nature of irrigation from season to season and from year to year (i.e., from rice in the wet season to upland crops in the dry season);

5. Changes in soil moisture management throughout the season and from season to season;

6. Water management efficiency of the farmers (crop water requirements versus the farmers' irrigation demands);

7. The preference for certain hours of irrigation (daytime versus nighttime) and for no irrigation on holidays;

8. The distribution of cropping patterns and cultural activities;

9. Arrangements for operation and maintenance of the distribution network (discipline within the system);

10. The implications of water charges and water rights; and

11. The management of supplies less than demands.

Bishop and Long (7) provide steps for designing a rotation schedule. In the example they give, water is managed down to the odd number of minutes. While offering a very equitable distribution of the water supply (in terms of both timing and amount), such a schedule seems impossible to manage, let alone maintain. Kaewkulaya (48) developed an irrigation rotation schedule for a large scale project in Thailand with multiple crops. Singh, et al. (81) discuss the evaluation and improvement of rotation systems using the Ganga Canal of India as a case study.

Burt and Lord (14) discuss demand theory and application. The control of modified demand irrigation is considered by Clemmens (18). Merriam and Davis (63) describe a demand irrigation project in Sri Lanka. Downstream regulation of sloping canals is approached by Burt (13) as part of the hardware design for demand irrigation. Manz (60) and Yoo, et al. (106) developed systems analysis techniques to effectively inventory large irrigation projects for system planning.

Kim and Busch (54) cite the major perceived problems of water organizations responsible for operation and management of demand type irrigation systems as anticipating demand and supplying enough water. "Demand tends to be nonuniform and simultaneous. This indicates that delivery of water cannot be scheduled long in advance because farmers have not (and perhaps cannot assess) their irrigation needs far in advance. In addition, most farmers require water at the same time" (p. 4).

Several researchers have suggested methods for predicting irrigation demands (1, 5, 16, 17, 38, 49, 58, 79). Ploss, et al. (72) discuss extension of on-farm irrigation scheduling throughout the distribution system to coordinate water deliveries with requirements at the farm level. Buchheim and Brower (11) modified the Irrigation Management Services program of the U.S. Bureau of Reclamation to predict diversion requirements for an entire irrigation project. Kim and Busch (54) conclude that statistical simulation and prediction of irrigation demands at the project level has more advantages than physical simulation.

One of the objectives of this research is to employ the UCA Model as a tool to design irrigation schedules and to compare on-demand with rotation among UCAs and internal to the UCAs. Results from such study and design are reported in the fifth section.

Reliability

If water is not available at the right times and in the right quantities needed for crop production, it is of little value to the farmer. An unreliable supply reduces farmer willingness to invest in the other inputs required to realize the full benefits from irrigation. Regardless of the irrigation schedule, the reliability of the water supply is critical for its efficient use.

Reliability from the farmer's viewpoint, and from the perspective taken here, is the certainty of a water supply to realize the benefits of irrigation. As such, it implies the delivery of water on a timely basis with sufficient flow to operate the on-farm application systems efficiently.

It may be argued that reliability should only refer to the certainty of a given supply hydrograph; and that reliability, as defined above for the farmers, describes an ideal water supply rather than one which is simply reliable. Such argument, however, has little relevance to the farmers. Reliability would be trivial if it meant, for example, that there was a hundred percent probability of the entire season's water supply occurring in a short period of time. Therefore, reliability must refer to the qualitative nature of the water supply in relation to crop production demands as well as its quantitative disbursement.

Potential crop production levels have been raised significantly in the last three decades by new fertilizers, pesticides, and crop varieties. Unfortunately, agricultural investment risks have also risen because of rapidly escalating production costs and a sluggish growth in commodity prices. For example, it appears that new crop varieties under intensive fertilization are more sensitive to moisture stress. Sensitivity to drought is further accentuated by the tendency of hybrid varieties to have shallower root systems than traditional local varieties. Thus, the reliability and timeliness of the water supply are critical to achieving maximum yields.

Chambers (15, page 5) noted, "Often a more reliable supply of water, known about in advance, would lead to more widespread adoption of high-yielding practices than any conceivable amount of good advice from agricultural extension."

Research in North India suggests that yields obtained under small private irrigation systems, such as tube wells where farmers have control over the water supply, are notably higher than yields obtained under the large government owned and operated systems (73). The small private systems, operated by the farmers in accordance to the perceived crop irrigation demands, are simply more reliable.

> "...a farmer with his own, private source of irrigation has essentially complete control over it and can apply it according to his crop's needs, so the crop has adequate irrigation. In contrast, canal irrigation supply is apparently not amenable to effective water management or control" (73, p. 9).

The higher yields obtained under these small farmer controlled systems are not limited only to the more timely nature of the water supply; they are also due to the farmers' willingness to adopt high-yielding practices when their water supply is reliable.

The farmer's real time response to managing his part of the irrigation system is dependent upon his past experience and his confidence in the irrigation delivery system. The reliability of the water supply at the farm level influences farmer decision making with regard to how much land to irrigate, what to plant, what level of agronomic inputs to apply, and what and how much to invest in the on-farm water application system. Several researchers have discussed the application of decision theory and risk analysis in the study of irrigation practices (20, 26, 27, 47, 53, 95, 97).

Some of the variables affecting the reliability of water at the field level are listed below. Those which are of a socio-economic nature (as opposed to strictly physical) are marked with an asterisk:

1. Distance and access* to the water supply at the UCA turnout;

2. Elevation of the field relative to the turnout;

3. Condition of the water course;*

4. Availability (flow, depth, economic feasibility*) of alternative water supplies;

5. Location of UCA within the main system;

6. Reliability of main system water deliveries;

7. The available water supply relative to the demand for the total system;

8. Attitude of officials towards farmers and visa versa;* and

9. Cooperation among farmers in the UCA.*

Clemmens and Dedrick (19) studied fluctuations in water deliveries in terms of the coefficient of variation and noted how the uniformity of water delivery affects on-farm water use. They found that the primary factor affecting the coefficient of variation was the location within the system. In general the coefficient of variation increases in the downstream direction. "Providing more flexibility [on-demand] to users without appropriate modifications to the delivery system controls may increase these fluctuations" (19, p. 11).

Reidinger's study of canal irrigation in northern India (73) showed that the supply of irrigation to the farm is highly variable and unpredictable from the farmer's viewpoint. Tyagi and Narayana (94) and Reidinger (73) have noted that because of uncertainties in canal deliveries, farmers are switching to tubewells to supply irrigation water.

The hydrograph shown in Figure 4, according to the interaction of warabandi and canal rotation, dramatically demonstrates the potential unreliability of the water supply at the UCA level over an entire irrigation season. This figure was derived from data presented by Reidinger (73, p. 123). Figure 5 was borrowed from Clemmens and Dedrick (19, p. 4) to show the typical nature of the water delivery hydrograph at the UCA level for a single irrigation event.

This research places special emphasis on analyzing the impact of the water supply reliability on water use efficiency and production. It is

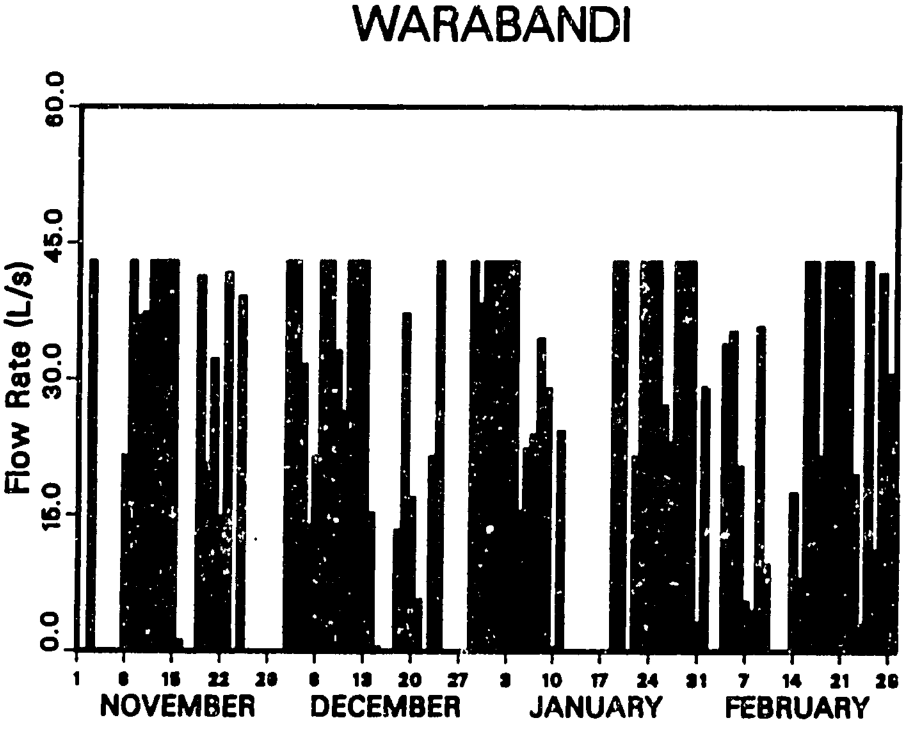


Figure 4. Water Supply Hydrograph at a Unit Command Area Turnout Under Warabandi and Canal Rotation in Northern India.

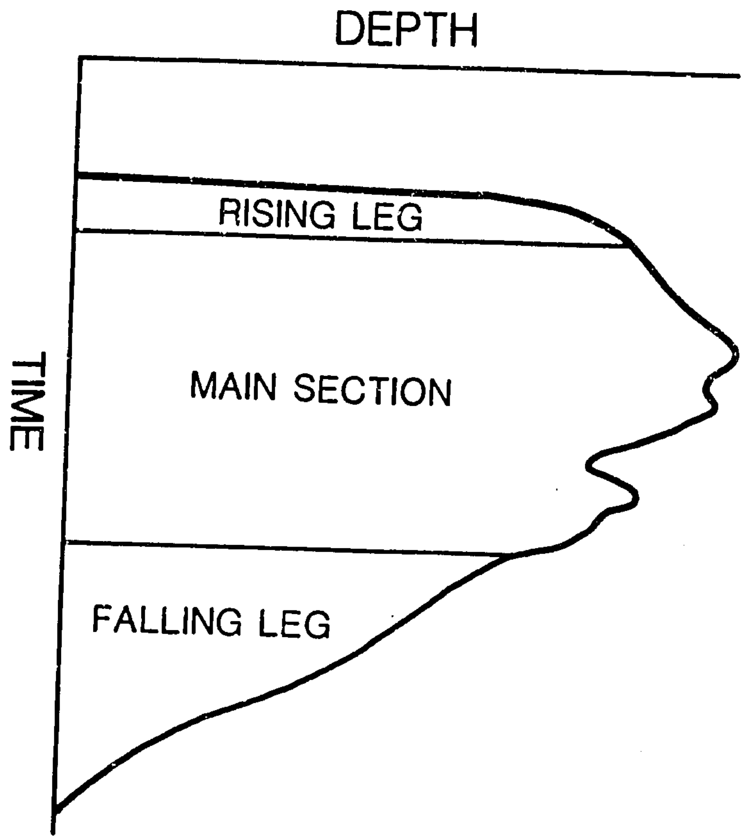


Figure 5. Example of a Supply Hydrograph for a Single Irrigation Event.

assumed that production is influenced directly by the water reliability and indirectly by the farmer's perception of this reliability. While it is straightforward to model the physical ramifications of a given water supply hydrograph, it is more complicated to evaluate how the farmer's perception of reliability affects his decision making. Rather than attempting to model farmer behavior, it is simply assumed that improved reliability is a high priority to the farmers.

Position

Physical location within an irrigation system has received widespread consideration in recent years. Keller, et al. (50) suggested the following terminology for water users according to their position within the system and primary source of water:

Head-ender
Upper reuser-- uses tail water (surface return flow)
Tail-ender
Lower reuser-- uses seeps, groundwater (subsurface return flow)
Tapper-- steals from system

The natural laws of water movement denote a more reliable surface supply closer to the source of diversion. System responsiveness (which is a function of lag time), seepage losses, and nonsanctioned use are all functions of distribution channel length. Except for situations where downstream control dictates the flow of water, the head-end naturally enjoys a more assured supply. Tail-end users of subsurface water (lower reusers) may, however, have the most reliable supply because of the natural dampening effect of porous media flow.

A head-end farmer in a head-end unit command area would most likely have a more favorable water supply than a head-end farmer in a tail-end UCA. As a result, one would also expect to find higher production in the upstream reaches of the system. A Cartesian basis for on-farm production as a function of relative position along the main system and within the UCAs is presented in Figure 6.

Several researchers (19, 66, 73, 77, 78, 87) have found that position along the main system is more influential on water availability than position within the unit command area. Svendsen (87) noted that this is particularly true when an irrigation association official lives within the UCA.

Position should not be thought of only in terms of location, it also includes the elevation of a field relative to the water supply. Svendsen (87, p.220) points out that "...within small regions of large irrigation systems, i.e., areas of one or two thousand hectares, location within the system is not necessarily the dominant factor in determining water adequacy." The relative elevations of sublaterals are critical determinants of the water received at a given UCA.

In the systems he studied in the Philippines, Svendsen (87) found the variability in yields among tertiary units (analogous to UCAs) three times greater than that within the tertiary units. The variability in the number of stress days was ten times greater. Not surprisingly, farmers in tail-end tertiary units were less inclined to invest in agronomic inputs. In tail-end areas only half as much nitrogen was applied as compared with the head-end areas. Nitrogen use explained most of the yield variance, however, nitrogen application was strongly correlated to the water supply.

Widanapathirana and Brewer (104) in their study of farmer responses to water deficits in the Gal Oya project found the difference between head-end area and tail-end area practices remained the same regardless of water shortages. Tail-end farmers 1) cultivate larger areas; 2) do land preparation in a shorter period of time (and use more hired labor); 3)show a lesser amount of staggering; and 4) use high seed rates because of a prevalence of "dry seeding." When tail-end area farmers use fertilizer rates comparable to those used in the head-end areas they obtained yields almost as high as those of the head-end farmers. This suggests that the adaptations of the tail-end area farmers are normally adequate.

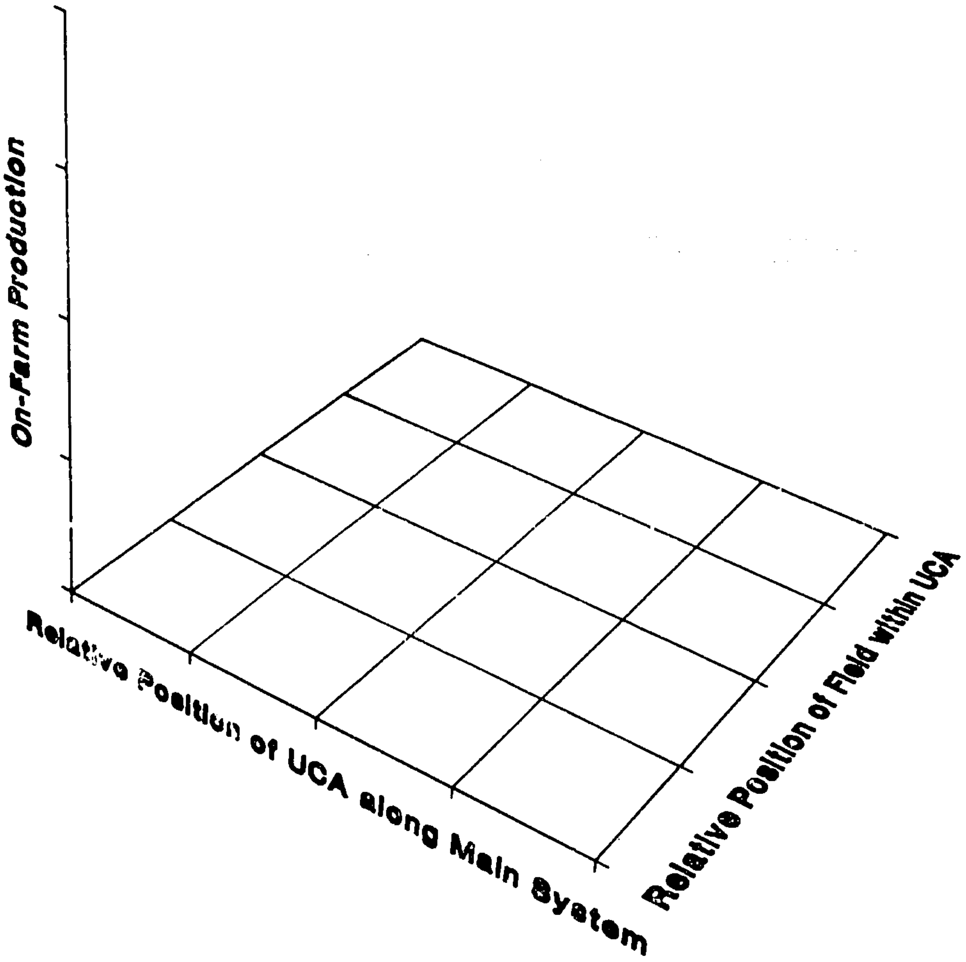


Figure 6. Cartesian Coordinates for Production as a Function of Position within an Irrigation System.

Conjunctive Use

The example unit command area in Figure 2 shows three fields with wells and one field to which water is pumped from the river. Such conjunctive use may imply constraints on the water supplied by the main system (forced cropping pattern, unreliable, or insufficient water supply, etc.). Tyagi and Narayana (94) found that, because of uncertainties in canal deliveries, the farmers are switching to tubewells to supply irrigation water. In an area where there was no history of groundwater usage there is now a density of 1 to 4 tubewells per 10 hectare.

Groundwater pumping and other forms of conjunctive use can be expensive alternatives to reliable surface water deliveries. The mere existence of conjunctive use, therefore, points to the high value farmers place on having a reliable, on-demand water supply, and is a strong indicator of the irrigator's response to uncertainty.

The degree of conjunctive use within an irrigation project may be used as a barometer to assess the general performance of the water delivery network. However, the presents conjunctive use is not always an indicator of main system failure. Some projects are designed with surface water scarcity and with full expectation of conjunctive use, while others may need groundwater to dilute saline surface supplies.

The groundwater system can provide a highly equitable water source. Where conveyance system efficiencies are poor and where a shallow, permeable, and extensive aquifer exists with good water quality, the greatest benefit of the irrigation system may be the unintentional recharge of groundwater.

In view of the significance of conjunctive use, a critical aspect to the analysis of irrigation systems lies in the linkages of the various hydrologic processes. The tie between surface water and groundwater (seepage, deep percolation, mining, and groundwater influent and effluent) is of particular importance. De Ridder and Erez (21) developed a model with these linkages to determine the safe and optimal groundwater withdrawal for a region in Iran. Lansford, et al. (57) developed a model incorporating weather simulation and economic analysis with similar goals for forming appropriate groundwater exploitation strategies for the High Plains of New Mexico and Texas.

The UCA Model monitors groundwater pumping but does not keep a water balance on the aquifer or estimate drawdown and the related pumping lifts. This would require an explicit groundwater model which is beyond the scope of this work. The linkages for such a model have been developed, however, and it would be a simple task to integrate groundwater modeling with the UCA Model.

Nonsanctioned Use

Water stealing at the UCA level is accomplished by tapping or checking of the distribution network, taking water out of turn, or taking more than one's share.

Nonsanctioned water use within a UCA is different from such use in the main system in that individuals are the direct winners and losers. If a farmer takes more than his share within the UCA, the next farmer in line, or the farmer after him, will receive less than his full share; the winners and losers will be easy to identify. On the other hand, if a farmer illegally taps into the main system, the water he takes may be a seemingly imperceptible portion of the total flow; where it is obvious who benefits, it is difficult to identify the individual losers. The less tangible the losers are, the less incentive there is not to steal water; therefore, one would expect illicit water use to be a bigger problem above the UCA turnout than below it.

From the total system viewpoint, nonsanctioned water use, in the form of checking at the UCA level, has less of an impact than checking of the main system. This is because the resulting inequity of checking at the tertiary level is much more disbursed than when checking occurs at higher hydraulic levels. Rosegrant (77, p. 22) suggests that "...within reasonable bounds, checking at the tertiary level may not be as harmful as it is often considered to be. Major losses do occur when the checking is at higher levels in the system."

The UCA Model permits analysis of the impact of nonsanctioned water use at the UCA level by giving a higher priority in the queuing system to those farmers who can take water from others.

Design Capacity

The design capacity of an irrigation system is usually determined considering short-term (often 10-day) peak demands (96). Some provisions are made to take into account the need for sufficient head at the farm level, and the differences in cropping mixes for individual farms compared with those for the project as a whole. Occasionally, a seemingly arbitrary factor may be applied to increase system capacity in the downstream reaches (user portion of the system) thereby providing flexibility in the timing and duration of irrigation events (12, 85). Thus, it is not uncommon for irrigation systems to be either undersized or oversized resulting in economic loss from low crop production or high capital cost.

As mentioned in the discussion on operation schedules, most of the factors that should be considered in the design of an operation schedule (refer to the list under that subheading) must also be taken into account when determining the system capacity. If an irrigation system is to be designed for manageability the operation schedule should be determined before the system capacity. In other words, the hardware should be designed around the software, not visa versa.

Often the design capacity of irrigation canals, laterals, and turnouts is based solely on the estimated peak consumptive use of the anticipated crop mix for the command area (12). Methods for estimating the peak evapotranspiration (ET) for the irrigation interval are well documented in the literature (23, 39, 45). Several recent studies have shown that the design ET rate should be based on a level of expected probability of occurrence (12, 23, 32, 45, 53). Khanjani and Busch (53, p. 961) cite research findings that "the effect of varietal climatic variation on consumptive use can be drastic. While the annual consumptive use can remain about the same from year to year, the peak daily use is subject to dramatic and often erratic differences."

Hagan and Wang (34, 102) provide a procedure for determining the minimum canal design capacity for irrigated rice that will result in high canal utilization without adversely affecting crop production. Several other studies have been conducted to determine the minimum design capacity required to obtain maximum yields from <u>single</u> crop systems. Fischbach and Somerhalder (29) and Fonken (31) conducted experiments to determine the minimum system capacity needed to produce high corn and sugar beet yields respectively. Vonbernuth, et al. (98) considered soil characteristics, irrigation depth, management policies, and climatic conditions in developing a computer simulation model to ascertain irrigation system capacity requirements for corn production.

Anticipating the cropping pattern for an irrigation project is difficult if not impossible, yet failure to do so can be disastrous. This is illustrated by the experience of the U.S. Bureau of Reclamation during the early history of the Columbia Basin Project in Washington (85). Three years after the initial water delivery many farmers leased their holdings which resulted in a shift from diversified cropping to a concentration of potatoes and beans in some areas of the project. The capacity of the conveyance system was inadequate to meet the peak demand of this nondiversified crop mix. A similar situation occurred in Iran when the land tenure policy changed in 1971 from small farming to agribusiness lease operations in irrigation project areas (25). The new larger farms required a 50 percent increase in canal capacity.

The relationship between the water delivered to the UCA and the UCA production is characterized by substantial and unavoidable uncertainty. This is because of the stochastic variability of physical inputs, the impact of socio-economic aspects, and the nature of water distribution throughout the UCA. Connor, et al. (20) state that most studies of water resource systems incorporate risk analysis as if only the system planners react to the effects of uncertainty. However, the end users also react to uncertainty, and their reaction affects the system as a whole. Farmers will adjust their cropping patterns in accordance to the perceived reliability of the water supply, thereby affecting overall system planning.

Connor, et al. (20) developed a reservoir-irrigation system simulation model which incorporates the water users' reaction to uncertain water deliveries in a manner which reflects their influence on the total system. The results from their study show that the inclusion of farmer reactions has recognizable effects on irrigation system design and farmer cropping plans. Just (47) arrived at the same conclusion when studying farmer response to changing risk.

Assumptions about irrigation efficiencies can have severe implications on system design capacity, yet predicting efficiencies can be as difficult as anticipating the cropping pattern. Many terms are used to describe irrigation efficiencies, resulting in a large effort to standardize definitions (8, 67). Kruse and Heermann (55, page 37) concluded from U.S. Bureau of Reclamation reports on water use in some federal irrigation projects "that it may be pointless to assign a typical efficiency for surface irrigation in designing new systems" and that "no one type of system is universally more efficient than another." Kim and Busch (54) reference an inflow-outflow water balance analysis of six irrigation projects in the Upper Snake River Region of southern Idaho. They found project efficiencies of 10 to 42 percent and estimated reasonably attainable efficiencies of 35 to 51 percent. Udeh and Busch (95) sum up the problems of irrigation efficiency assumptions in design:

> "Although used extensively, the irrigation efficiency term is not often completely understood as it is a complex function of many interacting and interdependent factors including irrigation

system characteristics, management, labor input, water rights, and institutional factors. Soil conditions, cropping patterns, and irrigation practices, all varying in time and place, also influence irrigation efficiency. In reality, irrigation efficiency is a probabilistic phenomenon. It is not adequately quantified as its actual value is never reliably known at the time of design and management decisions. A determinate value is usually assigned to irrigation efficiency thus possibly leading to an oversized or undersized irrigation system component. Errors resulting from using fixed efficiency values may be greater than those resulting from estimating evapotranspiration using climatic data" (p. 954).

Stamm (85) cites the experience of the U.S. Bureau of Reclamation on the Eden Project in southwestern Wyoming as an example of the consequences of using too high of an irrigation efficiency during project design. Using a farm irrigation efficiency of 58 percent it was determined that the available water supply was sufficient to fully irrigate 20,000 acres. After re-evaluation of the water supply, the project was reduced to 17,500 acres. When irrigation began, it was found that even with this reduced acreage the water supply was inadequate to meet the demand. Despite a record breaking two-year drought, one of the most significant factors affecting the inadequate water supply was the inability of the water users to obtain the projected irrigation efficiencies. Project-wide farm irrigation efficiencies were not more than 35 percent.

Gibbs (32) describes the procedure used by the U.S. Bureau of Reclamation for determining the design capacity of structures in the Garrison Diversion Unit. Moving mean ET values for intervals of 1 to 30 days were calculated from the daily weighted average ET of the crop mix. The mean for each interval plus one standard deviation was used as a sizing criteria. On-farm irrigation efficiency was fixed at 75 percent. Small turnouts and laterals were allowed a daily down time of two hours for moving sprinkle laterals while large branches were designed for continuous operation. It was assumed that crops with concurrent peak use periods would occupy less than 40 percent of the total project area.

The implications of operation schedules on design capacity have not been investigated thoroughly (18); however, some generalizations can be made. Systems designed for rotation have small design capacities compared with those designed for on-demand irrigation. The primary canals and diversion structures for rotation systems are designed for the peak continuous flow. Some flexibility may be given to the farmers by increasing the capacity of the system near its tail end. Larger design capacities are required for on-demand irrigation to allow for the probability of simultaneous withdrawals. Clement (16, 17) refers to the level of probability, for which a system is designed, as the quality or adequacy of the system.

The work by Clement (16, 17) deals explicitly with the determination of design capacity for demand systems. He first postulated that the number of outlets opened simultaneously on a pressurized system follows a binomial distribution. Clement (16) developed a formula to predict the number of outlets opened simultaneously, by assuming that when the total number of outlets in the system is large enough, the binomial distribution can be approximated by a normal distribution. Clement developed a later formula by assimilating the irrigation to a birth/death process (17).

Clement's formulas were used extensively for large scale sprinkler irrigation design in France. However, the assumptions used in their derivation do not incorporate the probability of any outlet being open, the flexibility that should be given to the water users, or the impact of agronomic parameters. The importance of these aspects in determining system design capacity causes Clement's work to be of limited applicability.

The work by Abdellaoui (1) emerges as the most applicable for determining irrigation system design capacity. He applied queuing theory to the simulated demand an area represented by fields of varying size, crop mix, soils, planting dates, and irrigation efficiencies. He used two indices to measure system performance. The first was based on statistics of waiting times for irrigation; while the second was based on statistics of the ratio of actual to potential evapotranspiration (an indicator of yield).

An irrigation system capacity design chart resulting from Abdellaoui's work (1) is presented in Figure 7. The four curves give levels of probability (system quality) of a field not having to wait more than four days before delivery of irrigation water. Figure 7 shows the reduction in required system capacity per unit area served as one moves up the system. In other words, at a probability level of 95 percent of no field having to wait more than four days for an irrigation, the design capacity for a lateral serving 200 ha would be 1.20 l/s/ha while that of a canal serving 3000 ha would be 0.95 l/s/ha. Note that this is a hypothetical situation with a limited number of stochastic variables being considered.

Water Requirements

The primary linkage between the unit command area and the larger irrigation system is the aggregate demand for and response to the water supply at the UCA inlet. The aggregate demand represents the cumulative water requirements of the fields in the unit command area over the operating horizon of the system. It includes the internal distribution losses (management inefficiency, channel seepage, evaporation, and phreatophyte consumption), on-field wastage (deep percolation and surface runoff), and the farmers' estimates of field irrigation requirements.

The UCA demand represents the water supply which maximizes the collective benefits from irrigation as perceived by the farmers and is, therefore, the optimal water supply regime without of supply or capacity limitations. The perspective taken here is that the farmers are the ones who do the optimizing.

Ideally system management should respond to an aggregate demand as determined directly by the farmers. This is not possible unless there

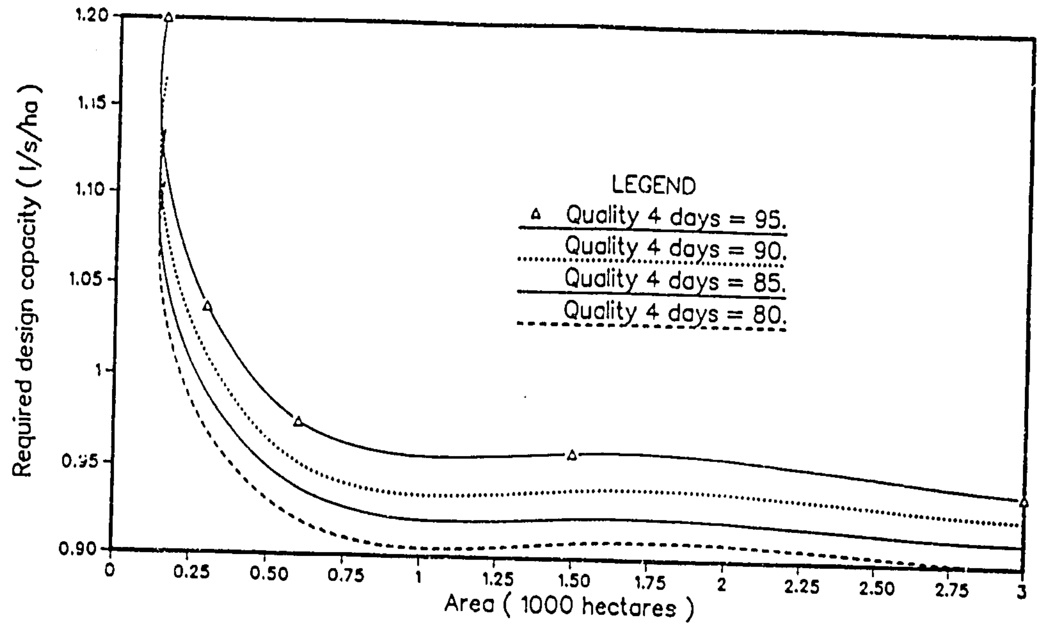


Figure 7. Irrigation System Design Capacity Chart for Different System Qualities (Probability of any field having to wait more than four days for irrigation).

is good vertical communication within the system or downstream hydraulic control. Typically, systems are designed for upstream control and communication up and down the system is problematic; therefore, the aggregate demand must be forecasted.

Forecasting the aggregate demand for continuous flow and rotation schedules is a straightforward, volume-balance procedure. Predicting the UCA irrigation requirement for systems operated on-demand is more complicated.

Methods for predicting crop water requirements are well documented in the literature (12, 23, 39, 45, 56, 79). Kundu (56) showed that a crop growth simulation model can be effectively used to determine optimal soil water depletion and replenishment levels and the timing and amount of irrigations. After the weather is known this is a different matter than before; yet there is a lead time required for travel time through the system.

Another problem is that crop water requirements are generally different (in both timing and amount) from the irrigation demands expressed by farmers. Three possible reasons for this discrepancy are listed below:

1. Crop growth (and farmer response) is only indirectly related to soil water. Under high evaporative conditions, crops may wilt even when soil water is sufficient. Under low evaporative demand, crops may not show signs of stress even when soil moisture is

limiting. Farmers respond according to the appearance of their crops. Stressed crops will mobilize farmers to get water.

2. Few farmers are aware of the actual soil water status. They have a general idea of when a field needs watering, but they lack the technique to accurately measure soil water deficits.

3. Irrigation is only one of the many activities a farmer needs to schedule. Thus, the farmer will want to irrigate at the time and in the manner most convenient.

The difference between actual crop water requirements and farmer demands is expressed as the irrigation management efficiency of the farmers. The peak water requirement may be for land preparation. This is particularly true for paddy production and when human or animal power is used to prepare fields for planting. Before land preparation, field surfaces are uneven and, with some soils, severely cracked. Thus, it is not unusual for pre-season irrigations to be the least efficient.

Other aspects complicating the prediction of demand include: changes in soil moisture management (i.e., allowable depletion) throughout the season and from season to season; the priority of uses within the UCA; the effects of irrigation timing, frequency, duration, and discharge; UCA distribution channel hydraulics (conveyance efficiency); changes in the nature of irrigation (i.e., paddy to upland crop) from season to season and from year to year; and the implications of uncertainty on farmer decision making.

Water Supply Density

Some researchers (66, 87) have used the dimensionless concept of relative water supply (RWS) as an independent variable in the analysis of farmer response to water availability. The RWS is the ratio obtained by dividing the water delivered to an irrigation unit (field, farm, UCA, etc.) by the irrigation demand of that unit. The RWS can be calculated for any specified period of time, but generally a single value is determined for an entire cropping season.

Oad and Levine (66) present the RWS as "an indicator of the relative scarcity of water, consequent social tension in the farming community, and the irrigation behavior of farmers within an irrigation system."

The RWS concept was originally developed and applied to mono-culture conditions (primarily rice cultivation). In areas where more than one crop is grown, farmer decisions of what crops to plant, when to plant, and how much area to plant in response to a given or perceived water supply will change the demand and thus the value of the RWS. When the water supply is scarce relative to the irrigable land area, farmers will make agronomic decisions which tend to result in a near constant RWS. This has been shown by Keller, et al. (50) and Malhotra, et al. (59). The resulting near constant RWS is greater than unity by an amount corresponding to farmer aversion to uncertainty and lack of farming finesse.

The RWS should be considered as a dynamic variable. When applied to an entire growing season, the utility of the RWS concept has some important limitations. Most crops vary in sensitivity to water stress over the different stages of growth. Therefore, a low RWS during one stage of the growing season will have a different implication than at another. This is further complicated by the changing soil water storage capacity. Moreover, farmers may choose to delay planting or other cultural activities until a certain RWS is reached, thereby changing the RWS with time.

A similar but more descriptive concept of water supply density and tension was developed by Keller, et al. (50). They defined the water supply density as the ratio of the water supply to the demand during the period of peak water requirement. By defining density for the peak demand period for the crop mix, and by expressing supply and demand using flow rate rather than equivalent depth of application, they avoided most of the limitations with the RWS discussed above.

Keller, et al. (50) hypothesized that farmers tend to make decisions resulting in water supply densities near one and that systems, therefore, should be designed with comparable densities. During their appraisal of the Asian irrigation sector, they observed some projects with designed water supply densities as low as one-third. Not surprisingly, the actual irrigated areas of these projects were only a third of the target command areas.

The "water tension" in an irrigation system was defined by Keller, et al. (50) as inversely proportional to the water supply density. Thus, as the water supply density becomes smaller, the tension in the system increases. The concept of "water tension" reflects the degree of social tension in a farming community and serves as an indicator of irrigation behavior. The notion of tension also implies a limit on how far water can be stretched and what the actual irrigated command areas potentially are.

The UCA Model does not employ either water supply density or RWS concepts. Since the model tracks supplies and demands, it can easily calculate either variable. It is understood that the degree of water tension in a system serves as an indicator of certain behavior (notably water stealing, equity of water distribution, crop selection, and planted areas). However, in order to predict specific behavior, field observations would have to be used to correlate behavior to water supply density. It is suggested, therefore, that data for the model be collected from different parts of the modeled irrigation system which reflect different water supply densities.

Deficit Supply

A deficit at the field level may result from an insufficient water supply to meet the full demand for all fields, the position of a field in a UCA or of a UCA in the system, implications of the share system (allocation, nonsanctioned use, design of the operating schedule), unusual weather conditions or inadequate system capacity resulting in checked flows.

Aside from specifying the irrigation schedule, the most important aspect of the share system (set of rules and tools governing allocation) may be the allocation of shortages.

At the main system level, water is allotted to the various UCAs according to the operating schedule (on-demand, rotation, continuous flow), the physical constraints of the distribution system (capacity, lag times), and the rules governing the appropriation of a water short supply. Under rotation, perhaps only those UCAs in turn at the time of shortage will receive reduced supplies. On a demand system, shortage may be shared equitably by all the UCAs.

The water requirements of any given field within the command area are transparent to the main system as is the allocation of water within the UCA. Water allocation to the individual fields making up a UCA is governed primarily by the irrigation schedule and the formal and informal rules for the appropriation of a short water supply. The hydraulics of the UCA distribution network may have little or no effect on the allocation of water to individual fields; however, sometimes adjustments are made to account for channel filling, drainage, and seepage losses.

When the supply is less than the demand, the tendency is to cut the flow rate rather than to reduce the length of the irrigation turn. This is particularly true for rotation schedules since reducing the length of turn can completely alter the rotation. However, flow rate is a critical design parameter for all field application systems (sprinkle, trickle, and surface). Therefore, more uniform and efficient irrigation would result if the length of turn was decreased rather than the flow rate. This also gives the farmer more flexibility to decide how best to manage his attenuated water share.

When faced with a short supply, a farmer has a choice between reducing irrigated area or of deficit irrigation. Angeles and Hill (3) found that with rice it is better to irrigate a smaller area with a full supply rather than a large area with a deficit supply. English and Orlob (27) suggest that when the available water supply is limited, the objective should shift from maximizing yield to maximizing water use efficiency (yield/unit of water). English and Nuss (28) discuss designing for deficit irrigation from this perspective. Under the inevitable uncertainty of agriculture, most farmers, particularly subsistence level farmers, will opt to reduce their risk rather than to maximize their production (20, 26, 47).

Trava (91) and Trava, et al. (92) developed a linear program for optimal allocation of available water to various fields on a farm. Pleban, et al. (71) used a branch and bound algorithm to minimize labor while optimizing allocation of water among fields.

Many other researchers have discussed optimal irrigation practices (4, 10, 21, 33, 42, 43, 53, 86, 88, 93, 95). The objective function for most of these optimization procedures is to maximize farm production. This may not lead to the optimal solution from the farmers' perspective. Farmers may be interested in minimizing risk, labor, credit, and dependency on the one hand, while maximizing flexibility and convenience on the other. Production is obviously important to farmers, but maximizing the probability of a minimum acceptable level of production within set limits for labor, credit, flexibility, and convenience, may represent the highest priority. Therefore, the farmers are the ones who should do the optimizing.

Widanapathirana and Brewer (104) studied farmer responses to deficit water supplies on the Gal Oya Left Bank (Sri Lanka). They found farmers react to expected water shortages by: (1) reducing the area cultivated; (2) reducing the amount of time for land preparation with the consequence of increasing dependence on hired labor; and (3) reducing staggering (variation in planting dates from field to field) which reduces conveyance losses. "Both head and tail farmers adapt their practices to the expectation of a water shortage based on information received from government officials."

Implications of Computer Modeling

Main system operations are reflected in the operation of the UCA; therefore, UCA operations can be influenced by changes in the main system. This is one of the key assumptions behind the irrigation system modeling activity at Utah State University. If the main system supplies water unreliably, or at a time and in a quantity out of synchronization with the actual demands of the UCA, the water will be used inefficiently at the farm/field level. However, if appropriate management and hardware changes are identified at the main system level, such that water is delivered to the UCAs on a more reliable and timely basis, there will be a corresponding increase in water use efficiency within the UCA.

Concern is often expressed that comprehensive computer models, like these developed at Utah State University, are too complex and require too much data to be implemented in developing countries. It is a misunderstanding of computers and an underrating of the capabilities of developing country personal which leads to the conclusion that computer models are too complex. However, concerns about model data requirements are legitimate and deserve further consideration.

It is not a characteristic of comprehensive models that they require more data than simple models. Nor do they necessarily need more data than is required for effective system operation. However, in the event that they do demand more data, well conceived models can make better use of limited data than simplified models. This is because the assumptions made in lieu of missing or poor quality data can be, and generally are, more accurate and realistic than the assumptions inherent in a simplified modeling approach requiring less data.

Some additional arguments in support of comprehensive irrigation system models and the associate data gathering required include:

1. Computer models may get the engineers out in the field more rather than less (as is often argued). This has been observed in the Gal Oya Project in Sri Lanka.

2. Good models serve as a validation of data.

3. The data required by the models are the same as the data required to effect any system management improvement.

4. Good models make data collection important and useful.

5. With comprehensive models, one can take less data and end up with more data/knowledge about the system.

6. Data acquisition generally improves vertical communication within a system and increases the knowledge (vertically and horizontally) of the system.

One potentially powerful use of computer simulation models is for training system operators. Comprehensive models are better training tools than simplified ones. To use the analogy of a flight simulator, a simple model gives the "pilot" only the stick. A complex model gives him the throttle, pedals, gauges, and flaps as well.

Chambers (15) points out that a lot of "back-of-the-envelope" type calculations are already being used to improve main system operations. He warns, "The days for computers may come, but like other forms of hardware, they could once again provide an excuse for not starting action now." While computer hardware and software are potentially powerful tools for more effective management, they are not essential for improving system operation. In fact, the implementation of computer technology would hinder improved system performance if it either increased the communication gap between system operators and the farmers or resulted in delayed action.

A list of some management considerations which can and cannot be addressed with the Utah State University irrigation system models is presented in Table 2.

Other Issues

The issues which follow need mentioning but do not necessarily fit into the general categories listed above.

The organizational success of farmers in a UCA in operating and maintaining their portion of the irrigation distribution network plays a significant role in the effective use of the water, both in terms of total production and in the equity of production among farms within the UCA. This is a dynamic situation that changes between periods of plentiful and scare water supplies during any season and from season to season. Also, the water losses in the system are significantly affected by the organizational capability for maintaining the water delivery and removal channels.

The distribution and diversity of cropping patterns and cultural activities have interesting implications for the command area. Under homogeneous cropping and cultural practices, the demand for irrigation

Table 2. List of Some Management Considerations Which Can and Cannot be Addressed with the USU Irrigation System Models.

A. Overall Irrigation System Management Considerations

1. Can be addressed

    a. The size of the UCA
    b. Reliability of the water supply
    c. Communication link between the UCA and the main system
    d. The operating rules and delivery methods
    e. Data requirements for improved management
    f. Relative water supply
    g. Waterlogging
    h. Conjunctive use of ground water (or other water sources)
    i. Unusual weather and water supply situations
    j. Water charges
    k. Seepage losses
    l. Changes in the nature of irrigation from season to season and from year to year

2. Cannot be addressed

    a. Dichotomy between the collective good and individual well-being.
    b. Economic return from irrigation
    c. Availability of markets, transportation, credit, labor
    d. Bribery

B. Main System Management Considerations

1. Can be addressed

    a. Preference of irrigation hours
    b. Distance from source to supply (lag time)
    c. Operation and maintenance
    d. Reliability
    e. Data requirements for improved management
    f. Effect of modeling on management intervention
    g. Water allocation
    h. Adaptability of the main system for technical changes in cropping systems and methods of applying water to lands
    i. Excessive water spills

2. Cannot be addressed

    a. Water rights -- right to use versus best use
    b. "Illegal" water use -- tapping or checking of the distribution network
    c. Attitude of officials (may not care)

Table 2. (continued)

C. UCA Management Considerations

1. Can be addressed

    a. Affect of mechanization on land preparation water requirements and the distribution of planting dates
    b. Field water supplies less than the demand
    c. UCA distribution channel hydraulics (conveyance efficiency)
    d. Water allocation and scheduling
    e. Nonsanctioned water use
    f. Contrast between water use efficiency and production
    g. Flow management of deficit supplies
    h. Homogeneous versus heterogeneous cropping/cultural patterns
    i. Effects of timing, frequency, duration, and discharge on crop mix and production.
    j. Priority of uses within the UCA
    k. Estimation of crop water requirements
    l. On-farm irrigation methods
    m. Water management efficiency of the farmers
    n. Conjunctive use

2. Cannot be addressed

    a. Formal and informal arrangements for operation and maintenance of the UCA distribution network (UCA discipline)
    b. Salinity and drainage
    c. Farms versus fields
    d. Land tenure

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emerges simultaneously from all fields in the UCA. This gives the aggregate demand hydrograph of the UCA a "skyscraper" appearance requiring a large system capacity. Distribution efficiencies under homogeneous cropping conditions tend to be higher than under more diversified situations. Limitations in the supply automatically cause more heterogeneous cultural activities by forcing some farmers to delay planting or make other adjustments.

From the total productivity standpoint, diversified cropping is better for both the system and the farmers than the mono-culture practice typical of paddy irrigation. The system benefit is due to the reduction in peak water requirements. Angeles and Hill (3) in their modeling of run-of-the-river irrigation in the Philippines found that, provided the costs for additional drainage are within certain bounds, net annual project benefits can be increased by growing a mixture of rice and soybeans rather than rice only as is traditionally done.

Other issues which should be mentioned include: waterlogging; salinity and drainage; water charges; irrigation and the land poor (see Silliman and Lenton, 80); land tenure; economic return from irrigation; availability of markets, transportation, credit, and labor; and formal and informal arrangements for operation and maintenance of the UCA distribution network (UCA discipline). These are all important issues requiring increased attention, but are beyond the scope of this work.

Key Modeling Concepts

The issues presented above can be addressed by employing some principal modeling concepts. Some of these are presented below. These concepts are important to understanding the unit command area modeling logic.

Physically Based Model

The UCA Model is a physically based model interfacing water supply from the main system with demand at the UCA turnout. The supply hydrograph to the UCA is the primary driver for the model. The approach of the model is to use physical principles to provide a mathematical framework by which the aggregate demand and response of the fields making up a UCA can be estimated. It is assumed that social and economic characteristics can be integrated within this physical framework.

Interfacing with the Main System

Interfacing of the UCA Model with the main system begins with the calculation of the aggregate demands for all UCAs comprising the irrigated command area. These demands can be expressed for any period of time ranging from one day to an entire year. Subject to the water allocation rules, the available water supply, and the hydraulic constraints of the main system, water is delivered to the UCAs in response to their demands. If the water supplied by the main system is different from the demand, the UCA Model is then used in the response mode to determine how this variance affects the individual UCAs. This process repeats itself until the irrigation interval of interest is complete.

Two Problems -- Demand and Supply

There are two primary cases which must be considered by the UCA Model. The first is determining the irrigation requirement, or demand, for a UCA as a function time. The second is estimating how a UCA responds to the water supplied by the main system. This is the aggregate demand and response behavior of the fields making up a UCA, rather than the demand and response of individual fields. The response and demand modes of the model are discussed in detail in the next section.

Fields Are the Modeled Population

The UCA is that point in an irrigation system where the allocation and distribution of water among groups of fields ends and among individual fields begins. Thus, UCAs are modeled as populations of fields associated with a single turnout. Fields are characterized by soil type, cropping pattern, planting lag, and other variables. Fields are distinguished from farms in that a single farm may consist of more than one field.

If a farmer owns more than one field he must allocate water to his various fields. An important question arises on the difference between a farmer's allocation of water among his fields and the allocation of water among farms in the UCA. The UCA Model treats all fields independent of farms. The assumption, therefore, is that water allocation on a farm is the same as that in the UCA at large. This is probably when the fields owned/operated by a farmer are not contiguous, but may be challenged when a farmer's fields are all physically connected.

Aggregate Behavior

A basic assumption of the UCA Model is that the behavior of the UCA can be represented as the aggregate of the individual fields comprising the UCA. The inputs for the model describe the distribution functions for the field characteristics, rather than data on a field-by-field basis. The output from the UCA Model shows the accumulated demand and supply of all fields in the UCA, irrigation efficiencies for the UCA by crop and growing season, cross correlation of the field characteristics, and planted area, harvested area, and estimated yield for each crop. Data for individual fields is not part of the output.

The aggregate behavior of fields planted to different crops, on varying soils, as computed by the UCA Model, is distinctly different from the behavior that would be estimated with a lumped modeling approach. The UCA Model does not treat the UCA as one large farm with each crop-soil combination treated as a single field. While the inputs and outputs from the model are in a statistically aggregate form, internal to the model, fields are considered individually.

The tendency will be to use the UCA Model to optimize the operations of the irrigation system as a whole. While this may result in the greatest common good, it must be remembered that optimization of the aggregate is different from maximization/optimization of the desires of individual small farmers.

Water Allocation and Distribution

The formal and informal rules governing the allocation and distribution of water make up the share system. From the UCA modeling standpoint, the aspects of the share system which must be represented are the scheduling of irrigations and the allocation of shortage.

Irrigation Scheduling. The irrigation schedule provides the basis for water allocation and distribution internal to the UCA. The UCA Model is programed for three schedules (continuous flow, rotation and on-demand) with variations on each. This gives the model the flexibility to represent the full range of schedules identified by Replogle (74).

Allocation of Shortage. Little thought appears to have been given to how farmers in a UCA allocate water when the available supply at the UCA turnout is less than the accumulated demand of all the farmers. While the UCA Model can be used to investigate this process and to suggest alternative allocation schemes, it would be best to study observed behavior below the UCA turnout.

As will explained in the following section, fields needing irrigation "arrive" in queue. The order of fields in queue can be on either a first-come-first-served basis or ranked according to relative access to the turnout, crop value, degree of stress, and farmer finesse. When water supplies are short, water can be allocated to those fields first in queue, distributed equitably to all fields in queue, or allotted in a manner favoring those first in queue but with some adjustment for equity. The UCA Model can be used to investigate all of these alternatives.

Determining Demand

Being a physically based model, the UCA Model cannot predict the irrigation demand as it would actually emerge from the farmers. Rather, the model predicts demands based on a chosen method of irrigation scheduling. If an on-demand schedule is implemented, irrigation demands are tied to the soil moisture deficit via the management allowable depletion (MAD). A crop growth simulation model is used to determine soil moisture depletion and replenishment levels and the timing and amount of irrigations. If a rotation schedule is imposed, irrigation demands are keyed to the rotation and are either fixed or variable depending on the nature of the schedule.

In any case, the estimated irrigation requirements are adjusted to reflect irrigation management efficiency, the conveyance efficiency (from the turnout to the field), and the on-field irrigation uniformity. The management efficiency reflects, in part, the human element inherent in determining irrigation demands without explicitly modeling this phenomenon.

Land Preparation

The water for land preparation may be the peak water requirement for the crop season. The availability of water at the time of land preparation is critical to determining when fields are planted, the distribution in planting dates within a command area, and the subsequent irrigation schedule.

Mechanization, or the lack thereof, can significantly affect land preparation water requirements and the distribution of planting dates. Farmers with tractors may not require water for land preparation; whereas it is required to loosen the soil when human or animal power is used for plowing. Since tractors can work the ground faster, the land preparation period is reduced with mechanization.

The UCA Model calculates the water requirement for land preparation and planting based on crop specific data. For most crops this is the water required to raise the soil water content to field capacity. For rice, some level (i.e., 10 cm) of ponded water may be required. The planting lag (period from the beginning of land preparation to field planting) is dependent on the crop and degree of mechanization and is entered as a field characteristic.

Farmer Response to Water Shortage

When faced with a water shortage the farmer has the choice of reducing the area he irrigates or of irrigating the entire area with a deficit. The more risk adverse the farmer, the more he will tend to reduce the irrigated area to meet full demand on the irrigated portion.

The UCA Model assumes all farmers within a unit command area will respond in the same manner to supply deficits. This may appear to be a weak assumption as head-end farmers are faced with less uncertainty, and therefore less risk, than tail-end farmers. However, this is compensated for by the queuing system which may give priority to head-end farmers, thereby assuring them less deficits than tail-end farmers. If shortages are shared equitable by all farmers in the queue, then farmer response will likely be similar.

Farmer response to deficit supplies is treated in the UCA Model as a constant fraction representing the minimum farmer-tolerated ratio of supply to demand. For example, at a tolerated ratio of 75 percent, a farmer will accept a deficit irrigation of no more than 25 percent and will begin cutting back on his irrigated area once supplies dip below 75 percent of demand.

Multiple Growing Seasons

Almost all agricultural activities are adapted to the preceding activities and events. This is particularly true for crop succession. The land preparation and planting of a second crop are directly tied to the harvest of the first crop and the remaining soil water. Therefore, it is important for the UCA Model to be able to cover multiple cropping seasons without having to be reconfigured between plantings.

Irrigation Efficiency

Farmers (and to a large extent, system engineers) are less in control of their water supply than they are controlled by it (73, 87). Therefore, water use efficiency is a function of the supply. If the water delivered to a field is significantly less than the field demand, the irrigation efficiency for the field will tend to be high. Conversely, if the field water supply is more than the demand, the efficiency for the field will tend to be low. Thus, irrigation efficiency is a dynamic phenomenon changing with each irrigation event.

For these reasons, irrigation efficiency is a computed output of UCA Model rather than an input. Furthermore, since a high irrigation efficiency implies that at least some fraction of the field does not receive a full supply, a yield reduction factor, based on the average depth of application and the calculated irrigation efficiency, is also be computed.

Most command area models treat irrigation efficiency as a constant input (1, 5, 20, 24, 33, 65, 72, 75, 77, 91, 93, 105). Angeles and Hill (3) took the novel approach of using irrigation efficiency as a model calibration parameter.

Irrigation efficiency is calculated in the UCA Model using a constant value for the coefficient of uniformity and assuming a linear uniformity model. The method of calculation is based on procedures discussed by Hart and Reynolds (36), Hill and Keller (41) and Solomon (84).

Production Probability

It is important that the crop production predicted by the UCA Model be interpreted according to the probability of occurrence rather than strictly in terms of the averages provided by the model. This is because the model must rely on relationships obtained from experimental data. The actual yields obtained from the various fields of the UCA will vary depending on the farmers' finesse with inputs and knowledge of irrigated agriculture. A factor is included among the field characteristics to help account for this variability. Events and conditions not dealt with by the model will also have an effect on the outcome. As English (26, page 917) warns, "Inevitably there will be a great deal of uncertainty associated with the estimates produced by such models [crop production models] due to variability of model inputs and the uncertainty inherent in the models themselves."

METHODOLOGY: THE UNIT COMMAND AREA MODEL

This section presents the Unit Command Area Model in detail. It opens with a review of some relevant models from the literature followed by the objectives of the current modeling activity and an introduction to the overall flow of the UCA Model. The bulk of this section consists of a detailed description of the model. The section concludes with a brief discussion of model usage.

Review of Models in the Literature

The discussion here is confined to hydrologic (as opposed to hydraulic) models of irrigation systems and processes. Most agro-hydrologic models simulate crop-soil-water interactions for a single field. Modeling multiple fields, with multiple crops and soils, is a more complicated process generally incorporating single field models as submodels.

Single Field Models

Single field models are comprised of submodels for estimating evapotranspiration (ET), maintaining a soil-water balance, and predicting crop growth and yield. Literature related to crop water requirements, growth, and yield modeling is abundant (12, 22, 23, 37, 39, 45, 76, 86). Most single field models are designed for irrigation scheduling purposes (5, 10, 38, 40, 49, 56, 61, 64, 88, 89, 93) and can be adapted for system design (29, 31, 98) and optimization (86, 93).

Bernardo (5) developed a computer program to predict supplemental irrigation requirements for tropical and subtropical climates using monthly climatic data together with a soil water balance and long term daily precipitation. Tsakiris and Kiountouzis (93) used an inventory control model to determine the timing and amount of irrigations which minimized the total cost per unit time for each growth stage of a single crop.

The crop simulation model, CRPSM, developed by Hill, et al. (37, 38, 40) and Keller (49) is used as the basis for the on-field submodel of the UCA Model. CRPSM is a complex model with several options for predicting ET, multiple soil layers, a growing root zone, and crop phenology and yield simulation. Evapotranspiration is split into evaporation and transpiration components with evaporation occurring only from the top soil layer. This model is discussed in detail later in this section.

Multiple Field/Project Level Models

Most multiple field models combine fields with the same crops and soils (11, 20, 21, 24, 30, 33, 43, 48, 54, 57, 71, 75, 79). Some treat the entire area below a turnout as a single field with average characteristics (3, 52, 60, 72, 77). A common reason for modeling multiple field irrigation systems has been to predict the emergence of demand in order to optimize the allocation and distribution of water (2, 3, 11, 21, 33, 43, 52, 54, 72, 92).

Connor, et al. (20), Dudley, et al. (24), and Moore (65) studied stochastic water supply and demand functions using simulation models coupled with linear and dynamic programming techniques. Long term simulation runs were made by Dudley, et al. (24) to determine the most economical acreage to irrigate and the associated reservoir size. Water users' response to uncertainty, advocated by Connor (20), was not incorporated. The computer model developed by Windsor and Chow (105) combines dynamic and linear programming to determine the type of irrigation system and the amount of irrigation best suited for multiple crops and soils in a humid area.

Maidment and Hutchinson (58) modeled a large irrigation area taking into account the size of the irrigated area, soil types, cropping pattern, operation schedule and weather variation. They averaged out the demand hydrograph to avoid the unrealistic "sky-scraper" appearance resulting from high demand on one day and low on the next. The U.S. Bureau of Reclamation has developed a procedure whereby the aggregate demands of multiple fields are determined by monitoring reference fields (11). From their modeling effort, Kim and Busch (54) concluded that statistical simulation and predication of irrigation diversions has advantages over physical simulation.

Angeles and Hill (3) developed and combined irrigation water demand, crop yield, and water allocation models to study a Philippine run-of-the-river irrigation project. Fitzgerald and Arnold (30) used a computerized soil moisture budget to determine irrigation dates for 14-day rotation periods in a large irrigation project in New Zealand.

Anderson and Maas (2) developed a model to determine the best allocation of a limited water resource among crops and farms. Their model simulates decision making by the operators of a water distribution system and the farmers. The complexity of the model limits its practical application to the study of 10 farms, 9 crops, and a 14-period irrigation season.

Rosegrant (77) developed a three part model for paddy irrigation in the Philippines: (1) daily water allocation and distribution; (2) farm level water balance; and (3) farm decision model. The farm decision model predicts the dates of land preparation, transplanting, and harvest based on soil moisture levels; and estimates optimal fertilizer use and crop yields using a stochastic production function incorporating a crop moisture index together with risk neutral or risk averse decision rules. Rosegrant used the model to study continuous flow and rotation irrigation schedules over a 20-year period.

Udeh and Busch (95) were able to closely predict actual irrigated areas using a decision theory optimization model. Their model is flexible enough (by solving the various components of Bayes' equation) to accommodate entirely subjective data which can be updated when observed data becomes available.

Pleban, et al. (71) used the branch and bound algorithm to optimally allocate available water to the fields making up a farm in such a manner that labor is reasonably considered. The farmer is not required to consecutively irrigate fields that are far apart and under a different water delivery system. The model groups fields into a smaller number of individual units to better consider spatial aspects. Since this program determines irrigation dates and amounts for an irrigation system serving multiple fields (covering several crop and soil types) this approach would be applicable to a UCA.

Relying on the analogy between a queuing system and an irrigation system, Abdellaoui (1) developed a computer simulation model to estimate system design capacity requirements. Either a single server (turnout) or multiple parallel servers can be studied. Field demands are estimated using a simple soil water budget. Abdellaoui's work closely parallels this effort and is referenced throughout this section.

Expert System Models

An exciting new era in computing has evolved with the development of fifth generation modeling, making possible expert system models and artificial intelligence. To date, most agricultural expert system models have been limited to the analysis of micro issues. The potential implications of expert systems at the macro level (for example, as a driver for the Utah State University combined irrigation system modeling package, or to investigate sector-wide planning alternatives) are fascinating.

Jones (46) gives an overview of expert systems as they might be applied to agricultural models. Smith, et al. (83) show the use of an expert system model to aid farmers in making agricultural decisions (planting and replanting alternatives) during crop production.

Problems/Limitations of Reviewed Models

Some of the general problems and limitations of the reviewed models are discussed below. The intent is not to be critical of previous work, but rather to profit from past experiences in order to avoid these shortcomings in the UCA Model.

Many studies have been conducted to remedy specific problems on an individual project or area basis. However, the results tend to be too site-specific for widespread transfer.

There are many agro-hydrologic models, but most are for one field, soil, and crop; those for multiple fields tend to combine fields with the same characteristics (crop, soil, etc.), thereby ignoring the important interactions related to water allocation.

Most computer models tend to be physically based without giving attention to socio-economic aspects. The question arises of how to integrate social and economic characteristics with physical descriptions of the system. Decision models similar to the one developed by English and Orlob (27) or Rosegrant (77) are reasonable starting points.

Most models of water delivery systems do not incorporate risk. Those that do, with a few notable exceptions (2, 20, 26, 27, 77), incorporated risk as if only the system planners respond to uncertainty. The end users also react to uncertainty, and their response affects the entire system. For example, farmers will adjust their cropping patterns in accordance to the perceived reliability of the water supply, thereby affecting overall system planning and operation (20). "When uncertainty is included in the analysis it may substantially alter the selection of optimal decisions" (26, p. 921).

Typically, optimization procedures are for large farms or project level optimization. Optimization of the aggregate is different from optimization of the desires of individual small farmers.

Other common limitations of the reviewed models include: failure to consider the implications of land preparation on peak water requirements and timing of other agricultural activities; the use of constant values for irrigation efficiencies and other stochastic variables; and the inability to rank water allocation among fields.

The UCA Model is not without shortcomings; however, consideration has been given to ways in which the model can be used and adapted to minimize its limitations. The model is developed in a generic modular fashion, providing flexibility for the future incorporation of additional submodels. Suggests for these additions are included in the Recommendations. Adaptive methods of using the UCA Model to avoid certain limitations, are discussed at the conclusion of this section.

UCA Modeling Objectives

The primary objectives of this modeling effort were to develop the UCA Model and the interface between the UCA Model and the Utah State University main system models. The criteria for the UCA Model were:

1. A physically based computer program incorporating additional subprograms for the simulation of different physical and non-physical (socio-economic) phenomena;

2. To permit detailed studies of single fields using experimental data and calibrated of crop-soil-water processes;

3. To have an on-demand operation for generating the demand hydrograph for a unit command area represented by multiple fields, cropping patterns, and soil types;

4. To include a response mode of operation whereby given a supply hydrograph the model predicts the UCA response in terms of crop yields, planted and harvested areas, and water efficiency measures;

5. To be user-friendly, permitting usage by personnel with different disciplinary backgrounds and minimal computer skills;
6. To be capable of simulating field characteristic data and daily weather data without observed values; and
7. To be readily portable in the micro computer environment.

General Overview of the UCA Model

General Model Description

The UCA Model is comprised of two integrated submodels -- the on-field submodel and the UCA water allocation and distribution submodel (or queuing system simulation submodel). The on-field submodel maintains soil-water balances for all fields in the UCA and predicts crop growth, consumptive use, and yield in response to irrigation events and weather conditions. The UCA water allocation and distribution submodel allots water from the UCA turnout to individual fields according to the aggregate field demand and the rules governing the share system.

The integration of these two submodels permits the calculation of the aggregate UCA field demand as a function of time. This represents the "optimal" supply hydrograph to the UCA. The UCA response to the actual water supply is predicted by allocating the available supply and updating the soil water balance for each field on a daily basis.

The fields of a unit command area are individually characterized by soil type, crop rotation, relative access to the water supply, size, initial soil water, well capacity, conveyance efficiency, uniformity of irrigation, planting lag, and level of agronomic inputs and farmer finesse.

UCA Model Flow

The overall flow of the model is presented in Figure 8. Detailed flow charts for the water allocation and distribution submodel and the on-field submodel are shown in Figure 12 and 16.

The UCA modeling process begins with entering the information describing the unit command area. This includes the rules for water allocation and distribution (queuing system data), the UCA field characteristics, the weather data, and, if running in the response mode, the supply hydrograph. Refer to Table 3 for a summary listing of the data requirements for the model.

Once all data have been read by the model, the queuing system is initialized and the UCA fields are generated. Field generation is a complete modeling activity in itself. It starts with defining the different cropping patterns, soil types, and irrigation schedules within the UCA. Unallowable combinations of field characteristics (for example, some cropping patterns may not be compatible with some soils) must be identified also.

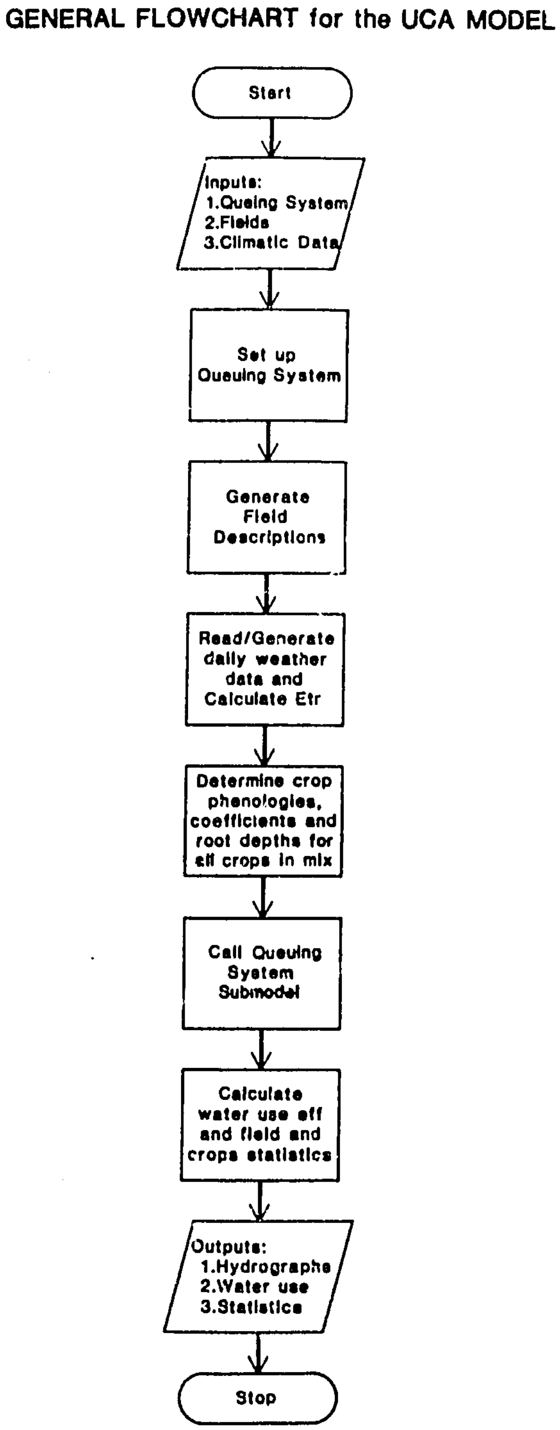

Figure 8. General Flow Chart for the UCA Model.

Table 3. Outline of Data Requirements for the UCA Model.

A. Queuing System Description

1. Weighing factors for ranking the queue
2. Water allocation rules for a short supply
3. Turnout capacity (lps)
4. Water supply period
5. Operating hours per day
6. Water stealing and percent
7. Management efficiency of farmers
8. Field fraction irrigated to full supply
9. Irrigated area reduction factor

B. Field Characteristics

1. Relative access of field to the water supply
2. Field size (tenth ha)
3. Soil type
4. Initial soil water content
5. Cropping schedule (dates and rotation)
6. Planting lag (days)
7. Irrigation uniformity coefficient
8. Conveyance efficiency from the UCA turnout
9. Well (or alternative water source) capacity (lps)
10. Level of agronomic inputs

C. Climatic Data

1. If using observed daily data, need:

    Temperature (°C)
    Precipitation (mm)
    Solar radiation (ly)
    Dew point (°C)
    Wind run (km)
    Evaporation pan (mm)

2. If simulating daily weather data, need monthly means and standard deviations of:

    Reference crop evapotranspiration (mm)
    Average daily temperature (°C)
    Number of rainy days in the month
    Total precipitation for the month (mm)

D. Supply Hydrograph (If running the model in the response mode)

E. Soil Characteristics

F. Crop Specific Data

Fields are then randomly generated, subject to the allowable combinations of field parameters and the statistical distribution patterns based on observed data. Field characteristics can be entered on a field by field basis, but this can be a long and tedious task (depending on the number of fields in the UCA), and rarely are such field specific data available.

Following the generation of the field characteristics, daily reference crop evapotranspiration is computed from either observed or simulated weather data. The resulting daily temperature and ET data are then used to drive a phenological clock computing crop growth stages, transpiration coefficients, and root depths for the earliest and latest planting dates of each crop in the mix.

After all field data, weather data, and crop data have been generated, operation of the water allocation and distribution submodel begins. This is an iterative procedure, cycling through all fields of the UCA for each day of the simulation run. (See Figure 12.) The overall process is outlined in Table 4. The various subprocesses are discussed in the following section.

The UCA modeling concludes with the statistical analysis of the aggregate water supply, demand, and efficiencies by crop and season; planted and harvested areas and yields for each crop; and cross correlation of field characteristics and tracked variables (field water supply, use and efficiencies, planted and harvested areas, and crop yields).

Sample outputs from the UCA Model are included in the Appendices.

Detailed Model Description

The following detailed description of the UCA Model parallels the overall flow of the model as described above and in Figure 8. This ordering is useful for developing the interactions of the various modeling processes. Some sections might be easier to understand if presented in a different order, but doing so would mask the logical flow of the model. An exception is made, however, for discussion of the model data requirements. Rather than appearing at the beginning, detailed explanations of the model inputs are interspersed throughout the appropriate sections which follow.

Field Generation

The characteristics used to describe the fields individually, and the unit command area collectively, are listed in Table 5 along with the variable type (continuous or discrete) and the cause of determination (farmer decision, state of nature, or function of the water supply). Except for the soil type and cropping schedule, all field characteristics are continuous. For example, a field may be any size but is limited to a specific soil type.

Table 4. Outline of the Daily Water Allocation and Distribution Algorithm.

```
For each day
    For each field
     1. If the field is not planted, determine the land preparation
        water requirement (amount and timing); else, if the field
        is planted

          a. Determine the current crop growth stage, transpiration
             coefficient, and root depth; and
          b. Determine the irrigation demand (if the requirement
             is greater than the preset minimum depth of irrigation)

     2. Determine field priority in the service queue

     3. Allocate water to field

     4. Supplement with conjunctive use if field has such option
        and allocated water is less than demand

     5. If the field is not planted, determine the area to be planted
        and the planting date; else, if the field is planted

          a. Reduce the irrigated area (harvested area) if the total
             field water supply is less than the demand and
          b. Remove permanently from the service queue if the water
             stress is too severe

     6. Call on-field submodel (Field water balance)
    Next field
Next day
```

Table 5. Unit Command Area Field Characteristics According to Type (Continuous or Discrete) and Cause of Determination (Farmer Decision, State of Nature, or Function of the Water Supply).

Characteristic	Type[1]	Cause of Determination: Farmer[2] Decision	State of Nature	Water Supply
Access to water supply	C		X	X
Field size	C		X	
Soil type	D		X	
Initial soil water	C		X	X
Cropping schedule	D	X	X	X
Planting lag	C	X	X	X
Irrigation uniformity	C		X	X
Conveyance efficiency	C		X	X
Conjunctive use capacity	C	X	X	X
Level of agronomic inputs	C	X	X	X

[1] C = Continuous, D = Discrete

[2] Some decisions may be imposed by the system administration.

<u>Relative Access to Water Supply</u>. Field access to the turnout water supply depends on the physical position of the field within the UCA, and the socio-economic status of the farmer/operator of the field. If the UCA is well disciplined, the socio-economic status of the farmer may be of minor importance. Because of the natural laws governing the flow of water, a field's physical position relative to the turnout (distance, elevation, number of channel bifurcations, etc.) will always be of some significance.

Relative access is a lumped parameter requiring some subjectivity by the model user. Equation 1 is present as a possible means for estimating a field's relative access:

$$\begin{aligned} \text{Access} = \quad & C1 * \text{relative distance from the turnout} + \\ & C2 * \text{number of channel bifurcations} - \\ & C3 * (1 - \text{number of channels supplying field}) - \\ & C4 * \text{political strength of farmer} \end{aligned} \tag{1}$$

Values for relative access should range from 0 (high access, close to the turnout) to 100 (low access, far from the turnout). C1 through C4 are weighing factors for the access determinates. The relative distance from a field to the turnout can be estimated as a percentage of the greatest distance dimension for the UCA. In well disciplined UCAs, C2 through C4 may be set to zero.

The example UCA shown in Figure 2 is presented in Figure 9 to illustrate the relative access concept and to show possible field values. Notice that the access values increase with distance from the turnout. Some fields toward the tail-end have good access (low values) which might be attributed to the political strength of the farmers of those fields.

The relative access of the fields in the UCA to the water supply at the turnout is used by the model for ranking the fields in the irrigation queue and for determining those fields in a position to take water out of turn (steal).

<u>Field Size</u>. Field sizes tend to be larger in the tail portions of UCAs (see Figure 9). This is probably because of the more extensive nature of agriculture under low water supply densities, as opposed to intensive production where water is more reliably abundant.

In Table 3 field size is listed as being a state of nature only. It might be argued that a farmer may vary his field size in response to the water supply. It is suggested here, however, that once established a field remains fixed. What may vary are the cultivated and irrigated portions of a field.

Since the UCA Model is concerned with the aggregate response of the fields rather than with the fields individually, a UCA can be modeled without dividing it into fields exactly as it appears in reality.

There is a direct and obvious relationship between the average size of the fields and the number of fields. From the modeling standpoint, the

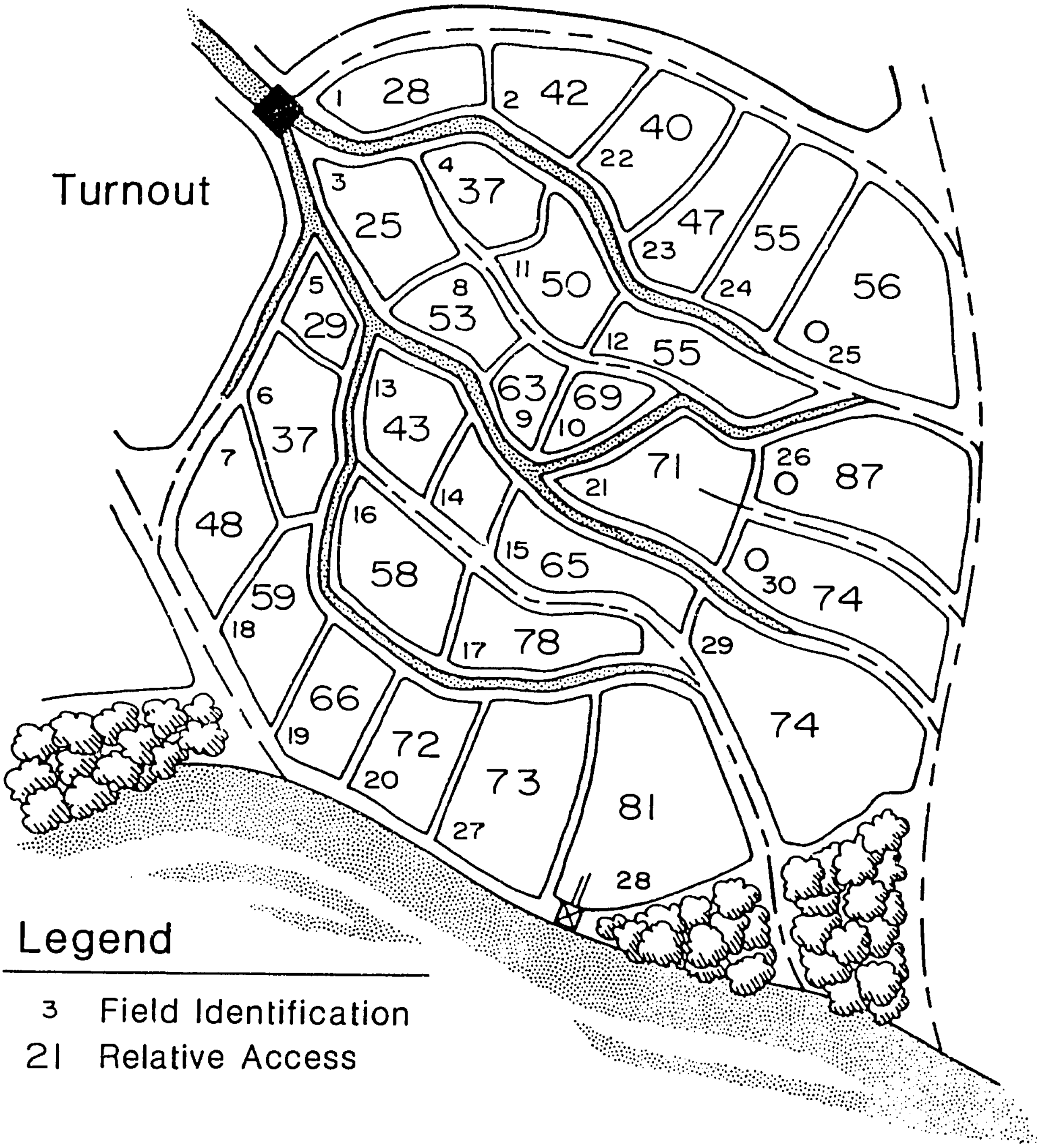

Figure 9. Example Unit Command Area Showing Relative Access to (or Distance from) the Water Supply at the Turnout.

fewer the number of fields, the faster and more efficiently the model will run. The model user must, however, use at least as many fields as there are permutations of field characteristics. The implications of field size and number are studied in the next section.

Soil Type. The UCA Model may be dimensioned for any number of soil types. A field, however, can contain only one soil type. If an actual field has two or more soils, it must be subdivided. An example of soil type distribution is shown in Figure 22 in the next section.

A soil type is defined by its depth, infiltration rate, and soil layers. Each soil layer is referenced by textural classification and water related properties -- saturation water content, field capacity, wilting point, percolation rate, and thickness. The top layer of each soil type is further described according to the amount of water the can be evaporated from it under atmospheric conditions, and the nature of the evaporation equation.

From the standpoint of the UCA Model, only those soil properties which affect soil-water relationships are important. Therefore, soil types can be combined when their distinctions make no difference to the model.

Initial Soil Water. Since most field management decisions (i.e., land preparation, planting, and irrigation) depend on the soil water status, the model must have a starting point. The initial soil water, expressed as a percent of the readily available soil water, provides this beginning point and is the tie-in for subsequent runs.

Cropping Schedule. The cropping schedule for a field is described by the cropping intensity, the crop grown each season, and the window from the beginning of land preparation to the latest acceptable planting date for each crop/season.

The cropping schedule is selected by the farmer in response to the perceived reliability of the water supply in conjunction with a host of other facts ranging from environmental considerations to other employment opportunities. The simulation of decision making is discussed later in this section.

Planting Lag. The planting lag refers to the time in days from the beginning of land preparation to the end of planting (or transplanting) for the field in question. The planting lag is primarily a function of the length of time it takes for land soaking and puddling of paddy rice, and for plowing and seed bed preparation of non-rice crops. Thus, the planting lag is a function in part of the crop to be grown.

The method of cultivation and the accessibility and use of hired labor directly affect the time required for land preparation. If small tractors are available, or hired labor employed, the planting lag may be substantially reduced over the time required for land preparation using animal power.

The distribution of planting lags within a UCA can significantly affect the nature of the demand hydrograph. If all fields have close to the same planting lag, demands will tend to occur simultaneously for those fields having the same cropping schedule, and the demand hydrograph will show short-term, high peaks.

The distribution of planting lags and the effect of mechanization are shown in Figure 10.

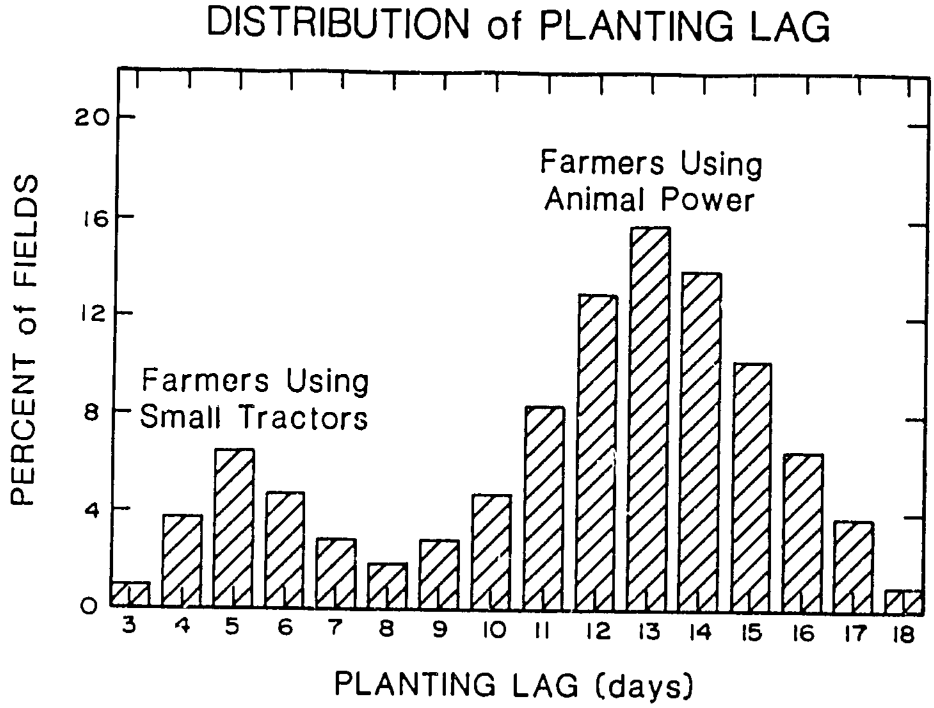

Figure 10. Planting Lag Distribution Showing the Potential Effect of Mechanization.

Irrigation Uniformity Coefficient. Rather than assuming a constant value, the UCA Model calculates field irrigation application efficiencies as a function of irrigation uniformity. The cumulative linear distribution model of irrigation uniformity is used with a constant value for the coefficient of uniformity. This allows irrigation efficiency to vary with each irrigation event depending on the water supplied and the soil water requirement at the time of irrigation.

The uniformity approach can also be used to determine the amount of water required (assuming a flexible irrigation schedule) to insure full irrigation of any portion of the field. Use of an assumed irrigation efficiency would imply a water demand to fully irrigate the entire field with each irrigation.

Tyagi and Narayana (94) used irrigation uniformity instead of efficiency in their data collection to study constraints to improved on-farm water management in India. Irrigation uniformity is estimated from the depth of infiltration, an easily measured field variable. Irrigation efficiency, on the other hand, is difficult to measure directly.

The linear coefficient of uniformity (UCL) is given by:

$$UCL = 1.0 - 0.25\ b \qquad (2)$$

where b is the slope of the line resulting from linear regression on the dimensionless cumulative frequency curve (99). The UCL can also be estimated from Christiansen's coefficient of uniformity (UCC) by:

$$UCL = 0.011 + 0.985\ UCC \qquad (3)$$

The cumulative linear distribution model, as it affects irrigation efficiency and yield computations, is discussed in detail under the model outputs section.

Conveyance Efficiency. The conveyance efficiency is used in the UCA Model to specify watercourse losses from the UCA turnout to the fields. The UCA Model does not consider channel hydraulics. The use of a temporally constant conveyance efficiency to each field may be a model limitation. The order of field irrigation affects the channel filling and drainage schedule, and as a result, the conveyance efficiency. The model user must be aware of this and make appropriate adjustments. For example, higher conveyance efficiencies might be used when rotation schedules are imposed than when irrigation is on-demand.

Conjunctive Use Capacity. The UCA Model does not model groundwater flow. Conjunctive use of groundwater, or of any other water source, is limited only by the pumping capacity of the well in the field. The potential effects of the amount of pumping on the available conjunctive supply (i.e., draw down) are not taken into account. However, the model does keep track of the total pumped volume, so adjustments to pumping capacities can be made externally.

Level of Agronomic Inputs. The level of agronomic inputs is used to describe the amount of fertilizer and other yield-enhancing inputs applied to a field. This relative term is used as a multiplier to predict crop yield. As such, it can reflect farmer finesse, financial constraints, and other yield-affecting aspects.

The notion here is that if two different farmers farm identical fields, raising the same crop, planted on the same day, they will obtain different yields. The level of agronomic inputs can be used to account for this difference.

The level of agronomic inputs is also included in the ranking equation for the prioritized queue. It accounts for the likelihood that a farmer who invests heavily on inputs will work hard to obtain the water required to realize the benefits from those inputs. The UCA Model user can assume a relative level of agronomic inputs of 100 percent for all fields to nullify the effect of this term.

Land Tenure. Land tenure is not included as a field characteristics. This may be a limitation in areas where tenure plays an important role in the allocation of water among farms and fields. It is presupposed that if a farmer receives water allocations for more than one field, he reallocates the water among his fields only if they are contiguous. The modeling assumption is that a ranked queue and the allocation rules of the UCA also apply at the farm level.

Decision Variables. Table 5 and the discussion above show that the cropping schedule, planting lag, conjunctive use capacity, and level of agronomic inputs are all the result of farmer decisions. It could even be argued that the irrigation uniformity and conveyance efficiency are also the result of farmer decision making since the nature and condition of the application and distribution system are largely controlled by the farmer.

A farmer's decisions are strongly influenced by the reliability of the water supply and his perception of this reliability. The farmer's real time management of irrigation is dependent upon past experience and confidence in the irrigation delivery system.

A problem faced in developing the UCA Model, therefore, was how to represent the farmers' decision making in a physically based model. If the model was to be used only for the prediction of the demand hydrograph, simulation of farmer decision making could probably be ignored. Since the UCA Model operates in a response mode and a demand mode, farmer decisions (in terms of what to plant, when to plant, how much fertilizer to apply, etc.) could not be neglected.

Four different methods were identified for estimating those field characteristics which depend on farmer decisions:

1. Have the model user assume the role of a farmer;
2. Make multiple model runs, adjusting field characteristics until some maximum is reached;
3. Use decision theory coupled with utility functions; or
4. Base decisions on operating rules obtained from farmer interviews and field observations of aggregate farmer behavior.

Having the model user assume the role of a farmer and make decisions accordingly has all the problems inherent with computer modeling that concern sociologists. Generally, the engineers who will be using the model have neither the personal experience nor cultural sensitivity to think like the farmer/clients they serve. The decisions made by the model user would be different from those of the farmers, and the danger would exist of the model becoming an imposition.

Making multiple model runs, adjusting field characteristics until some maximum is reached, has important limitations in application and in computation. From the applied standpoint, it would be difficult, if not impossible, to determine the objective function of the farmers. The irrigated area, total production, water use efficiency, or economic return could be maximized; but any one of these alone may not represent the collective objective. The primary objective of some farmers may not be the same for all farmers. Furthermore, maximizing for one farmer may result in minimizing for the next. This would be particularly true in a command area where the idea of limited good is strong.

Even if a suitable overall objective function could be identified, from the computational viewpoint, it would be particularly cumbersome to orient the model to find a global maximum. The number of possible solutions resulting from the potential crop mixes, planting dates, planted areas, and fertilizer application rates, alone, would be enough to frustrate such effort. The problem is further compounded by the lack of means to efficiently initiate the required pattern search.

Using decision theory coupled with utility functions is the most intellectually intriguing of the four approaches. The decision theory approach assumes that farmers make rational decisions which maximize their expected utility. Farmers in general, and subsistence level farmers in particular, tend to be risk averse; therefore, their utility is maximized by reducing their risk.

Rosegrant (77) developed a farm decision model for estimating optimal fertilizer use to achieve yield objectives. His model was based on a stochastic production function incorporating a crop water index together with risk neutral and risk averse decision rules. English (26) used utility functions in a decision analysis to determine the most favorable water use strategies and cropping patterns for six different farmers. He showed that, when water is limiting, a risk averse farmer would use more water per unit of land and put less land into production than one who is more willing to take risks. Udeh and Busch (95) used decision theory to determine optimal irrigated areas on a project wide basis.

While the decision theory approach is rigorous, it has some important practical limitations, the biggest of which is due to the nature of utility. A farmers utility function changes from year to year and with each cropping season. Furthermore, utility curves vary from farmer to farmer. This explains in part why farmers within the same UCA may make different decisions given similar resources.

As English (26) explains, "The difficulty of determining a person's true utility function and the dynamic nature of utility make routine use of this approach impractical." (p.921)

Basing decisions on operating rules obtained from farmer interviews and field observations of aggregate farmer behavior is the method recommended here. This approach realizes that the farmers are the ones who do the optimizing. With time and experience and good information, farmers tend to optimize the use of their perceived resources. Sampling from different areas, where water supply explains the primary differences observed in aggregate behavior, will permit configuration of the model to represent the observed variations in response.

This fourth, and recommended approach, runs the risk of the model being used without the necessary field observations being made. If the model user fails to initialize the model with actual field data, this method will have the same problems as the first.

Random Field Generation. Field characteristic data can be entered on a field by field, characteristic by characteristic basis if the necessary data are available and the model user has the required patience to enter all the information. A more expedient, and probably equally accurate, method of describing a UCA to the model uses the probability density functions of the various field characteristics, and randomly generates values for each field.

The easiest approach, when faced with a sparsity of data, would be to assume averages for all characteristics, but as Mendenhall, et al. (62) point out:

> "...it is better to take random observations from the probability distributions involved than to use averages to simulate the performance of the system. This is true even when one is only interested in the average aggregate performance of the system, because combining average performances for the individual elements may result in something far from average for the overall system" (p. 152).

There are three mathematical techniques for computing the probability density function of a variable from a population sample: (1) the method of distribution functions; (2) the method of transformation; and (3) the method of moment generation. These are described in detail by Mendenhall, et al. (62) and Solomon (84) and will not be discussed here as they are more relevant to data manipulation outside the UCA Model than internal to it.

The current version of the UCA Model incorporates seven probability density models: uniform, normal, log-normal, gamma, beta, empirical, and discrete. The normal, log-normal, gamma, and beta models were adapted from Abdellaoui (1).

The empirical model allows data generation for any probability density function regardless of its shape. This model is used by simply entering the points from the frequency distribution and is the best choice when the formal density function or parameters are unknown. An example of when the empirical model would be used is illustrated by the planting lag distribution shown in Figure 10. The discrete distribution model is a variation of the empirical model for generating discrete characteristics (cropping schedule and soil type).

Some combinations of generated field characteristics may be incompatible when they occur on a single field. Possible examples of this include crops with high labor requirements raised on large fields and rice grown in sandy soils.

Rather than using conditional probabilities, the UCA Model checks for compatibility among generated variables and calls for a new random variate whenever incompatibility is identified. This procedure is not as rigorously sound as using conditional probabilities and can lead to some artificial skewness; but it is much simpler and provides more flexibility, both from the modeling development and usage standpoints.

This trial and error procedure makes the model sensitive to the order of variable generation. The current version of the UCA Model generates field characteristics in the order of: relative access, conjunctive use capacity, field size, soil type, initial soil water, irrigation uniformity, conveyance efficiency, cropping schedule, planting lag, and level of agronomic inputs. Except for the conjunctive use capacity, this puts the generation of decision variables after the state of nature characteristics.

The conjunctive use capacity is generated following simulation of the relative access. This is because it can be easily predicted given the water supply, is generally only affected by the relative access (i.e., fields with good access to a reliable water supply do not need to rely on conjunctive use), and is important to the determination of the remaining characteristics. If the order of variable generation is deemed inappropriate or inefficient it can be changed easily.

To simplify data entry and field generation, the UCA can be divided into blocks. There is a minimum of one block per UCA and a maximum equal to the number of fields in the UCA. The irrigation schedule and distribution functions for the field characteristics are different for each block. This allows the analysis of spatially consolidated variables and conditions as opposed to scattered. For example the cropping schedule, soil type, and irrigation schedule may be the same for a portion of the UCA and can be looped into a single large block. In this respect, a block can be thought of a miniature homogeneous UCA. The example UCA illustrated in Figure 22 might be divided into two blocks along the soil boundary.

In a later section the UCA Model's sensitivity to variable value (level), variance, and distribution will be studied as it relates to field generation. The field generating procedure is outlined in Table 6.

Field Data. The field generation procedure, using the statistical distribution of field characteristics, gives the UCA Model considerable flexibility. By random sampling from an irrigation project, an average or typical UCA can be generated. Ideal UCAs, UCAs under high water tensions, and UCAs under normal conditions can be sampled to generated unit command areas representing specific situations.

Weather and ET Simulation

Perhaps the most important input data for simulation of agricultural systems is weather data. The UCA Model requires daily values of maximum and minimum temperature, solar radiation, evapotranspiration (ET), and precipitation. These data are necessary for predicting crop phenology,

Table 6. Outline of the Field Generation Process.

```
Define cropping schedules
Rank crops according to value
Define soil types
Define unacceptable combinations of field characteristics
Divide the UCA in to blocks
For each block

     1. Enter the number of fields in the block
     2. Define the irrigation schedule for the block

          On-demand schedule
          Rotation schedule
          Continuous flow (In this case fields become lumped
          entities reflecting the group of fields receiving
          water one from the other)

     3. For each field characteristic

          For each field in the block

              i. Generate random characteristic or enter field
                 explicit value
             ii. Check for field characteristic compatibility; if
                 incompatible generate a new random variate.

          Next field

     4. Next characteristic

Next block
Run field statistics
```

consumptive use, and yield, and for maintaining the soil water balances. Daily weather data can be entered directly, or simulated from monthly means and standard deviations.

Observed Daily Data. If observed daily data are to be used, the specific data required depend on the ET equation employed. The UCA Model permits the user to select from among the modified Penman, the Hargreaves, and Jensen-Haise type evapotranspiration equations or to use evaporation pan data.

The modified Penman equation requires daily maximum and minimum temperature, maximum clear day and actual solar radiation, humidity, and wind run. The Jensen-Haise type equation requires average daily temperature and solar radiation. The latest version of the Hargreaves equation requires only maximum and minimum temperature. If evaporation pan data are used, they must be accompanied by average daily temperature and a monthly pan coefficient.

Information on these methods of ET prediction is readily available in the literature (12, 23, 35, 39, 45); thus, they will not be discussed further.

In order to use the UCA Model to study command area response over a range of potential climatic conditions, a long term (20-year plus) record of daily weather data is necessary. In most situations where the UCA Model will be applied, historic weather records of sufficient length will be unavailable. When available, such data are generally unreliable. This is particularly true for solar radiation data.

Simulated Daily Data. The alternative to using observed weather data is to use synthesized data; but in order for this to be practical, the synthesized data must match the observed climatic pattern for the area being study.

Richardson (76) developed a daily weather simulation model to generate input for a selected crop model. The crop growth characteristics and yields obtained using the simulated weather data were not significantly different from those obtained using actual data. Lansford, et al. (57) used simulated weather data to evaluate and forecast appropriate agricultural decision strategies.

The data required for daily weather simulation by the UCA Model include the mean and standard deviation for each month of the year of reference crop evapotranspiration, average daily temperature, number of rainy days in the month, and the total monthly precipitation. The minimum and maximum fraction of solar radiation at the top of the atmosphere reaching the earth's surface must also be provided.

Monthly expected evapotranspiration, temperature, and precipitation data for 644 stations around the world are published by Hargreaves (35). Estimates of the minimum and maximum fraction of solar radiation reaching the earth's surface are given by Doorenbos and Pruitt (23) as a function of latitude.

The weather simulation process begins by generating the mean ET data for each day of the year. The ET values are then randomized to simulate the stochastic variation observed in actual data. Daily temperature and solar radiation are calculated to correlate with the randomized ET data. Finally, random rainfall events are generated which coincide with cloudy days predicted as a function of the solar radiation. The details of this process are listed below:

1. Long-term mean ET for each day of the year is generated using a procedure developed by Keller (49). The mean daily ET values entered for each month are converted to the expected value for the first of each month using numerical integration. The mean daily ET for each day is then estimated using a forth order

Lagrangian approximation and the expected values for the first of each month.

2. Mean daily temperature is generated using the same procedure, with the exception that a third order Lagrangian approximation is employed instead of a forth.

3. The daily solar radiation arriving at the top of the atmosphere is calculated for the site latitude using spherical geometry.

4. Random deviates for ET are generated assuming a normal distribution. This assumption is supported by the research findings of Doorenbos and Pruitt (23), Jensen (45), and Keller (49). Khanjani and Busch (53) found the probability distribution of accumulated potential ET followed a log-normal distribution pattern.

5. Random average daily temperatures are generated based on the ratio of the randomly generated ET to the mean daily ET to the power of z where:

$$z = \frac{\ln(1 - STT/T)}{\ln(1 - STET/ET)} \tag{4}$$

   and STT and STET are the standard deviations of temperature, T, and ET respectively.

6. Daily solar radiation, Rs, is generated by back calculation of the Hargreaves ET equation using the randomly generated daily ET and average temperature values. The simulated Rs values are then checked for fit between the bounds defined by the maximum and minimum fraction of radiation reaching the earth's surface. If out of bounds, the Rs value is set to the appropriate boundary value and the average temperature simulated for that day is adjusted.

7. The maximum and minimum daily temperatures are calculate by adding and subtracting half of the daily temperature difference for the average temperature. The daily temperature difference (difference between the maximum and minimum temperature) is calculated as a function of the square of the ratio of the solar radiation received at the earth's surface to that received at the top of the atmosphere.

8. The number of rainy days in each month is determined as a random deviate of the mean and standard deviations supplied as inputs, and assuming a normal distribution. The rainy days in each month are then predicted as those days with the lowest ratio of solar radiation received at the earth's surface to that received at the top of the atmosphere.

9. Finally, the depth of precipitation for each day with rain is generated, assuming a log-normal distribution, and using the monthly mean and standard deviation supplied as inputs and adjusted for the simulated number of rainy days.

A pseudo year is used to seed the random number generator which drives the normal and log-normal distribution models. The frequency, in days, of random variate generation can be controlled to range from zero, for mean data only (no randomization), on up. (A frequency of roughly five days was found to give the most realistic results.) Keller (49), using time series methods discussed by Bowerman and O'Connell (9), derived an auto regressive function for forecasting ET data given the ET for the current day and the long-term mean ET. This same function is used in the UCA Model when the frequency of random variate generation is greater than one day.

Crop Phenology

The UCA Model incorporates four different phenology clocks for the prediction of crop growth stages: summation of days, 50-86 Fahrenheit growing degree days, 40-77 growing degree days, and summation of ET. These phenology clocks are discussed in detail by Hill, et al. (39, 40).

The UCA Model uses the data file, CROP.DAT, to maintain data for all crops in the potential mix. CROP.DAT contains the phenology clock values, transpiration coefficients, soil water stress limits, and lambdas for yield calculation for each growth stage; the maximum value for the transpiration coefficient; the beginning and ending root depths; the allowable depth of standing water; the land preparation water requirement; the adjustment factors for the length of the land preparation and harvest periods; and the crop yield potential. CROP.DAT can easily be edited by the model user to make any necessary site specific adjustments. A third order Lagrangian interpolation is used to estimate daily crop transpiration coefficients and root depths.

Rather than computing and storing the crop phenology, transpiration coefficients, and root depths for each field, these data are determined for the earliest and latest possible planting dates for each crop in the mix.

The crop phenology and related values are computed for each day and each field by linear interpolation between the equivalent values for the earliest and latest planting dates for the crop in question. Computation of the transpiration coefficient by this process is illustrated in Figure 11.

This procedure greatly reduces computer memory requirements, since only the planting dates (as opposed to the daily transpiration coefficients and root depths) for each field need to be stored.

UCA Water Allocation and Distribution

Water delivered to the UCA by the main system is allocated to individual fields by the UCA Model's water allocation and distribution

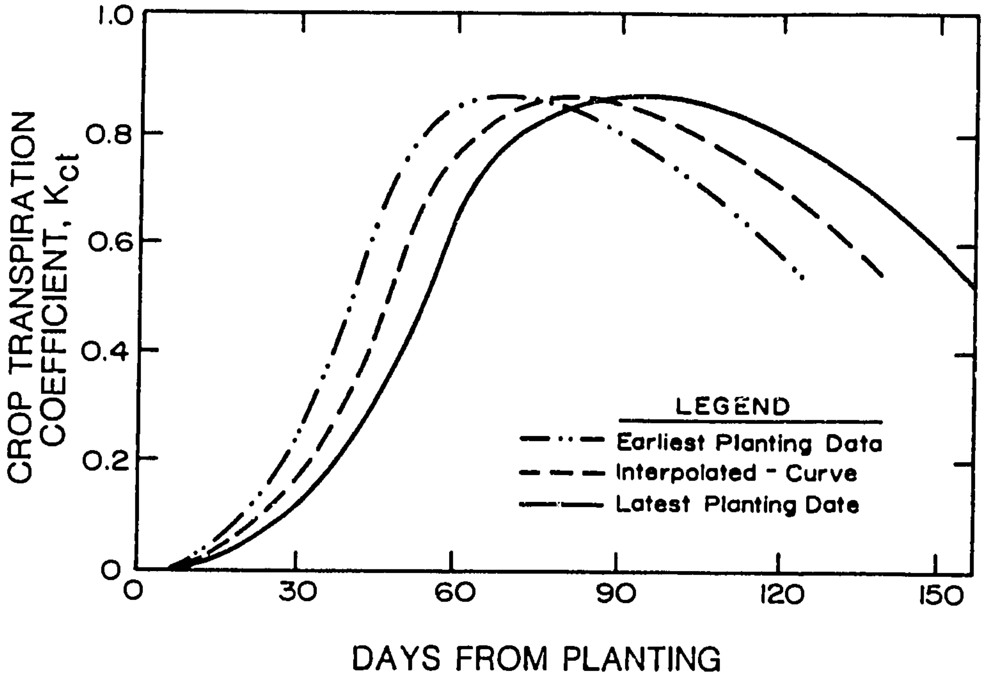

Figure 11. Computation of the Transpiration Coefficient by Interpolation Between Values for the Earliest and Latest Planting Dates for the Crop.

submodel, QUEUE. This submodel is the heart of the UCA Model. Besides allocating the turnout supply, QUEUE is also aggregates the demands (water requirements) of all the fields within the UCA to express the combined demand on the main system.

Queuing System Analogy. A queuing system is any system representing the arrival and servicing of a set of "customers." In an irrigation system the fields are analogous to the customers, and the turnout to the UCA from the main system is analogous to the service facility. All queuing systems have a set of operating rules which govern the arrival of customers, the positioning of customers in queue, and the servicing of customers.

Abdellaoui (1) developed the analogy between irrigation systems and queuing systems. Taha (90) lists ten characteristics of queuing systems. These are presented in Table 7 together with the unit command area analog.

Queuing theory provides for estimating one or more characteristics given the other characteristics. When applied to irrigation, queuing theory statistically relates the characteristics of the command area to the temporal distribution of water demand. For example, the variances in soils, planting dates, crops, and sizes of fields cause the aggregate demand for irrigation water to have a statistical distribution which can be predicted without explicitly modeling the individual fields.

White, et al. (103) point out the difficulties in the analysis of transient birth-death processes (queuing systems), and question the practicality of applying queuing theory under such conditions. Bhat (6) defends the utility of queuing theory but admits the limitations of the theory when applied to transient situations.

Queuing System Simulation. Because of the transient nature of irrigation, queuing theory is not directly applied in the UCA Model; rather, the analogy between irrigation and queuing systems is used as a basis for simulation.

Queuing systems can be simulated using either variable or fixed time increments. Fixed time increment simulation is appropriate when large (relative to the total simulation period) time steps can be used. Variable time increment modeling is more efficient when the simulated events are short and temporally dispersed. Abdellaoui (1) developed a command area model using next event simulation (variable time increment). He selected this approach since the length of time to serve a field (depth required divided by the unit flow rate) can be small (tenths of an hour in a pressurized systems).

The UCA Model uses a fixed daily time step. The total volumetric demand for all fields in the UCA is determined for each day, and divided by the number of operating hours per day. This gives the demand flow rate which is then subject to being less than or equal to the available supply for that day or the turnout capacity, whichever is more limiting. This approach, while being efficient because of the large daily time step, predicts and responds to the integral of the daily hydrograph, thus becoming transparent to any flow fluctuations which might occur within a given day.

Subroutine QUEUE. This subroutine is comprised of a single daily loop encompassing five basic subprocesses -- the calculation of each field's water requirement, the ranking of fields in queue, the calculation of the total UCA demand, the servicing of fields in queue, and the calculation of each field's irrigated area and maintenance of its soil water balance. Each of these subprocesses consists of a loop iterating through the fields comprising the UCA. The flow chart for Subroutine QUEUE in presented in Figure 12. Estimating the water requirement for each field begins by checking whether the water requirement for land preparation has been met.

All fields go into queue at the beginning of the land preparation period. Planting is keyed to land preparation and occurs so many days (planting lag times a crop adjustment factor) after the land preparation water requirement has been met. If the water required for land preparation is not supplied within a specified interval, the field will not be planted and will remain fallow until the next growing season.

If the water requirement for land preparation has been met, the field is flagged as having been planted and is checked for the current degree of water stress, if any. A field is taken permanently out of queue for the remainder of the cropping season (by setting the harvested area equal

Table 7. The Analogy Between an Irrigation System and the Ten Characteristics of a Queuing System.

Queuing System Characteristic	Irrigation System Analog
1. Service facility and population of customers	UCA turnout and fields
2. Input process = arrival pattern	Irrigation turn, management allowable deficit, etc.
3. Distribution of customer service times	Length of irrigation turn
4. Design of the service facility = number of servers and arrangement	1 UCA turnout
5. Service discipline	First-come-first-served or ranked according to field priority
6. Finite or infinite source of customers	Finite number of fields
7. "Human" behavior: balking; reneging; and jockeying.	Too many fields in queue, leave queue after a rain, and select alternate water supply
8. Time dependent (transient) or time independent (steady state) system	Time dependent due to the transient nature of consumptive use
9. Measures of effectiveness	UCA production, area irrigated, water use efficiency, etc.
10. Optimization of system	What size of UCA, turnout capacity, operation rules, etc. will tend to optimize the design?

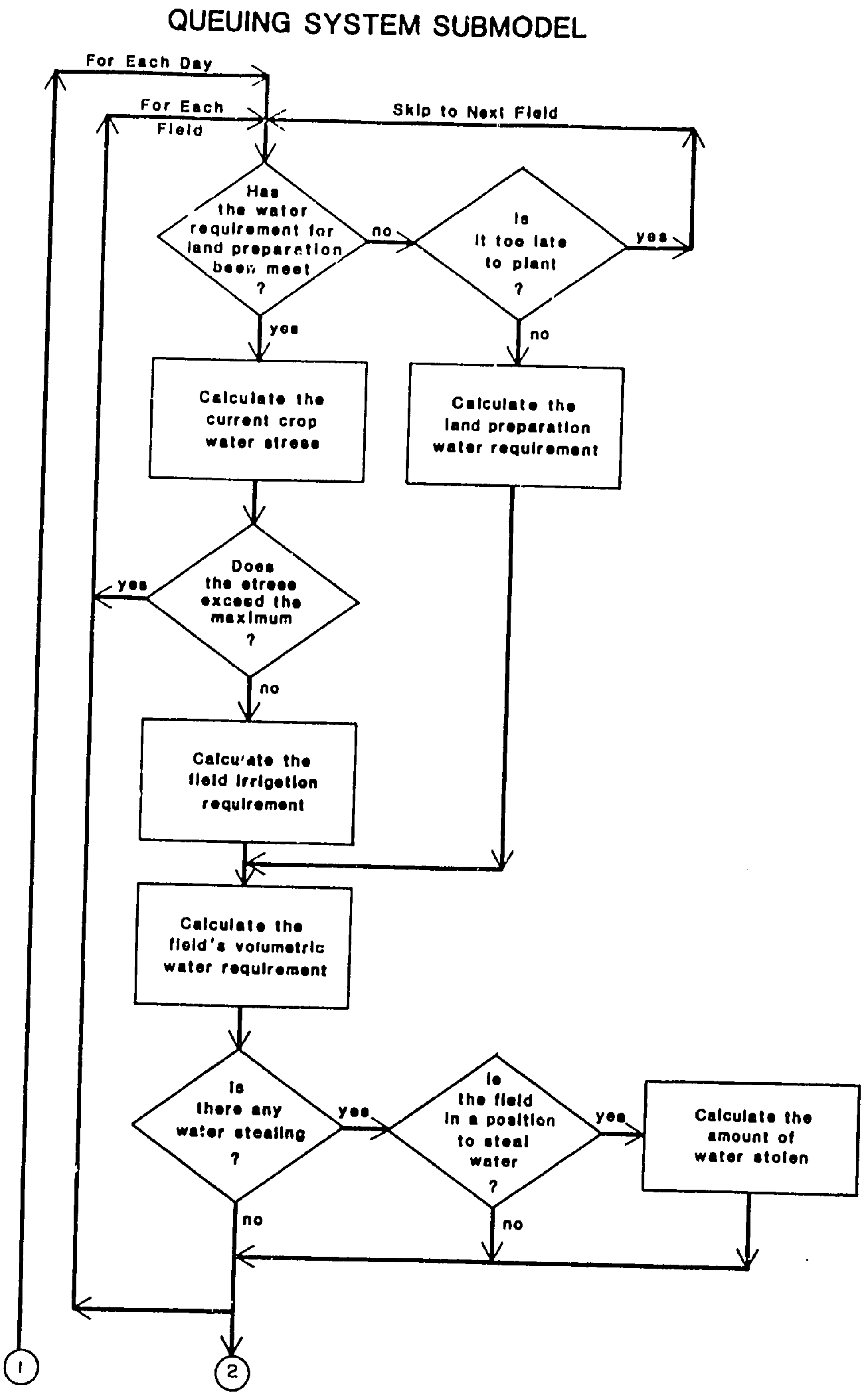

Figure 12. Flow Chart for the Queuing Simulation Subroutine, QUEUE.

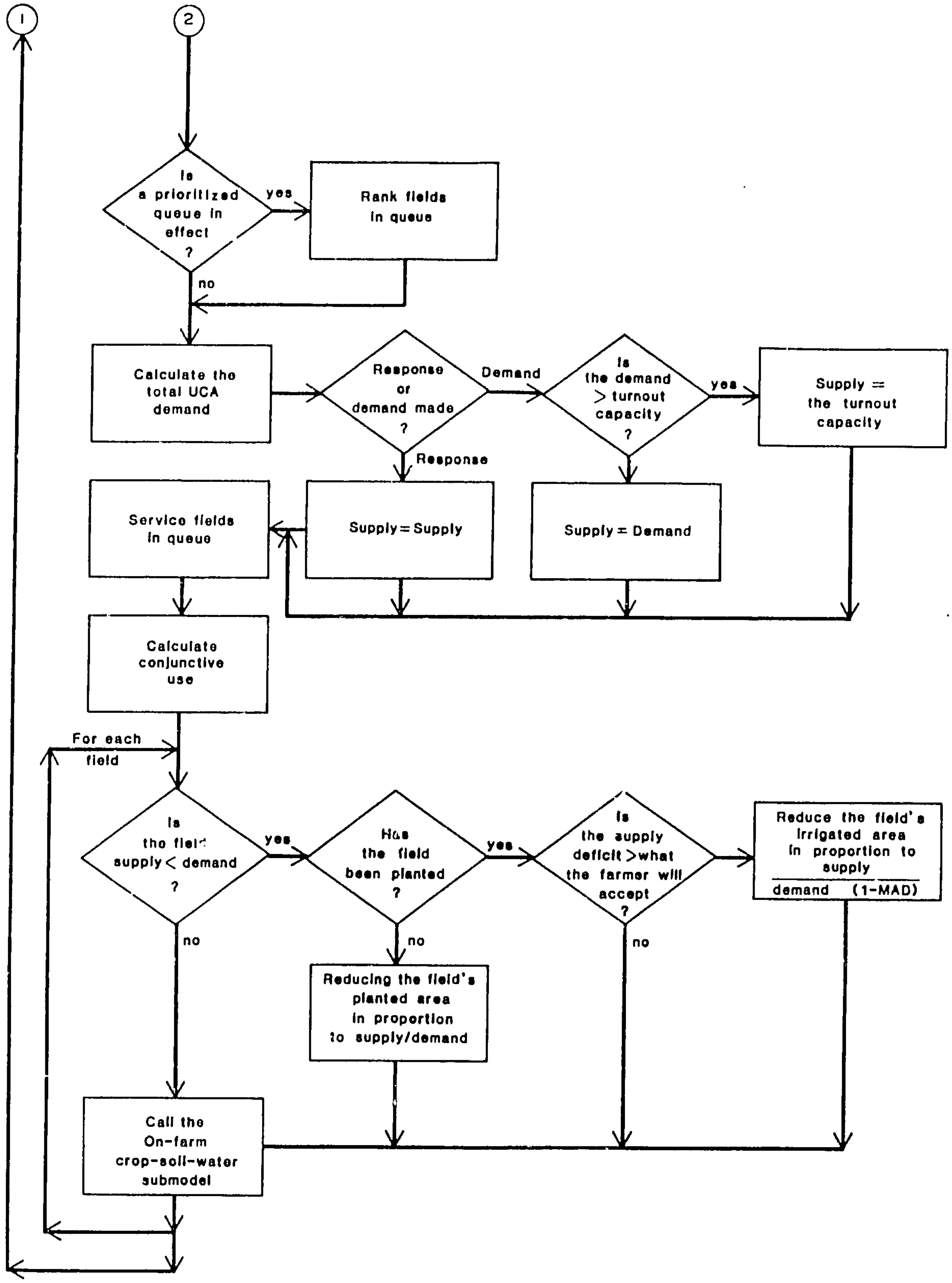

Figure 12. Continued.

to zero) if the stress is greater than some maximum defined by the crop-soil combination.

The water requirement for land preparation is a function of the crop, soil, and current soil water status. The available soil water (percent by volume) required at planting is stored as a crop specific variable in the CROP.DAT file. The irrigation requirement for a field is determined as a function of the irrigation schedule. Internal to the unit command area, three different irrigation schedules may be implemented -- continuous flow, on-demand, and rotation.

Under continuous flow irrigation, water, when available, flows continuously from the turnout to the fields. As such continuous flow irrigation might be considered a special case of rotation with a one day frequency. Continuous flow is modeled by lumping all fields getting water from the same tertiary point (fields that would be on the same quaternary) into one large field. Since the model reduces irrigated area when water is below demand, the situation of head-enders versus tail-enders is simulated.

With on-demand irrigation, each field gets the amount of water determined by its independent demand. On-demand irrigation is modeled on a field-by-field basis, and is triggered by the management allowable depletion (MAD). The MAD may be either a fixed depth, a fixed percent of the available water in the root zone or a variable percent tied to the crop growth stage. The MAD represents the field's soil water demand rather than the farmer's demand which may be a limitation of this approach.

Under rotation irrigation water is rotated from field to field by turn. Rotations are scheduled on a fixed period basis starting with the day the field is first irrigated. The date of initial irrigation is determined as an outcome of the queue in which all fields are initially entered.

Water stealing within the UCA is modeled as the taking of water out of turn. As such, it only has applicability when a rotation schedule is imposed. Other forms of water stealing (i.e., taking more than share) are implicitly modeled by the ranked queue. The model user provides the percentage of fields that steal water. Fields in a position to steal water are then determined according to their relative access to the turnout.

In order to force usage of any excess water which might be delivered to the UCA turnout, a queue-all option can be set whereby all fields enter the queue each day. This option has validity in the response mode only. Irrigations can be either fixed or variable depth with any of the three schedules, and are always assumed to be variable depth when the queue-all option is set or when irrigation is taken out of turn.

The model user defines the minimum and maximum allowable net depths of irrigation. These are used to keep the variable depth irrigations within reason. If the variable depth irrigation requirement is less than the minimum, the irrigation requirement for that field on that day is set to zero. If the water requirement for land preparation is less than half of the minimum irrigation depth, it is set to zero; otherwise, it is set to whichever is greater -- the minimum depth of irrigation or the land preparation water requirement.

The field water requirements are then adjusted for the conveyance efficiency, the farmer irrigation management efficiency, and the on-field application uniformity. The conveyance efficiency from the UCA turnout to each field is assumed to be temporally constant. The irrigation management efficiency of the farmers is assumed to be a constant for the UCA, and is applied only to variable depth irrigation.

Rather than assuming a constant application efficiency for each field irrigation event, the UCA Model relies on the concept of application uniformity. As stated before, the linear distribution model of irrigation uniformity is used.

The linear distribution model was originally proposed for sprinkle irrigation. Solomon (84) gives an in-depth discussion of irrigation distribution models, and concludes that for simplicity the uniform distribution model gives the most satisfactory results regardless of the irrigation method. The popularized term "linear distribution model," referring to the uniform distribution model, would be more correct if "cumulative" was added at the beginning. This is because the cumulative distribution function of a uniform distribution is linear. Walker (99) provides a description of this model which is summarized here using the definition sketch shown in Figure 13.

The uniform distribution model is derived by linear regression on the dimensionless cumulative frequency curve:

$$D = a + b\,A \qquad (5)$$

where: D is the dimensionless infiltration depth obtained by dividing the actual depths by the mean applied depth; A is the dimensionless cumulative irrigated area expressed as a fraction of the total irrigated area; and a and b are coefficients of regression. From Eq. 2, the slope, b, of the cumulative distribution can also be derived by:

$$b = (1 - UCL)/0.25 \qquad (6)$$

where UCL is the field characteristic for the linear coefficient of uniformity.

The equation for the cumulative linear distribution is given by:

$$D = D_{min} + (1 - A)b \qquad (7)$$

where D_{min} is the minimum dimensionless applied depth, and is equal to 1 - 0.5 b. Therefore, Eq. 8 can be expressed as:

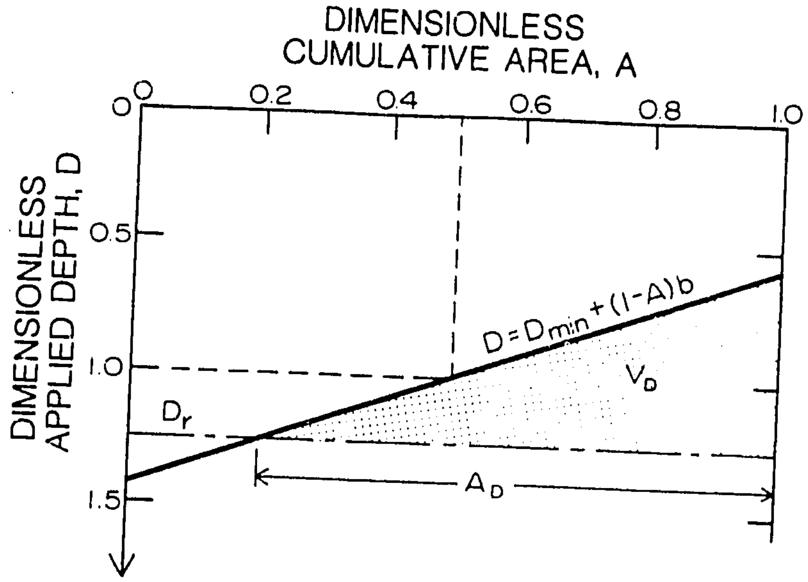

Figure 13. Definition Sketch for the Cumulative Linear Distribution Model.

$$D = 1 - 0.5\ b + (1 - A)b \tag{8}$$

The deficitly irrigated area, A_D, can be expressed as 1 - A at the point of intersection between the dimensionless required depth to fill the root zone, D_r, and line given by Eq. 8. (See Figure 13.) Thus, by substitution:

$$D_r = 1 - b(0.5 - A_D) \tag{9}$$

Realizing that D_r is equal to the dimensional required depth, ∂_r, divided by the mean applied depth, ∂, Eq. 9 can be converted to:

$$\partial = \partial_r/(1 - b(0.5 - A_D)) \tag{10}$$

In this context, the deficitly irrigated area, A_D, becomes a farmer decision variable ranging in value from zero (no tolerated deficit) to 1.0. For example, if the coefficient of uniformity is 75 percent (b = 1.0) and the farmer irrigates the entire field to the depth required, then the average applied depth will be twice the average depth required to fill the root zone. A constant value for A_D is assumed for all farmers in the UCA.

Returning to the queuing simulation, the adjusted irrigation depth required for each field is converted to a volumetric requirement by multiplying by the field's irrigated area. The volumetric water requirement for all fields is then summed to obtain the total water requirement at the UCA turnout.

The position of a field in the service queue is determined on a first-come-first-served basis or ranked according to field priority. A field's priority, P, is calculated daily by the linear function:

$$\begin{aligned} P = {} & W_1 * f(\text{relative access}) + \\ & W_2 * f(\text{relative crop value}) + \\ & W_3 * f(\text{current crop stress}) + \\ & W_4 * f(\text{level of agronomic inputs}) \end{aligned} \tag{11}$$

where W_1 through W_4 are weighing factors entered by the model user. The field variable functions are set such that each ranges between 0 and 1. It is recommended that the weighing factors be assigned values between 0 and 100. A weighing factor value of zero nullifies the variable function it modifies. For example, if the UCA Model is applied to a situation where relative access accounts for all the variance in field water supply, then W_1 might be assigned a value of 100 and the other weighing factors values of zero. A bubble sort is used to rank the fields from high to low priority. A planted field is always given priority over an unplanted field.

If the model is being run in the response mode, the water supply allocated among the fields is equal to the water supply delivered to the UCA turnout for that day. If the model is running in the demand mode, the allocated water supply is set equal to the volumetric demand, subject to the turnout capacity constraint.

If the available water supply is less than the total demand of the queue, the shortage may be shared equally by all the fields in the queue, full supply may be given to those fields first in queue, or some combination of these two rules may be applied.

These allocation rules are illustrated in Figure 14. The total demand is represented by the stack of individual field demands. The field demands are stacked according to priority starting with the highest priority demand on the bottom. The thickness of each demand block represents the volumetric demand of the associated field. The total allocated supply is represented by the area below the "equity line."

The allocation rules are defined by the full supply limit (expressed as a percent of the total available supply) and the slope of the "equity line" (expressed in gradians). If the shortage is to be shared equally by all fields in queue, then the full supply limit is set to zero and the slope of the "equity line is set to 100 gradians. Likewise, if full supply is to be given to the fields first in queue, then the full supply limit is set to 100% and the slope of the "equity line" is set to zero. The modeled implications of the different allocation rules are studied later.

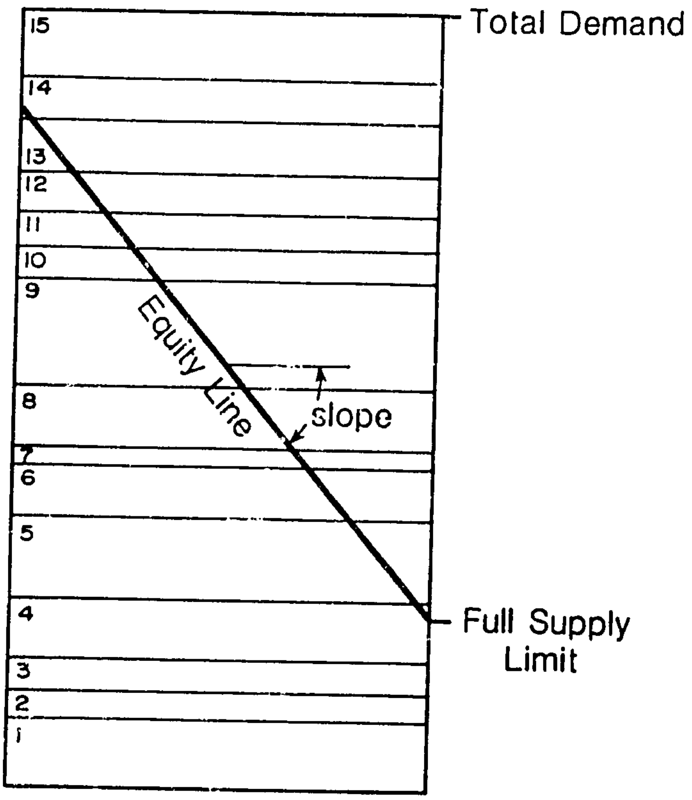

Figure 14. Illustration of the Allocation of Water When the Turnout Supply is Less than the Demand.

Conjunctive use is considered only when the supply allocated to a field is less than its demand, and the field has a tube well or some other water source specified in the input data by a pumping capacity greater than zero. Currently, the UCA Model does not incorporate a hydraulic linkage between the conjunctive use and the water supply for conjunctive use (i.e., ground water pumping and aquifer recharge).

Each daily iteration of the queuing simulation concludes with the calculation of the irrigated area for each field in the service queue, and a call to the on-field submodel for all fields in the UCA.

If the total water supplied (turnout allocation plus conjunctive use) to a field does not meet its demand, the irrigated area of the field is reduced such that the demand for the adjusted field size better matches the supply. If the expressed demand is for land preparation, the planted area of the field is reduced in a like manner.

The planted/irrigated area reduction factor is calculated as a function of the ratio of the field's water supply to its demand as illustrated in Figure 15. The model user enters the degree of deficit, D_D, a farmer will tolerate before reducing the planted/irrigated area. This value is assumed to be a constant for all farmers in the UCA.

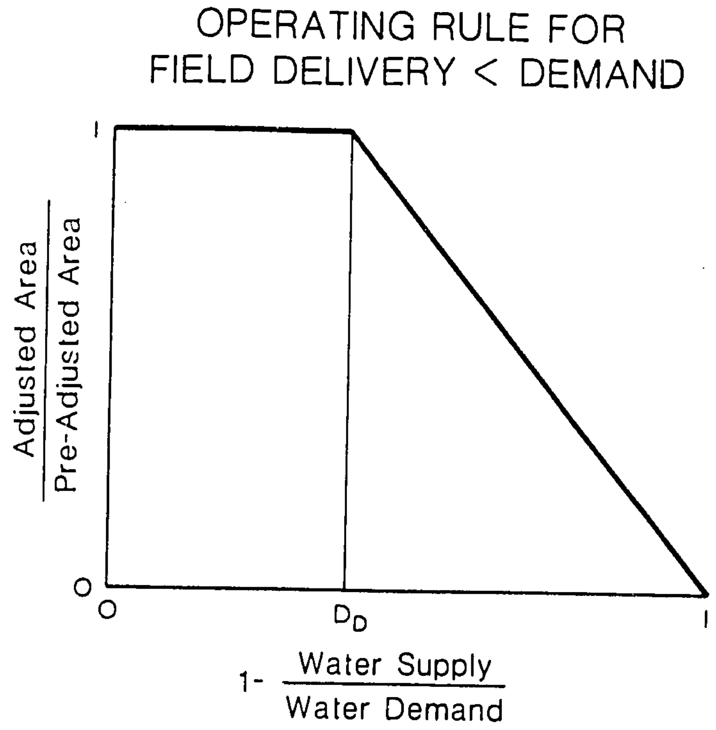

Figure 15. Field Irrigated Area Reduction in Response to a Deficit Supply.

On-Field Water Balance

The on-field crop-soil-water submodel consists of three primary subroutines -- IRRIGATE (for estimating irrigation requirements), WATERBAL (for maintaining the soil water balance and estimating crop water requirements), and YIELD (for predicting crop yield). The basis for the on-field submodel was derived from the crop simulation model, CRPSM, developed at Utah State University from 1979 though 1983 (38, 40).

The flow chart for the on-field submodel is shown in Figure 16. Those processes and inputs which involve socio-economic (nonphysical) interactions are marked with an asterisk.

As explained at the beginning of this section, the on-field soil submodel can be run independent of the rest of the UCA Model for a detailed study of a single field or with the queuing simulation submodel for the analysis of a UCA. In the later case, the on-field submodel is called for each field for each daily iteration of the queuing simulation. When being used for a single field study, the on-field submodel can be called for any period of time.

Irrigation System Model. The initial intent was to model each individual irrigation event. For sprinkle and trickle irrigation this would be a simple task; for surface irrigation it is more complex. The kinematic wave model for surface irrigation (100) was originally considered. However, though this is a simple model, it quickly bogs down the UCA Model with additional input data requirements and computations.

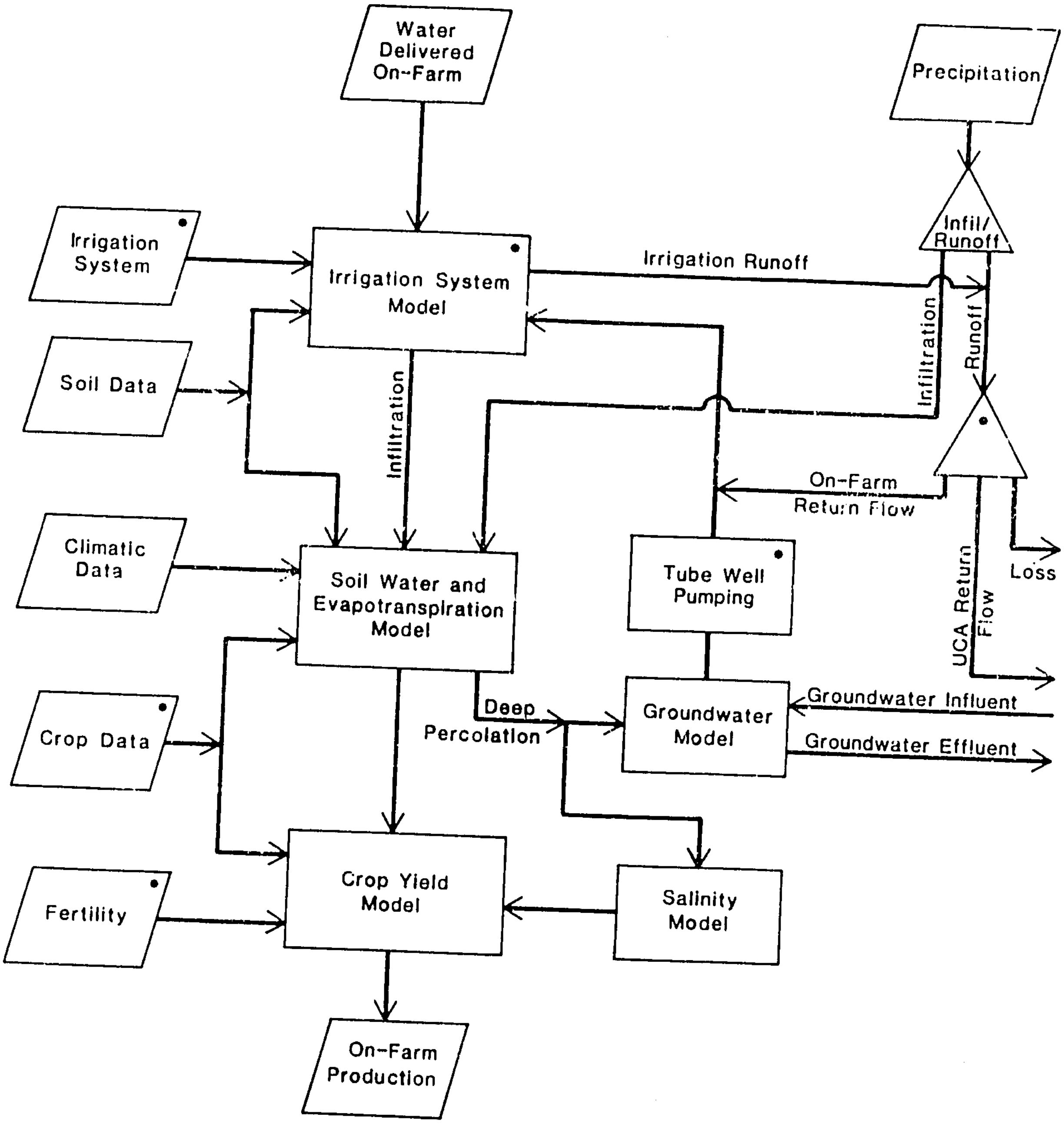

Figure 16. Flow Chart of the On-Farm Submodel. (Those inputs and processes which involve socio-economic interactions are marked with an asterisk.)

For simplicity and efficiency, the cumulative linear distribution model described above was selected. This permits a generic approach requiring only one parameter (the UCL) to describe the on-field application system. The field is treated as a lumped average. The surface runoff and depth of infiltration are calculated as outcomes of a surface water balance.

The average depths of precipitation and irrigation are added to the initial depth of ponded water. The depth of infiltration is calculated as a function of the controlling rate of water movement in the soil and subtracted from the water standing on the soil surface. The maximum depth of standing water on the soil surface is treated as a crop specific variable and stored in the CROP.DAT file. For paddy rice this is the maintained height of the bun spillway; for most other crops it is zero. Runoff is calculated as the depth of standing water in excess of the allowable amount.

<u>Soil Water Balance</u>. The soil water balance routine uses multiple soil layer root zone. Evapotranspiration is split into its evaporation and transpiration components. Evaporation only occurs from the top soil layer while transpiration is extracted from all soil layers comprising the root zone.

Data describing the soil profile are stored in the file SOIL.DAT for each soil type. These data include the soil water content at saturation, field capacity, and wilting point, the infiltration rate, the time it takes the soil to drain from a saturated state to field capacity, the evaporation limit, and the coefficients for the two evaporation equations. Besides these data, the model user must provide the number of soil layers, the depth of the soil profile, and the percolation rate (which is function of the surrounding conditions). These data are entered during field description as described above.

The depth of the root zone is determined by the crop and the soil. A growing root zone is maintained as a function of the crop phenology. The root depth is limited to either the maximum root depth for the crop or the depth of the soil, whichever is shallowest.

The movement of water through the soil is controlled by three different rates. Below field capacity flow is controlled by the infiltration rate. Between field capacity and saturation flow is controlled by the gravity drainage rate (volume between field capacity and saturation divided by time to drain). Above saturation the flow rate is controlled by the percolation rate, which is dependent upon the water table. For example, if the field has a sandy soil, the infiltration rate may be quite high, but if all fields in the area are raising rice, the water table will also be high, resulting in a reduced percolation rate. All rates are assumed to be temporally constant.

The infiltrated water from the surface water balance is added to the soil starting with the top soil layer and moving down. Each soil layer is filled to its saturation limit before moving to the next. Any water in above saturation in the bottom soil layer is treated as deep percolation.

If there is upward movement of water, it is added to the soil profile in the same manner only starting with the bottom soil layer. Water in excess of saturation in the top soil layer results in standing surface water. That is, surface water begins ponding as soon as the top layer is saturated.

The potential evaporation, E_p, of water from the top soil layer is calculated by:

$$E_p = K_e * WAF * E_{tr} \tag{12}$$

where E_{tr} is the reference crop (alfalfa or grass) evapotranspiration; WAF is the fraction of area wetted by the field irrigation system; and K_e is the evaporation coefficient. K_e is estimated:

$$K_e = 1 - K_{ct} \tag{13}$$

where K_{ct} is the crop transpiration coefficient. If K_e is less than 0.08 it is set equal to 0.08.

Two different equations are available for estimating actual evaporation, E, as a function of E_p and time (39). The first is recommended for most irrigation conditions and is given by:

$$E = E_p/(F1_e^{\,(T_w - 1)}) \tag{14}$$

where $F1_e$ is the soil evaporation coefficient for evaporation equation number one and T_w is the time in days since the last irrigation, precipitation event, or incidence of ponded water.

The second evaporation equation is suggested for sprinkle irrigation or frequent rainfall situations and is given by:

$$E = E_p\ (1.0 - (T_w/F2_e)^{\frac{1}{2}}) \tag{15}$$

where $F2_e$ is the soil evaporation coefficient for the second evaporation equation. Equations 14 and 15 give similar net results, but evaporation decelerates more rapidly with Eq. 15.

$F1_e$ and $F2_e$ are stored in the SOIL.DAT file. The model user has only to select the evaporation equation to be used and to enter the wetted area fraction, when describing the soil types at the description level.

Evaporation is extracted for the ponded water and the top soil layer only. The moisture extraction potential of evaporation is greater than that of transpiration; therefore, soil can be dried below wilting point under evaporative conditions. The soil water drying limit is specified in the SOIL.DAT file and is generally half of wilting point. If the estimated actual evaporation is greater than the surface and soil water available for evaporation, the evaporation is adjusted accordingly.

The potential transpiration, T_p, is calculated by:

$$T_p = K_{ct} * E_{tr} \tag{16}$$

The actual transpiration, T, is computed by:

$$T = K_s * T_p \tag{17}$$

where K_s is an indicator of the crop water stress.

Many different relationships have been proposed for estimating K_s. A good discussion is provided by Stewart, et al. (86). While K_s is a complex function of the evaporative demand rate, current soil water content, the soil, and the crop, the simple linear equation suggested by Hill, et al. (38) is used in the UCA Model. Here K_s is equal to 1.0 when the current available soil water fraction in the root zone, ASW, is greater than the limit, K_{cs}, specified by the crop and current crop growth stage. When ASW is less than K_{cs}, K_s is estimated by:

$$K_s = ASW/K_{cs} \tag{18}$$

Actual transpiration is extracted from the soil starting with the top soil layer and working downward. This results in an unrealistic extraction pattern since, in reality, roots would extract water from all soil layers simultaneously. For the UCA Model, however, this is unimportant because the purpose here is to maintain a field water balance rather than to predict the water content of each soil layer.

The daily loop of the soil water balance subroutine, WATERBAL, concludes with the drainage of any soil water remaining in the root zone in excess of the field capacity. The rate of drainage is specified by data in the SOIL.DAT file. Drainage starts with the top soil layer with the effluent being added to the adjacent lower layer, until at the bottom soil layer, the effluent is added to the deep percolation volume.

<u>Crop Response</u>. Many models have been proposed for the estimation of crop yield as a function of the available water supply, environmental stress, fertilizer applications, etc. Most yield models consider the ratio of actual transpiration or evapotranspiration to the potential to be the surrogate variable which best describes the effect of soil moisture on crop yield (10).

"It can be said that anything which affects yields, in any way whatsoever, affects the relationship between water use and yield" (26, p.918). This aside, the potential crop yield is predicted from the ratio of actual to potential transpiration for each growth stage, and multiplied by the level of agronomic inputs to obtain an estimate of the actual yield. A yield reduction factor is then applied to adjust for the uniformity of irrigation. This results in a distributed average yield for the field.

The equation used by Hill, et al. (38) to predict the potential crop yield, Yp, is the same as that employed in the UCA Model:

$$Yp = (T/Tp)_1^{\,lambda_1} * (T/Tp)_2^{\,lambda_2} * (T/Tp)_i^{\,lambda_i} * \ldots (T/Tp)_n^{\,lambda_n} \qquad (19)$$

where $(T/Tp)_i$ represents the ratio of the sums of actual and potential transpiration for growth stage i; $lambda_i$ is the associated power weighing factor; and n is the number of growth stages. The lambdas are crop and growth stage specific and are stored accordingly in CROP.DAT.

The interactions between agronomic inputs (i.e., fertilizer, pesticides, etc.) and the potential yield due to the water supply can be complex. Rather than attempting to model these various complexities, the relative actual yield is simply calculated as the product of the relative level of agronomic inputs and the relative potential yield, Yp. Since the level of agronomic inputs is a catch-all field characteristic, incorporating such aspects as farmer finesse, this approach accounts for some of the nonphysical aspects affecting crop yield. However, estimation of the net economic return is complicated by this lumped parameter approach because the costs cannot be dissociated.

The field water balance and resulting actual and potential transpiration are computed using the average depth of irrigation. In reality some portions of the field receive greater than the average depth while others obtain less. As a result, the relative actual yield predicted above, based on averages, is greater than the distributed yield since some of the field is over irrigated and some under irrigated.

To account for the resulting yield reduction, a factor is applied which is a function of the irrigation uniformity and the application efficiency. This yield reduction factor approaches 1.0 as the average applied depth approaches the net required. In other words, the more efficient the irrigation, the more severe the yield reduction. This is illustrated by Figure 17 and 18.

Hart and Reynolds (36) assumed a normal distribution model to study the effects of sprinkler uniformity on crop yield. Hill and Keller (41) used irrigation distribution uniformity to optimize system design. Here the cumulative linear distribution model described above is used to estimate the impact of irrigation uniformity and efficiency on the field average crop yield.

Since the yield model does not account for over irrigation, the yield reduction factor is only calculated for the under irrigated portion of the field. It is assumed that if a farmer reduces the irrigated area (and thus, the harvested area) of his field, he will cut that portion of the field that tends to be under irrigated. Therefore, the field area to apply the yield reduction factor to, ADH, is given by:

$$A_{DH} = (A_H - (1 - A_D)A_P)/A_H \qquad (20)$$

where A_H is the harvested fraction of the field; A_D is the deficiently irrigated fraction of the field as defined in Figure 13; and A_P is the planted fraction of the field. The derivation of Eq. 20 is graphically illustrated in Figure 19.

The yield reduction, Y_R', for A_{DH} is assumed to be directly proportional to the average dimensionless applied depth for the deficiently irrigated area, A_D; thus:

$$Y_R' = 1 - V_D/A_D \qquad (21)$$

where V_D is the deficit irrigated volume shown as the cross-hatched area in Figure 13.

From the equations derived earlier:

$$V_D/A_D = 0.25\ b - 0.5\ (1 - (\text{net demand/gross supply})) \qquad (22)$$

The yield reduction factor, YR, is computed as a multiplier to the estimated average relative yield for the entire harvested area:

$$Y_R = (1 - A_{DH}) + A_{DH} * Y_R' \qquad (23)$$

$$= 1 - A_{DH}\ (0.25b - 0.5\ (1 - (\text{net demand/gross supply})) \qquad (24)$$

Therefore, estimated relative yield, Y, for a field is:

$$Y = Y_R * Y_P * \text{level of agronomic inputs} \qquad (25)$$

The yield estimate, Y, can be converted from relative units to actual units (i.e., metric tons/hectare) simply by multiplying by the maximum crop yield potential.

The effects of salinity and water logging on crop yield are not presently incorporated in the UCA Model.

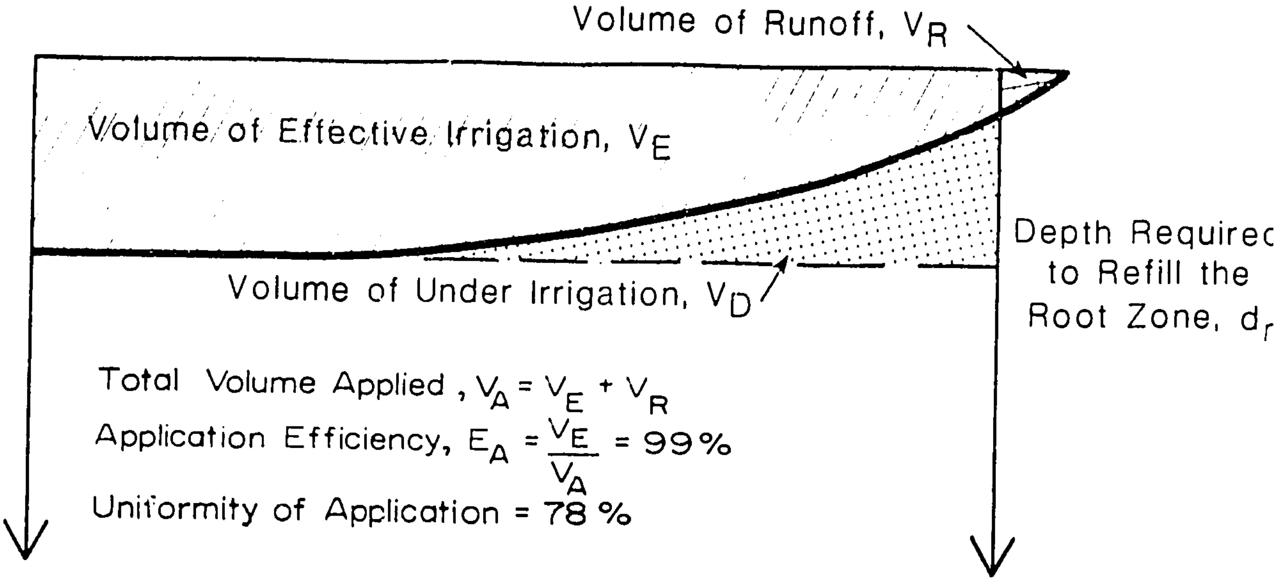

Figure 17. Graphic Example of Application Efficiency Under Deficit Irrigation.

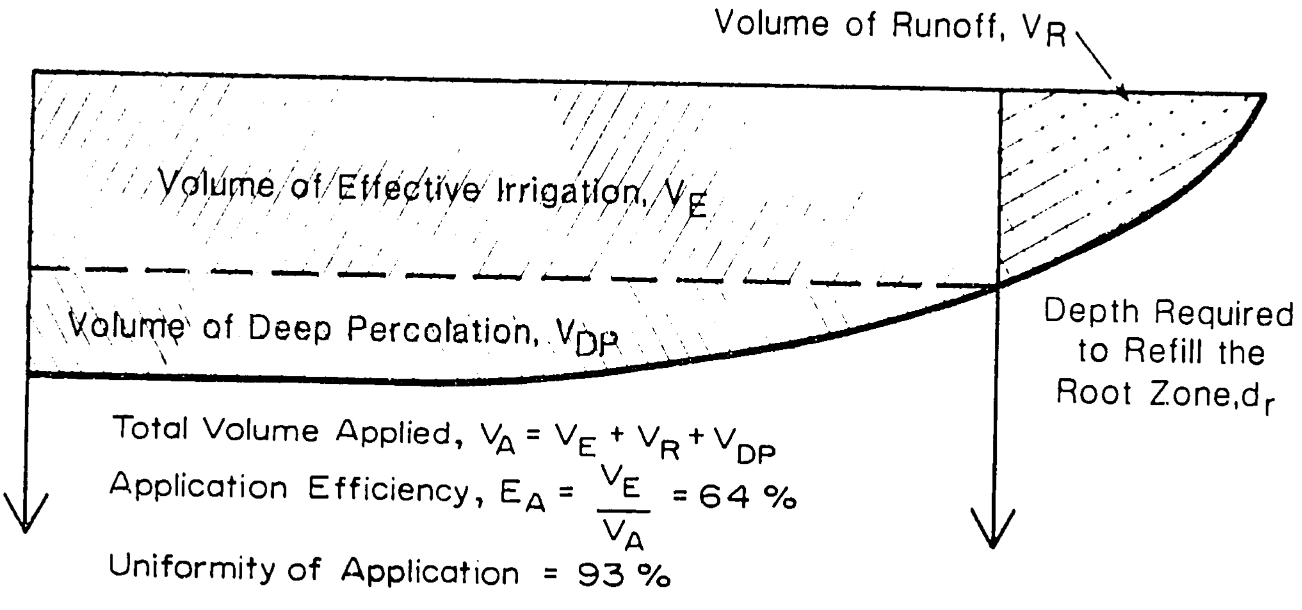

Figure 18. Graphic Example of Application Efficiency Under Full Irrigation.

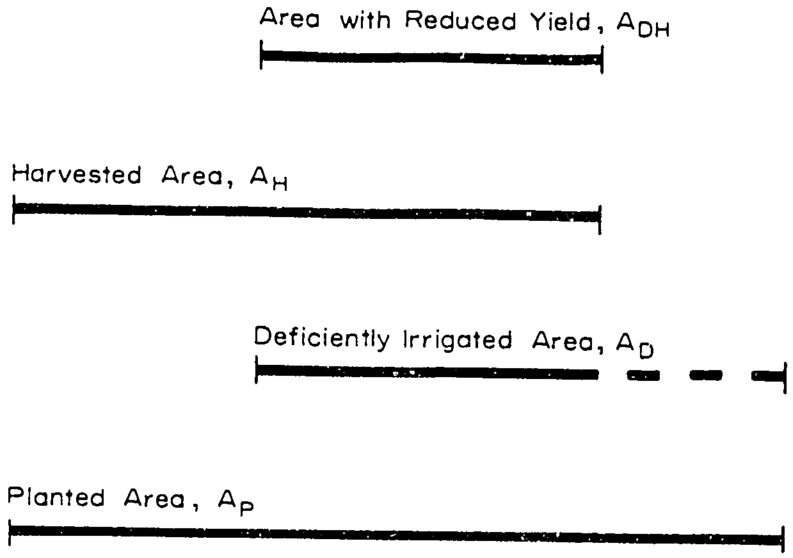

Figure 19. Graphical Derivation of A_{DH}.

UCA Model Outputs

Single Field Study. The UCA Model outputs for a single field study include, by model user selection:

1. Site and soils description;
2. Tabular listing by month of the daily weather and ET data;
3. Tabular listing by month of the daily cumulative phenology clock values;
4. Tabular listing by month of the daily soil water balance figures for each crop/irrigation schedule investigated;
5. Predicted crop phenology;
6. Summary of water use by growth stage and cropping season for each crop/irrigation schedule studied;
7. Yield prediction; and
8. Summary tabulation of all irrigations.

Unit Command Area Study. The UCA Model outputs for a multiple field study include:

1. Optional tabular listing by month of the daily weather and ET data;
2. Optional soils description;

3. Optional listing of the predicted crop phenology for the earliest and latest planting dates of each crop;
4. Description of the unit command area;
5. Optional supply and demand hydrographs;
6. Total UCA water use by season including conjunctive use (total pumping hours and volume) and efficiency estimates;
7. Irrigation application efficiency (gross supply/net demand) by crop and season;
8. Optional statistical analysis of all UCA field characteristics including cross correlation; and
9. Planned, planted and harvested areas; mean planting date; and yield estimates for each crop.

Example model output for single and multiple field analyses are given in the Appendices.

An important assumption of the UCA Model is that the behavior of a UCA can be studied from the statistically aggregated response of its individual fields. As explained throughout the above description of the model, the aggregation is predicted in terms of the average. The model user must bear this in mind, as the average may be very different from the median. This is because most of the modeled results do not necessarily follow a normal distribution. This is particularly true for crop production where the median is often less than the average (i.e., the yield from 50 percent of the harvested area may be less than 3.5 tons/hectare while the average yield is 4.0 tons/hectare).

General Program Notes

The UCA Model consists of two programs: UCAFILE for creating and editing all data files and for generating the UCA fields, and UCARUN for the unit command area simulation. Both programs are coded in ANSI Fortran 77.

In order to minimize computer memory requirements, 2-byte integer arrays were used for storage of all field characteristics and other large arrays. This results in a slight round-off error and limits the accuracy of field area calculations to one-tenth hectare, but these limitations are considered insignificant.

The total computer memory required to run the UCA Model configured for 500 fields, 5 blocks, 3 soil types (each with 2 soil layers), 10 cropping schedules, and 2 cropping seasons is 256K-bytes. Thus, the model can be implemented in most micro-computer environments.

Model Usage

Some notes on the UCA Model usage follow. Most of these have already been alluded to, but may have been lost in the text:

1. The model can be used for a detailed study of a single field or to study the interaction of multiple fields. It is recommended that the single field study be used before any multiple field analysis in order to calibrate the model. Most adjustments will be to data stored in the CROP.DAT and SOIL.DAT files.

2. The UCA Model has two modes of operation: a demand mode for system planning, operation, and design and a response mode for system operation, maintenance, and evaluation.

3. The process of interfacing the UCA Model with the main system is illustrated in Figure 20. First, the UCA Model, operating in the demand mode, expresses a demand hydrograph on the main system. The main system models then respond with a supply hydrograph. If the supply and demand hydrographs are different, the UCA Model updates by running in the response mode. The process repeats starting with the expression of a new demand hydrograph by operating the UCA Model in the demand mode.

   The UCA Model uses a daily time step; therefore, the supply and demand hydrographs are expressed in terms of the average flow rate for each day.

4. Since the UCA model does not include any channel hydraulics the size of the modeled UCAs is limited to areas within 1-day time lags for water delivery (from the UCA turnout to the furthest field in the unit command are).

5. The model assumes a single UCA water supply point (except for points of conjunctive use); therefore, in UCAs with multiple supply points (i.e., checks on the main canal) the supply points must be lumped into one, or the area served below each point must be treated as a separate UCA.

6. The UCA model cannot explicitly simulate the reuse of water (return flows) within the UCA. If reuse within the UCA is significant, the conveyance efficiency, management efficiency, and application uniformity can be adjusted upward. This will artificially represent the reuse condition, as more water will be available for allocation because of the higher use efficiencies.

7. The model can be used for study periods as short as one day or as long as a year, beginning with any day of the year. A modeled year does not have to start on January 1 and end on December 31. To best fit the agro-climatic conditions of India, for example, the modeled year might begin on June 1 and end on May 31.

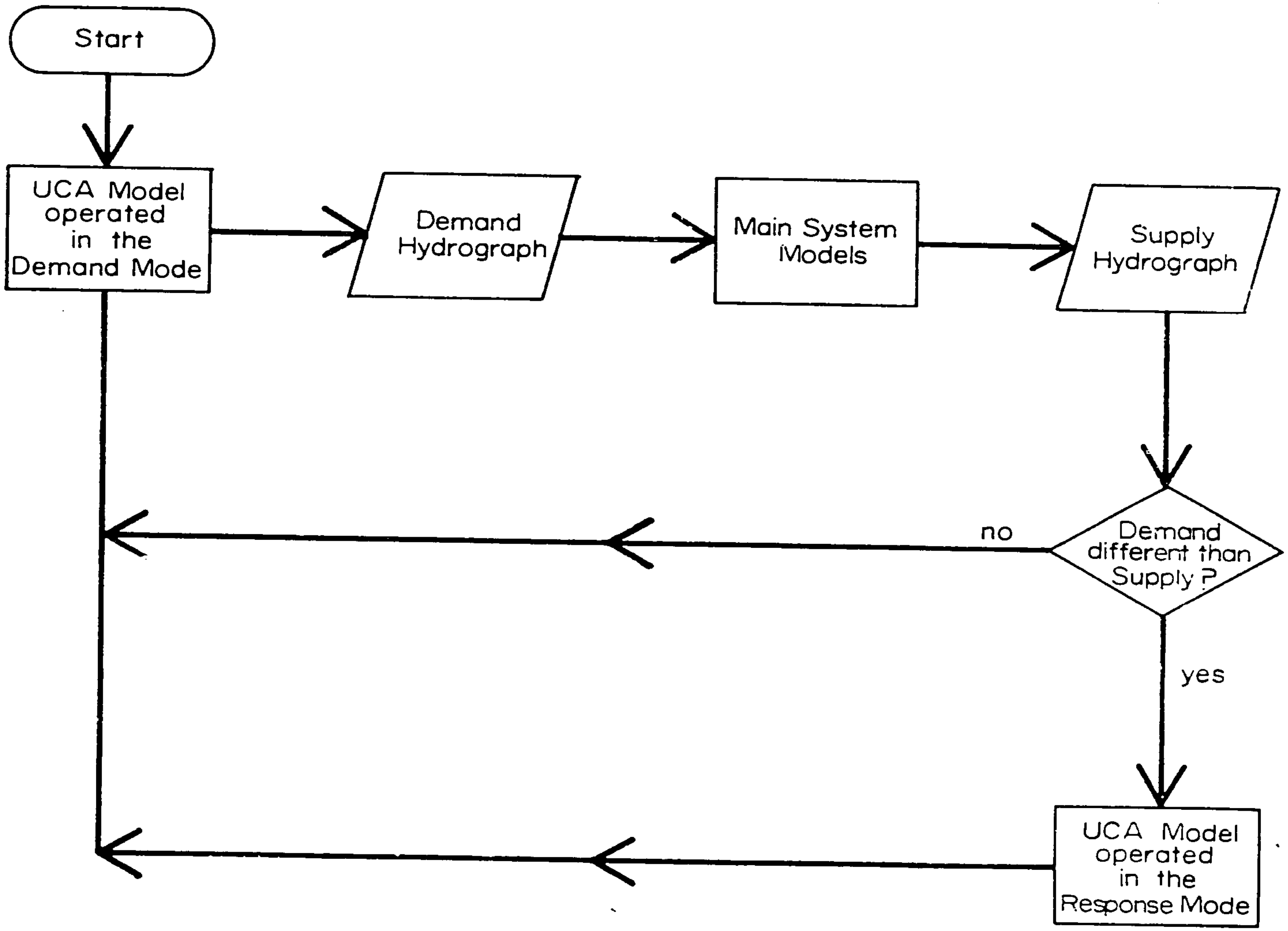

Figure 20. Interfacing of the UCA Model with the Main System Models.

SYNTHABAD CASE STUDY

In this section, application of the UCA Model is demonstrated using a hypothetical case, Synthabad. The pertinent details of Synthabad are described according to the UCA Model data requirements examined previously. The results from both single and multiple field analyses are then presented and discussed.

Overview of Synthabad

Synthabad was designed by Peterson (70) as an aid for developing and demonstrating the WMS II irrigation system models. "Synthabad is a hypothetical project, synthesized to simulate a medium-sized project in west central Maharashtra, planned and designed using methods in force circa 1970-80" (70, p.1). This simulated irrigation project is based largely on Peterson's extensive Indian experience, with secondary and limited primary data used as supplementary resources.

Besides the information provided by Peterson (70), several other sources were used to synthesize the data required to run the UCA Model (15, 51, 68, 69, 70, 73, 81, 82, 94). Keller, et al. (51) review USAID's irrigation sector strategy for India. Their report includes an interesting and useful analysis of the groundwater development potential in India. Patil, et al. (68, 69) provide detailed descriptions of the socio-economic conditions in the Girna Irrigation Project and Ghod Command Area in Maharashtra, India. Singh, et al. (81) evaluate a large distribution system in India (the Ganga Canal) and suggest potential improvements. Singh (82) discusses ways in which irrigation projects can be improved in India; most of which can be extrapolated to the world at large. Tyagi and Narayana (94) analyze constraints to farm level water management using data from 30 randomly selected farms in Haryana, India.

Detail Description of Synthabad

Synthabad is a scarcity zone (500-750 mm annual precipitation) project near Pune, Maharashtra. The project has a gross command area of 5,750 ha with a cultivatable command area (CCA) of 5,000 ha. There are 145 UCAs, each with an average cultivatable area of 34.5 ha.

The planned irrigation intensity is 88 percent of the cultivatable command area -- 36 percent in kharif (growing season during the summer monsoon, June-October) plus 52 percent in rabi (winter growing season, October-February). Thus, the irrigated command area is 0.88 * 5,000 = 4,400 ha.

The enlarged unit command area presented in Figure 2 is used as a template for the UCAs comprising Synthabad. The following details are organized according to the outline of the UCA Model data requirements presented as Table 3.

Since some of the field characteristics are dependent on the farmers, the UCA is divided into farms. In Maharashtra, farms average in size between 1.4 and 2.8 ha with 82.5 percent of the farms below 4.0 ha (70). Based on this same land distribution, Figure 21 shows the 34.5-hectare example UCA partitioned into 12 farms.

Queuing System Description

Priority Weighting Factors. For the sample runs, field priority is determined solely from the relative access to the water supply at the UCA turnout (highority-priority). No adjustment is made for crop value, degree of crop stress, or farmer finesse. Therefore, W_1 in Eq. 11 equals 100 and W_2 through W_4 are set to zero. In the next section the implications of different weighting factors are investigated.

Water Allocation Rules. Recall that when the water supply at the UCA turnout is short, full supply may be given to those fields first in queue, the available supply may be shared equitably, or a combination of these two alternatives may be imposed. Here, full supply is given to those fields first in queue.

Turnout Capacity. The design distribution capacity was 0.7 lps per cultivatable hectare with a resulting present average turnout capacity of 0.63 lps/ha. If the entire CCA was irrigated according to the planned schedule of 10 cm on a 14-day rotation, 0.83 lps/ha would be required. Assuming a conveyance efficiency of 80 percent internal to the UCAs, the maximum potential cropping intensity for a single season is (0.63 * 80)/0.83 or 61 percent of the cultivatable command area. The planned irrigation intensities of 36 percent in kharif and 52 percent in rabi are, therefore, well below the potential delivery capacity of the conveyance system.

Water is rotated among the turnouts on a minor canal such that the typical turnout is on for seven days and off for seven days. Therefore, the average turnout capacity is twice the 0.63 lps/ha water duty or 1.26 lps/ha. The turnout capacity for the 34.5-hectare, example UCA is 43.5 lps.

Water Supply Period. The canal system is operated from the beginning of kharif (June 1) through the end of rabi (February 28). The total annual available water supply for Synthabad, at a 50 percent probability of occurrence, is 30.78 million m^3. This is equivalent to a gross depth of 0.62 m per cultivatable hectare or 0.70 m per planned irrigated hectare. Since Synthabad includes a 20.7 million m^3 reservoir, the available water supply can be allocated in any reasonable manner throughout the period from June 1 through February 28.

Operating Hours. Capacity limitations require that the system operate 24 hours per day.

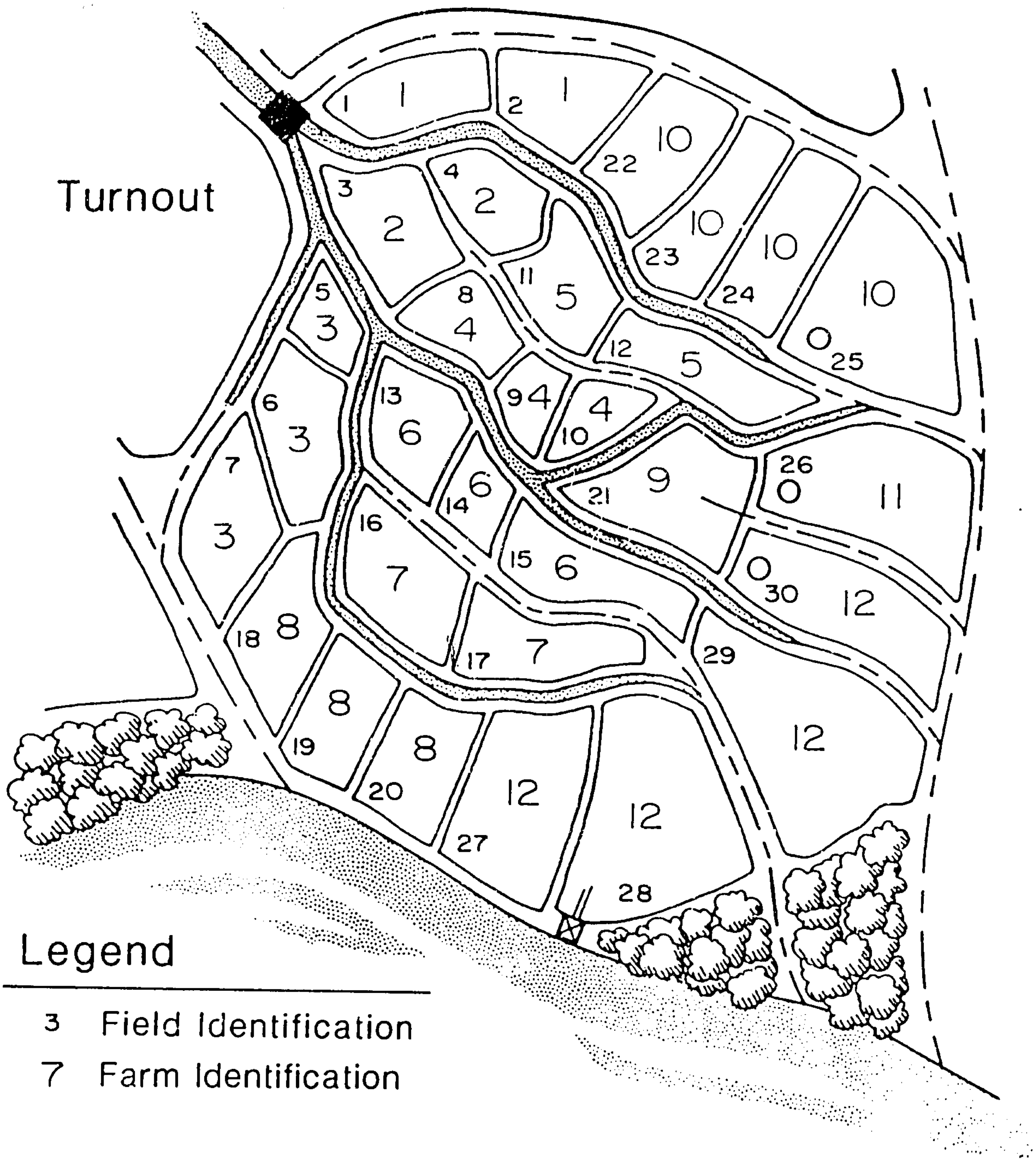

Figure 21. Example UCA with Farm Layout and Farm and Field Reference Numbers.

Water Stealing. Twenty percent of the fields in the UCA take water out of turn.

Management Efficiency. Since irrigation is on a fixed depth (10 cm) rotation, the irrigation management efficiency of farmers is 100 percent. (This variable is generally used only for flexible irrigation schedules to account for the difference between crop demands and farmer demands.)

Field Fraction Irrigated to Full Supply. This variable is used to adjust the field demand to account for the lack of uniformity in irrigation application. Since the gross depth of irrigation is fixed by the rotation schedule, the fraction of a field receiving full irrigation is set at 50 percent. This has the effect of nullifying the adjustment made for uniformity.

Irrigated Area Reduction Factor. The maximum degree of deficit irrigation, D_D, a Synthabad farmer will tolerate before reducing the irrigated area of his field is 25 percent. If the water supply at the field level is less than 75 percent of the demand, the irrigated area of the field is cut back in a linear fashion (see Figure 15) such that the irrigated portion receives 75 percent of the full irrigation requirement. If the supply is greater than 75 percent of the demand, there is no reduction in the irrigated area of the field.

Irrigation Schedule. The typical Indian irrigation schedule, and the one implemented in Synthabad, calls for a 10-centimeter gross depth of application on a 14-day rotation. The usual flow rate is 28 lps/ha which results in a 10-hour turn for a one hectare field.

Field Characteristics

The assigned values for the characteristics of all fields in the example Synthabad UCA are presented in Table 8.

Relative Access. The relative access of each field to the UCA turnout was computed using Eq. 1. The resulting field accesses are shown in Figure 9. Recall that the lower the access score the better the access to the water supply at the turnout.

Sixty percent of the access score was attributed to relative distance, 10 percent to the number of bifurcations, 10 percent to the number of channels serving the field, and 20 percent to the relative political status of the farmer/operator of the field. Political status was estimated as being directly proportional to the farm size.

Field Size. Field sizes were determined by planimetry and adjusted so that the total area of the UCA was equal to the 34.5-hectare average defined for Synthabad. The resulting average field size was 1.15 ha with a standard deviation of 0.58 ha. Field areas are given in Figure 22.

Table 8. Field Characteristics for Synthabad Example UCA.

Field #	Farm #	Area (ha)	Relative Access	Well Q (L/s)	Soil[1] Type	UCL (%)	Conv. Eff (%)	Crop[2] Type	Plant Lag (day)	Rel Input (%)
1	1	0.86	28	0.0	1	80	99	6	7	59
2	1	1.02	42	0.0	1	74	90	1	8	51
3	2	1.09	25	0.0	1	78	98	1	9	58
4	2	0.79	37	0.0	1	82	93	6	6	60
5	3	0.43	29	0.0	2	81	94	9	4	53
6	3	1.05	37	0.0	2	77	89	6	10	65
7	3	1.12	48	0.0	2	74	85	1	11	72
8	4	0.68	53	0.0	1	88	89	4	5	61
9	4	0.42	63	0.0	1	83	82	9	3	58
10	4	0.42	69	0.0	1	76	78	10	3	53
11	5	0.89	50	0.0	1	74	85	6	7	61
12	5	0.96	55	0.0	1	64	78	1	8	53
13	6	0.81	43	0.0	2	84	88	6	8	54
14	6	0.47	57	0.0	2	89	82	5	5	73
15	6	1.00	65	0.0	2	68	78	1	10	63
16	7	1.14	58	0.0	2	73	82	6	11	57
17	7	0.92	78	0.0	2	72	69	1	9	55
18	8	1.04	59	0.0	2	72	79	6	10	66
19	8	0.87	66	0.0	2	77	75	8	8	63
20	8	0.89	72	0.0	2	72	70	3	9	72
21	9	1.35	71	0.0	1	87	77	3	11	57
22	10	1.17	40	0.0	1	89	85	1	9	53
23	10	1.08	47	0.0	1	66	81	8	9	57
24	10	1.17	55	0.0	1	69	75	10	9	59
25	10	2.31	56	1.2	1	79	71	6	18	70
26	11	2.01	87	1.2	1	80	65	6	16	53
27	12	1.72	73	0.0	2	90	66	2	8	58
28	12	2.65	81	2.7	2	86	61	7	13	52
29	12	2.66	74	0.0	2	69	67	10	13	59
30	12	1.50	74	1.2	1	65	67	9	6	58
Average		1.15	56.4	0.20	--	77.3	80.0	--	8.8	59.4
Stand. Dev.		0.58	16.2	0.57	--	7.5	10.0	--	3.3	6.1
Maximum		2.66	87.5	2.65	--	90.0	99.4	--	18.0	73.0
Minimum		0.42	24.8	0.00	--	64.0	60.9	--	3.0	51.0
Median		1.03	60.8	0.00	--	77.0	79.8	--	9.0	58.0
Bins		Relative Distribution (number of fields per bin)								
0.20		9	5	26	--	6	5	--	7	9
0.40		14	5	0	--	7	5	--	13	10
0.60		3	8	3	--	5	9	--	6	5
0.80		1	9	0	--	6	7	--	2	2
1.00		3	3	1	--	6	4	--	2	4

[1] Soil type 1 = Clay Loam; Soil Type 2 = Black Cotton

[2] Refer to Table 10 for definition of cropping schedules.

Soil Type. Synthabad has clay loam soil in the upper half of the project and black cotton soil in the lower half. Typically a UCA would be all one soil type or the other. Since the example UCA is meant to represent the average conditions present in Synthabad, Figure 22 shows it partitioned with black cotton soils along the river and clay loam soils above.

Initial Soil Water Content. A uniform distribution was used to randomly generate initial soil water contents between 60 percent and 70 percent available capacity.

Cropping Pattern. The potential irrigated crops for Synthabad, together with their normal growing seasons and expected net return (in 1981 rupees), are presented in Table 9. The planned and actual cropping schedules are given in Table 10. Fields that are farmed during the rabi season are kept fallow during kharif to build up the soil water content.

Figure 23 shows cropping schedules assigned to the fields which balance the in season labor requirement and provide diversity for the farmer. Since farmers with small land holdings farm more intensively than those with large holdings, the fallow fields are generally associated with the larger farms. Those fields with conjunctive use potential are planted in both seasons.

The actual irrigated area in kharif is about 25 percent of the planned area while that in rabi is almost 95 percent (see Table 10 and Figure 23). Farmers push the planted area in the rabi season as far as possible, often resulting in rabi irrigated areas greater (120 percent) than planned. The reasons irrigated areas in kharif fall below expectations are not known (70). One possible explanation may be the lack of reliability in the water supply. System operators may place a high priority on insuring a full reservoir for the rabi season and, thus, fall negligent in meeting the kharif irrigation requirements.

Planting Lag. The planting lag is primarily a function of the crop type, the soil, the method of land preparation (animal power, small tractors, etc.), and the size of the field. The crop influence is handled as a crop specific variable in CROP.DAT; therefore, only the soil, field size, and method of land preparation need to be considered when determining the planting lag characteristic.

In this example, only farmer number 12 has a small tractor, the others all rely on animal power. The mean planting lag was estimated to be four days per hectare for fields tilled by small tractor and eight days for those plowed by bullock. In addition, the black cotton soil was considered to take 20 percent longer to work than the clay loam soil.

Irrigation Uniformity Coefficient. Given the average application efficiency, E_a, for a fully irrigated field, the linear coefficient of uniformity, UCL, can be estimated by:

$$UCL = 0.5 + 0.5 E_a \tag{26}$$

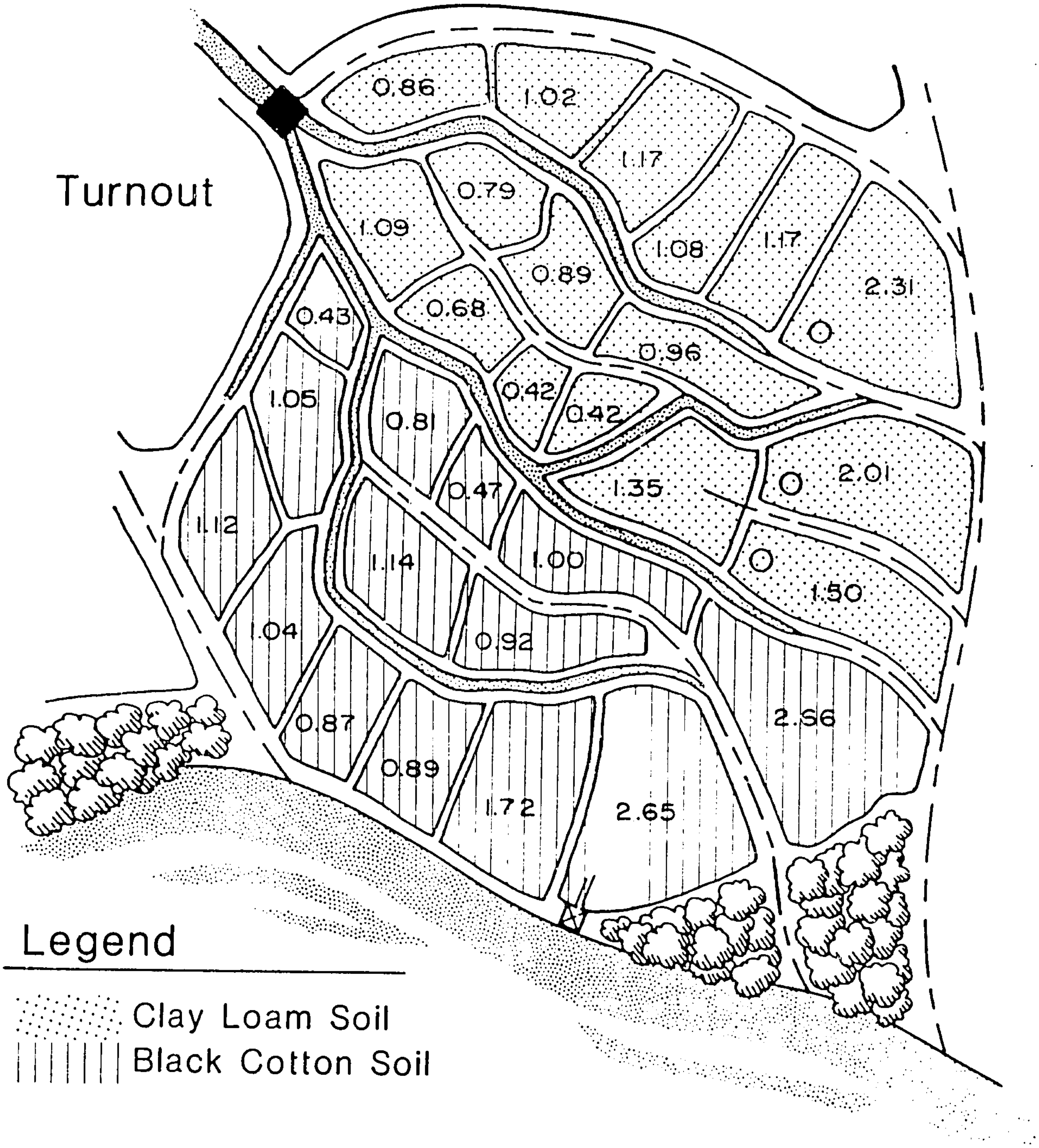

Figure 22. Field Size and Soil Type Distribution.

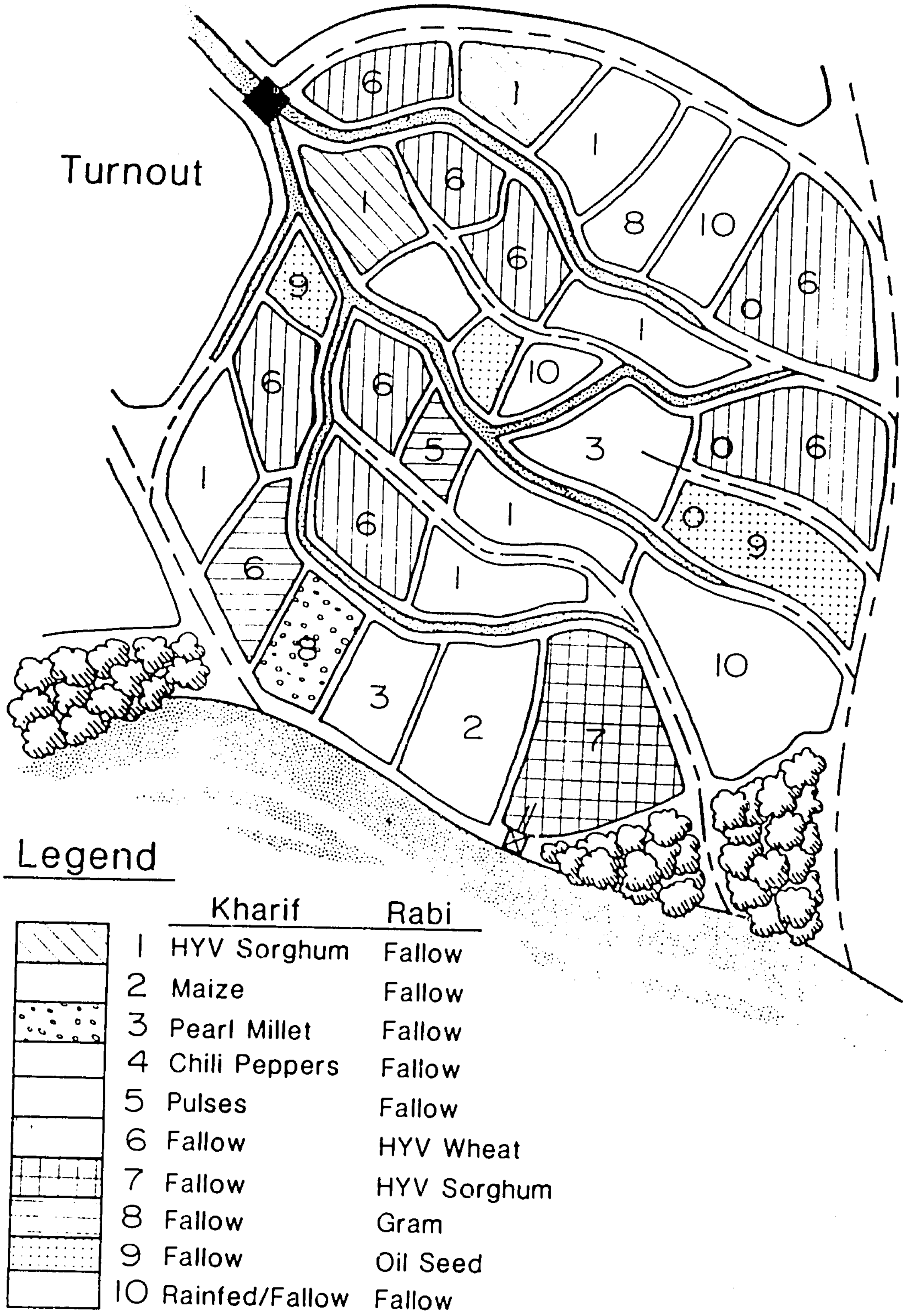

Figure 23. Planned (Numbered) and Actual (Patterned) Cropping Schedule Distribution.

Table 9. Potential Crops for Synthabad Showing Growing Period and Net Returns.

Season and Crop	Typical Growing Period	Net Return	
		Irrigated (R/ha)	Rainfed (R/ha)
<u>Kharif</u>			
HYV Sorghum	6/15-10/20	3596	617
Maize	6/15-10/20	3855	1052
Pearl Millet	6/15- 9/30	1933	317
Chili Peppers	6/01-10/31		
Vegetables	6/15-10/20	9302	
Pulses	6/15- 9/20	741	448
Groundnuts	6/15-10/25	2684	1289
Cotton	5/15-11/25	6954	594
<u>Rabi</u>			
HYV Wheat	11/01-2/28	2519	224
HYV Sorghum	10/15-3/20	3260	
Maize	10/05-3/10	3855	
Gram[1]	11/01-2/05	2006	
Oil Seed[2]	11/01-3/05		
Onions	9/15-2/05		
Vegetables	10/15-3/25	8392	
<u>Hot Weather and Year-Round Crops</u>[3]			
Groundnut	2/15-6/25	3894	
Vegetables	2/15-6/25	8392	
Fodder	2/01-6/30	3015	
Sugarcane	Year-round	11239	
Bananas	Year-round		
Grapes	Year-round		
Mango	Year-round		

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[1] Gram -- Mung beans, chick peas

[2] Oil Seeds -- Sunflower, safflower, mustard

[3] Hot weather (February - June) and year-round crops can only be grown where a conjunctive water supply is available.

Indian terms: Jowar=wheat, Bajra=corn, Ragi=sorghum

Table 10. Planned and Actual Cropping Schedule for Synthabad.

Schedule Number	Kharif Crop	Rabi Crop	Planned Area		Actual Area	
			(ha)	(%)[1]	(ha)	(%)
1	HYV Sorghum	Fallow	7.28	21.1	2.11	6.1
2	Maize	Fallow	1.72	5.0	0.68	2.0
3	Pearl Millet	Fallow	2.24	6.5	0.87	2.5
4	Chili Peppers	Fallow	0.68	2.0	0.00	0.0
5	Pulses	Fallow	0.47	1.4	0.00	0.0
6	Fallow	HYV Wheat	10.90	31.6	9.86	28.6
7	Fallow	HYV Sorghum	2.65	7.7	2.65	7.7
8	Fallow	Gram	1.95	5.7	1.51	4.4
9	Fallow	Oil Seed	2.35	6.8	2.35	6.8
10	Rainfed/ Fallow	Fallow	4.25	12.3	14.46	41.9

---

[1] Based on 34.48 ha of cultivatable command area for the example UCA.

Singh, et al. (81) found typical application efficiencies of 55 percent for fully irrigated fields. Thus, from Eq. 26, the average UCL for Synthabad is estimated at 77.5 percent.

Udeh and Busch (96) found that the probability distribution for irrigation uniformity followed a normal distribution. The UCL values in Table 8 were, therefore, generated assuming a normal distribution with a mean of 77.5 percent and a standard deviation of 7.5 percent.

Conveyance Efficiency. The average conveyance efficiency from the UCA turnout to each field is estimated to be 80 percent (81). The conveyance efficiencies, EC, presented in Table 8 were derived by:

$$EC = 100 - 20\ L/\bar{L} \qquad (27)$$

where L is the channel distance from a given field to the UCA turnout and $\bar{L}$ is the mean channel distance for all the fields.

Conjunctive Use Capacity. Because of uncertainties in canal deliveries, farmers with the resources to do so are supplementing with groundwater and water pumped from the river (farmer number 12). Typical densities range from 1 to 4 wells per 10 ha (94). For the dug wells common to Maharashtra, capacities range between 0.6 and 1.2 lps. Since the wells in the example UCA are close to the river, they all have capacities of 1.2 lps. The river pump for field number 28 has a capacity of 1.0 lps/ha for a total of 2.7 lps.

Level of Agronomic Inputs. Average yields in Maharashtra, based on data for the Girna (68) and Ghod (69) command areas, are about a third of the "good" commercial yield estimates given by Doorenbos and Kassam (22). It is presupposed here that half of the yield deficit can be attributed to unreliability of the water supply, and half to lack of farmer finesse and adequate levels of agronomic inputs.

The relative level of agronomic inputs (and degree of farmer finesse) was, therefore, assumed to range between 50 percent and 80 percent with an average value of 67 percent. In order to skew the production estimate, so that the median production is less than the average, the level of agronomic inputs was generated using a beta distribution with alpha of 2.0 and beta of 4.0.

Climatic Data

Because of the paucity of data, the option to simulate daily weather from monthly means and standard deviations was selected. This also permits the study of varying weather conditions without keying in different data.

The monthly climatic data for Synthabad are presented in Table 11. The monthly distribution of rainfall is shown in Figure 24. These data were derived from those published by Hargreaves (35) for Pune, India. The number of rainy days are based on monthly correlations using data for Parole Centre, India (68). The maximum and minimum fraction of extra-terrestrial solar radiation reaching the earth's surface at Synthabad were obtained from Doorenbos and Pruitt (23).

Supply Hydrograph

For the Synthabad case study the UCA Model is run in the response mode; therefore, a supply hydrograph must be provided. Water at the UCA turnout is on 7 days, followed by 7 days off, starting June 1 and running through February 28. Rather than supplying a constant flow rate during each on period, the flow is set equal to the demand, subject to the turnout capacity.

Soil Characteristics

The data describing the characteristics of clay loam and black cotton soils are presented in Table 12. These data are stored in the file SOIL.DAT.

Crop Specific Data

All crop specific data is stored in the CROP.DAT file. These data are site specific and must be calibrated against actual field observations. As a first cut, most of the required data can be obtained from Doorenbos and Kassam (22) and Doorenbos and Pruitt (23). The procedure is illustrated here for sorghum.

Table 11. Monthly Climatic Data for Synthabad. (Based on data for Pune, India)

	Evapotranspiration		Temperature		Rainy Days		Precipitation	
	Mean (mm/day)	Std	Mean (C)	Std (C)	Mean	Std	Mean (mm)	Std (mm)
Jan	5.3	1.06	21.3	2.1	0	1.1	2.0	16.5
Feb	6.4	1.28	23.1	2.3	0	0.3	0.0	2.5
Mar	7.4	1.48	26.5	2.7	0	1.2	3.0	17.5
Apr	8.4	1.68	29.3	2.9	1	1.6	17.8	24.0
May	8.6	1.72	29.9	3.0	2	4.8	35.1	73.5
Jun	6.6	1.32	27.5	2.8	7	2.8	103.1	42.0
Jul	4.1	0.82	24.9	2.5	12	6.9	186.9	105.0
Aug	4.6	0.92	24.6	2.5	7	5.6	105.9	85.5
Sep	5.6	1.12	25.0	2.5	8	6.0	127.0	91.5
Oct	6.1	1.22	25.5	2.6	6	5.4	91.9	82.5
Nov	5.6	1.12	22.9	2.3	3	5.7	37.1	86.0
Dec	5.1	1.02	21.1	2.1	0	2.2	5.1	33.0
Mean	6.2	1.23	25.1	2.5	3.8	3.6	59.6	55.0
Total					46	43.6	714.9	659.5

Maximum (and minimum) fraction of extra-terrestrial radiation reaching the earth's surface is 0.80 (and 0.31).

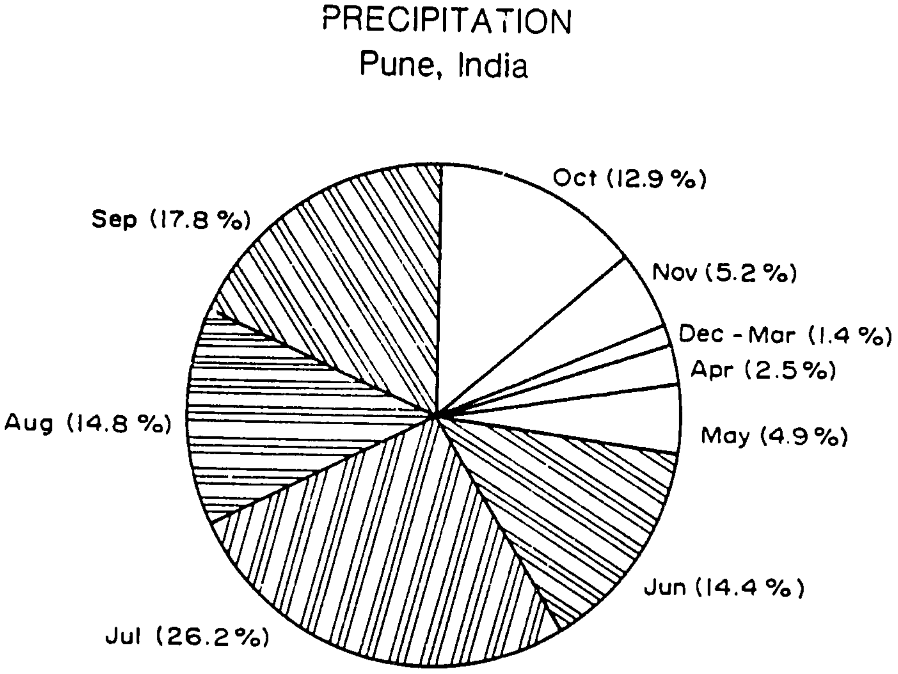

Figure 24. Monthly Distribution of Mean Annual Precipitation for Synthabad (Pune, India). The Summer Monsoon Season (Kharif) is Shown Shaded

Table 12. Soil Characteristics for Clay Loam and Black Cotton Soil.

Soil Name	SAT (% by Volume)	FC (% by Volume)	WP (% by Volume)	Infilt Rate (mm/day)	SAT to FC (days)	Wet Soil Limit (% Vol)	Evaporation Fact 1	Evaporation Fact 2
Clay loam	48.6	36.5	17.6	182.9	6.0	8.8	1.5	7.0
Black Cotton	47.0	38.8	25.1	144.0	5.0	12.6	1.3	14.0

The method outlined in FAO Paper 24 (23) is used to arrive at the crop evapotranspiration coefficients, K_c, for a grass ET reference. The K_c values are then converted to crop transpiration coefficients, K_{ct}, for an alfalfa reference. This is because the current version of the UCA Model assumes an alfalfa ET reference (this will become optional in a later version) and separates transpiration and evaporation.

The conversion from K_c grass to K_{ct} alfalfa is a two step process in which K_c values for an alfalfa reference are first determined such that at the peak K_c alfalfa is 83 percent of K_c grass. Values for K_{ct} are then derived by fitting a curve beneath the K_c alfalfa curve starting with $K_{ct} = 0.0$ at planting, and peaking with $K_{ct} = 0.96\ K_c$ alfalfa. This process is illustrated in Figure 25.

The length of each growth stage is taken from Doorenbos and Pruitt (23) when local information is not available. For sorghum raised in Pakistan, where conditions are similar to those of Synthabad, the initial stage (germination and early growth) lasts 20 days, the crop development stage (early growth to effective cover) lasts 35 days, the mid-season stage (effective cover to start of maturing) takes 40 days, and the late season stage (end of mid-season stage to full maturity or harvest) has a length of 30 days.

A 50-86 Fahrenheit growing degree phenology clock is used for sorghum since the crop is highly responsive to temperature with optimal growth between 74 and 85 degrees. The phenology clock values at the attainment of each growth stage were determined based on long-term mean daily weather data and an average planting date of June 15.

Lambdas for the relative yield calculation were derived from the ky values published by Doorenbos and Kassam (22) and assuming a transpiration deficit of 25 percent. The lambda for each growth stage is calculated by:

$$\text{lambda} = \ln(1 - 0.25\ \text{ky})/\ln(0.75) \qquad (28)$$

The resulting CROP.DAT data for sorghum raised at Synthabad is presented in Table 13.

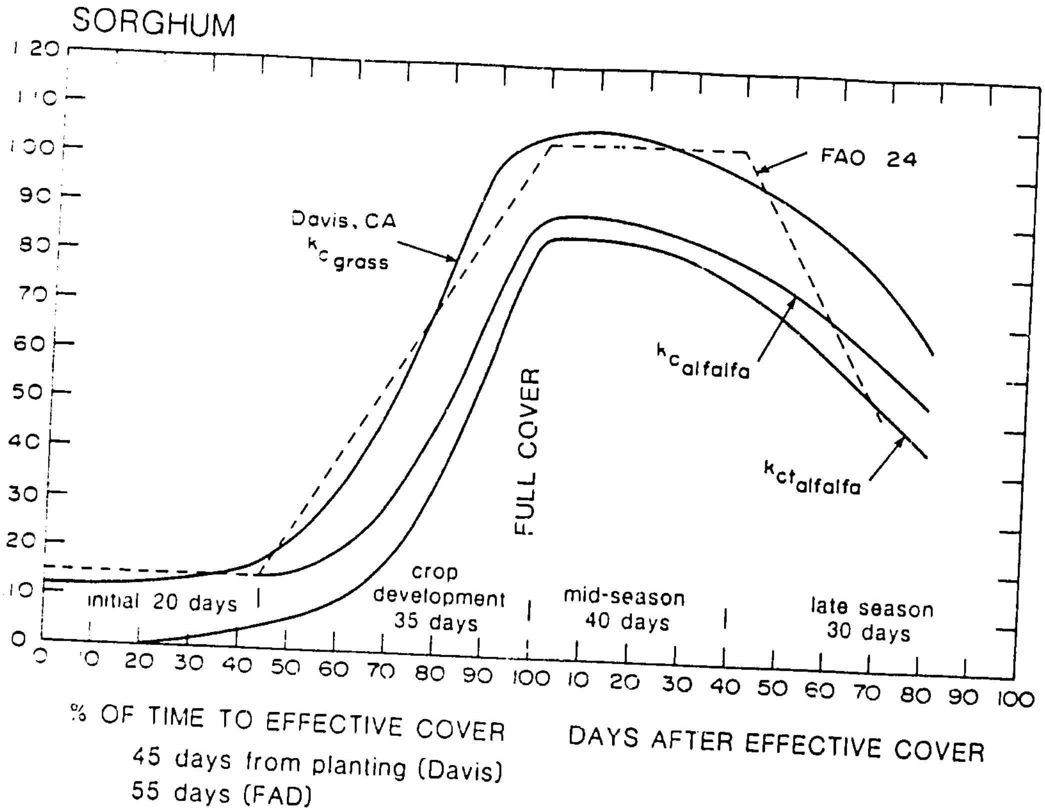

Figure 25. Derivation of Crop Transpiration Coefficient, K_{ct}, (Alfalfa Reference) from Crop Evapotranspiration Coefficient, K_c, (FAO 24 Grass Reference) for Sorghum Grow at Synthabad.

Table 13. Phenology and Yield Data for High Yielding Variety Sorghum Raised at Synthabad.

Growth Stage	50-86 GDD	K_{ct}	ASW at Stress	Yield Lambda
Planting	0	.00	.45	.00
Emergence	117	.00	.45	.18
Initial Growth	583	.04	.45	.22
Full Cover	1473	.85	.45	.75
Mid-season	2521	.78	.35	.29
Physiologic Maturity	3322	.54	.00	.00

Max. K_{ct} = 0.85; Max. Root Depth = 2.0 m at 1473 GDD; Yield = 5.0 ton/ha

Single Field Runs

The UCA Model was run in the single field mode using long-term mean climatic data to calibrate the CROP.DAT and SOIL.DAT files, and to analyze various irrigation schedules. Example output from modeling a single sorghum field is given in the appendices.

The model results, after calibration against data provided by Peterson (70), are presented in Table 14 for clay loam soil. The evapotranspiration values are for the 14-day, variable depth irrigation schedule (schedule #1). Differences in evapotranspiration due to the different irrigation schedules are insignificant.

The only significant difference between the clay loam and black cotton soils was in the evaporation from the soil surface. Evaporation from the black cotton soil was 24 percent greater than from the clay loam soil, resulting in a 7.6 percent greater irrigation demand.

Three different irrigation schedules of varying flexibility were studied. The first of these, as mentioned above, was a 14-day, variable depth rotation schedule; the second was a variable frequency, fixed depth (100 mm) schedule; and the third was a crop demand schedule of variable frequency and depth. The maximum depth of irrigation under schedules #1 and #3 was limited to 100 mm.

Near maximum potential yields were obtained for all crops under the three irrigation schedules, except for onions under the fixed depth schedule #2 because of their shallow root system.

All three schedules resulted in significant water savings over the planned fixed frequency and depth schedule of 100 mm on a 14-day rotation. Under the planned schedule, an average of 9 irrigations are required per cropping season for a total seasonal irrigation depth of 900 mm.

Normally, irrigation is not required during kharif provided the cropping season starts with soil water storage near field capacity. Peppers, however, with their shallower root system and longer growing season than other kharif crops, do require at least one irrigation during the season. The recommended irrigation schedule during kharif, therefore, is to provide a preseason irrigation to meet land preparation water requirements and in-season irrigations only as needed to supplement rainfall.

It is apparent from the results presented in Table 14, that as the flexibility in the irrigation schedule increases, the total seasonal irrigation requirement decreases. This supports the argument that on-demand irrigation is more efficient than other, less flexible, schedules. It should be remembered, however, that these data only reflect crop demands. When farmer demands are imposed, this tendency may not necessarily be observed.

While on-demand irrigation may be the most efficient at the field level, it can be difficult to carry out at the project level, unless the

Table 14. Evapotranspiration and Seasonal Irrigation Requirements Based on Three Different Irrigation Schedules for Potential Synthabad Crops on Clay Loam Soil (Single Field Analysis).

Season and Crop	Evapotranspiration			Irrigation Requirement		
	E + (mm)	T = (mm)	ET (mm)	[1] (mm)	[2] (mm)	[3] (mm)
Kharif						
HYV Sorghum	136	347	483	139	100	34
Maize	121	379	500	182	100	0
Pearl Millet	120	252	372	135	0	100
Chili Peppers	168	389	557	221	100	250
Vegetables	129	406	535	237	100	138
Pulses	107	230	337	92	0	0
Groundnuts	152	350	502	194	100	0
Cotton	176	639	815	444	200	100
Average	139	374	513	206	88	78
Rabi						
HYV Wheat	82	404	486	479	400	400
HYV Sorghum	119	503	622	591	600	500
Maize	102	539	641	603	500	600
Gram	73	268	341	298	300	300
Oil Seed	85	400	485	433	400	400
Onions	107	442	549	492	---	675
Vegetables	108	583	691	626	600	542
Average	97	448	545	503	486	488
Hot Weather						
Groundnut	121	558	679	655	600	500
Vegetables	106	599	705	635	600	700
Average	114	579	692	645	600	600
Year Round						
Grapes	454	664	1118	751	400	200

Irrigation Schedules:

[1] 14-day rotation with variable depth
[2] Management allowable deficit of 100 mm
[3] Management allowable deficit set equal to crop stress limit

water supply system is pressurized or automated to provide downstream control. For the conditions which prevail at Synthabad, on-demand schedules (such as the third one in Table 14) are not recommended at present. Implementation of such schedules could require drastic hardware and software modifications to the existing system.

The fixed frequency and fixed depth schedules (#1 and #2 in Table 14) are worth considering as alternatives to the planned fixed depth rotation (100 mm per 14 days) schedule. For efficiency at the field level, the fixed depth, variable frequency schedule (#2) is the best choice. From the viewpoint of managing the distribution system, the fixed frequency, variable depth schedule (#1) is probably the superior option. Just as water can be substituted for labor and other inputs at the field level, water can also be substituted for labor and other inputs at the main distribution system level.

Using the crop irrigation requirements for schedule #1 in Table 14 and assuming the same relative cropping pattern as given in Table 10, the weighted net irrigation requirement is 146 mm per irrigated hectare in kharif, and 470 mm per hectare in rabi. Since the available water supply at a 50 percent probability of occurrence is 616 mm per cultivatable hectare, there is sufficient water for a cropping intensity of 200 percent at an overall delivery and application efficiency of 100 percent. For the planned cropping intensity of 88 percent (36 percent in kharif and 52 percent in rabi), the required efficiency is 48 percent. For the actual cropping intensity of 58 percent (9 percent in kharif and 49 percent in rabi), the required efficiency is 40 percent.

Multiple Field Runs

The UCA Model was configured as described above, and operated for multiple fields using the same weather as for the single field runs. An example of the model output for the 14-day, variable depth irrigation schedule (schedule #1) is given in the appendices. A segment of the resulting, required water supply hydrograph is shown in Figure 26.

Under schedule #1, the turnout capacity of 43 L/s, with a main system water supply schedule of 7 days on and 7 days off, was found to be sufficient to meet the irrigation requirement for the planned cropping intensity of 88 percent, provided there was no water stealing. Water stealing had no adverse effects during kharif, but resulted in a 5 percent reduction in harvested area for the rabi season. Rabi fields adversely affected by water stealing also suffered a 10 percent yield loss. However, nonsanctioned water use resulted in only a 1 percent reduction in the overall water supply efficiency, and had no effect on the total UCA water requirement.

The planned irrigation intensity of 88 percent was easily realized with the fixed depth, variable frequency schedule (schedule #2). A portion of the supply hydrograph for this more flexible schedule is shown in Figure 27 for comparison with the supply hydrograph for schedule #1 shown in Figure 26.

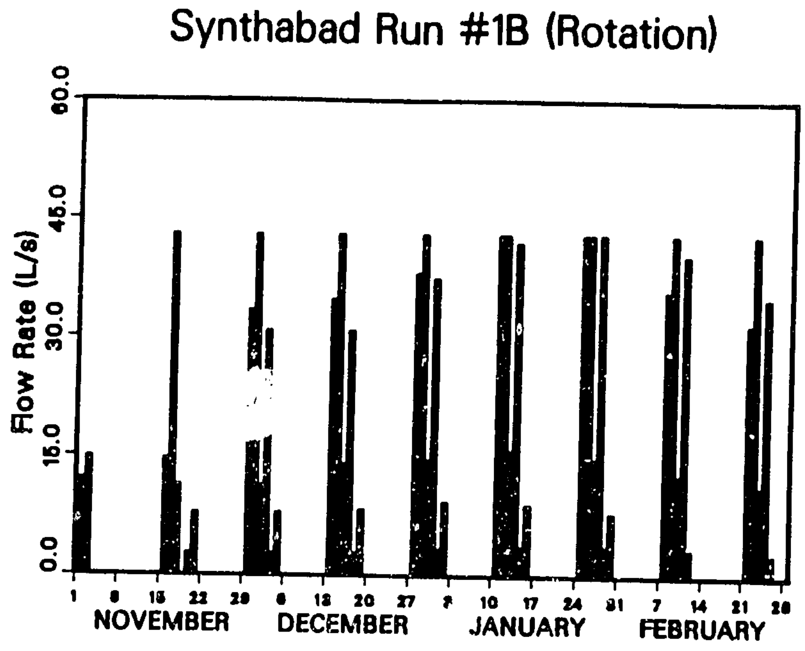

Figure 26. Rabi Segment of the Water Supply Hydrograph for the Synthabad Example UCA Under a 14-Day, Variable Depth Irrigation Schedule (#1) With No Water Stealing.

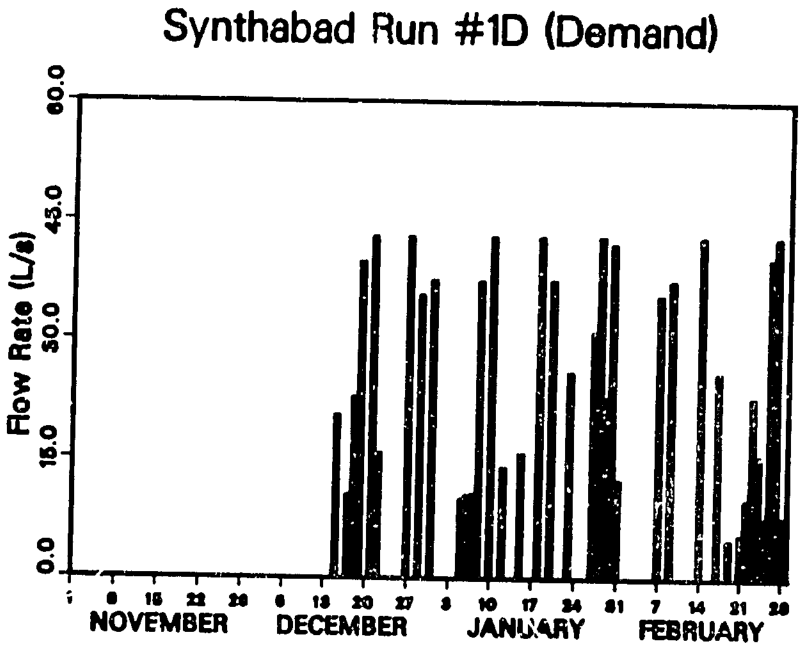

Figure 27. Rabi Segment of the Water Supply Hydrograph for the Synthabad Example UCA Under a Variable Frequency, Fixed Depth (100 mm) Irrigation Schedule (#2) With No Water Stealing.

Water stealing, under schedule #2, did not result in a reduction in planted or harvested areas, nor did it lead to a yield loss on disadvantaged fields. However, water stealing did create a 14 percent greater aggregate demand at the turnout, as compared with sanctioned water use, and resulted in a 5 percent lower water supply efficiency.

These observations of the effects of water stealing under the two different irrigation schedules lead to a now obvious conclusion. The more rigid the irrigation schedule, the more the effects of water stealing are confined to the UCAs. As irrigation schedules become more flexible (user oriented), the impacts of water stealing spread upwards through the main system.

The total annual water supply requirement at the turnout for schedule #1 is equivalent to 417 mm per hectare for the 34.5-hectare UCA under normal conditions. Since the 50 percent probable available water supply is 616 mm per cultivatable hectare, the required main system conveyance and operation efficiency is 68 percent. The average per hectare water supply requirement for schedule #2 under conditions of no water stealing is 341 mm. Thus, the required efficiency of the main system for this schedule is only 55 percent. However, since the turnout demand is more sporadic (compare the sample supply hydrographs in Figure 26 and 27) under schedule #2 than under schedule #1, the conveyance and operation efficiency of the main system would be expected to be lower.

The small sample set of 30 fields may induce some anomalies when modeling water management alternatives. Therefore, a larger number of fields is used in the next section to further explore the different irrigation schedules and queuing options.

UCA MODEL SENSITIVITY AND RESULTS

Results using the UCA Model to investigate the effects of various water management options and degrees of water supply reliability are presented in this chapter. UCA demand and response to the water supplied by the main system are tied to field characteristics, the number of fields, and the size of the UCA. Therefore, the model's sensitivity to the generation of field characteristics and to UCA size and number of fields are evaluated before the analyses of water management options and supply reliability.

Generation of Field Characteristics

A valuable feature of the UCA Model is its capability to randomly generate field characteristics. It is important, therefore, to determine the bounds of effectiveness for the field generation process.

Random Field Generation

The principal factors affecting random field generation are the seed number for the random generator, the number of fields generated, and the population density function and parameters assumed for each of the field characteristics.

The fields generated using various random number seeds can be thought of as different samples from a population. The number of fields generated correlates with the size of the sample.

Classical sampling theory states that as the size of a random sample increases, the statistic for the sample approach those for the population as a whole while the deviation among samples decreases. Therefore, one would expect the deviation among UCAs generated from different random seeds to decrease as the number of fields comprising the UCAs increased.

To test this, samples of 30, 50, 100, 150, 200, 250, 300, 350, 400, 450, and 500 fields were generated using 12 different random number seeds for each. The population density functions and parameters assumed for each of the field characteristics were taken from the Synthabad example UCA presented in the previous section (see Table 8).

The statistics describing the field characteristics for each sample were then calculated and pooled to compute the adjusted standard errors (standard deviation of the statistic divided by its mean value and the square root of the number of elements). The resulting standard error for each sample size is plotted in Figure 28.

The smooth curve drawn through the standard errors was derived by linear regression on the log-transformation of the number of fields in each sample set. The resulting equation is given by:

$$SE = 18.24\ N^{-0.507} \tag{29}$$

where SE is the standard error expressed as a percent of the mean error of average, median, standard deviation, and t-mean for each field characteristic, and N is the number of fields in the random sample. The coefficient of regression (r^2) for Eq. 29 is 0.996, indicating a near perfect fit.

Figure 28 and Eq. 29 show that the difference among UCAs, generated with different random seeds, decreases as the number of fields in each UCA increases.

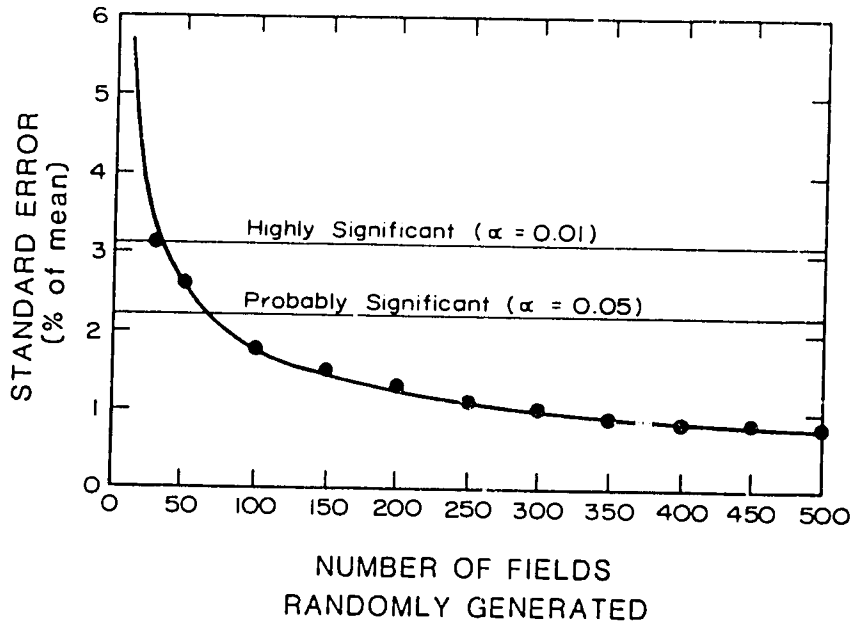

Figure 28. Standard Error Due to the Number of Randomly Generated Fields in a UCA Express as a Percent of the Mean Statistic.

For the 11 degrees of freedom here (12 random number seeds - 1), standard errors greater than 3.11 percent are highly significant (alpha = 0.01), while those greater than 2.20 percent are probably significant (alpha = 0.05). These values correlate to UCAs of 32 fields or fewer and 64 fields or fewer, respectively. Differences among UCAs of 65 fields or more are not significant for the Synthabad case.

The standard error for field characteristics generated assuming a normal, log-normal, or gamma distribution is shown in Figure 28. The beta distribution shows the same degree of sensitivity to the number of fields when the parameters of the distribution are equal, and becomes less sensitive as they diverge.

The discrete and empirical distributions are the least sensitive to the number of fields, but become increasingly sensitive as the number of intervals increases. With 11 intervals or more, the empirical and discrete distribution functions match the normal, log-normal and gamma distributions functions in sensitivity to the number of fields randomly generated.

If randomly generated field characteristics are forced to be compatible with one another (i.e., certain crops on certain soils) the standard error increases by about 13 percent over that given by Eq. 29. This results in highly significant differences among UCAs of 42 fields or fewer, and probably significant differences among UCAs of 83 fields or fewer. This may be opposite of what one would expect to result from forced compatibility. However, as the generation process proceeds from one characteristic to the next the forced compatibility causes an exaggeration in the standard deviation of the field characteristics.

Forced Compatibility Among Field Characteristics

The UCA Model uses a continuous regeneration technique to force compatibility among field parameters. A field characteristic is generated and then checked for compatibility with the other field characteristics already generated for that field. If the newly generated characteristic is incompatible with any of those created earlier, a new value is generated. This process repeats itself until the contingencies for each characteristic are met. Since this process is sensitive to the order in which the characteristics are generated, the model is programmed so that the order can be easily changed.

Except for the discrete field characteristics (i.e., soil type and cropping pattern), this procedure does not preserve the true interdependence that may exist between characteristics. From the model development and usage standpoints, however, it is much simpler to implement than the compound distribution functions that would be required to rigorously simulate interdependency.

To test the validity of the more simplified approach, UCAs were generated with and without forced compatibility. The cross correlation between the resulting field characteristics were then compared with those for the explicitly entered Synthabad example UCA.

Compatibility was forced using the following four constraints:

(1) Fields with a relative access to the turnout less than 56 had conjunctive use capacities of zero (no wells);

(2) Fields with conjunctive use options had areas greater than 1.5 ha.;

(3) Fields with a relative access less than 54 had a conveyance efficiency greater than 80 percent; and

(4) Fields less than 1.2 ha had a planting lag less than 11 days.

The resulting mean correlation coefficients (Pearson's r) for the paired characteristics of the above four constraints are given in Table 15. As would be expected, unconstrained field generation resulted in zero correlation when averaged over several runs. Using the above constraints resulted in some correlation in all four cases, but the correlations were less pronounced than with the explicitly entered data.

Table 15. Pearson's Correlation Coefficient for Four Pairs of Field Characteristics by Method of UCA Creation.

Method of UCA Generation	Access & Well Cap.	Well Capacity & Field Size	Access & Conv. Eff.	Field Size & Plant Lag
Explicit	.43	.67	-.93	.80
Constrained	.30	.53	-.52	.43
Unconstrained	.00	.00	.00	.00

Random Generation Versus Explicit Entry

To validate the UCA Model, it is important to determine whether the differences among explicitly entered UCAs and constrained and unconstrained randomly generated UCAs have significant effects on model outputs.

UCAs of each type were created by holding the area constant at 34.7 ha and varying the number of fields from 30 to 120, and then by holding the number of fields constant at 120 and varying the UCA size from 34.7 ha to 138.8 ha.

Since the differences among UCAs may be dependent upon the irrigation schedule, schedules #1 (14-day rotation, variable depth) and #2 (fixed depth, variable frequency) studied previously were used in separate runs.

Variations among the following were computed in terms of the standard error: (1) the harvested area; (2) the maximum demand; (3) the total demand, and (4) the total water supply at the turnout; (5) the mean; (6) standard deviation of the water supply at the field level; (7) the total consumptive use, the conjunctive use; and (8) the overall water use efficiency.

For the more rigid schedule #1, the standard error due to the deviation among the different methods of UCA creation (explicitly entered, constrained random generation, and unconstrained random generation) was less than 5 percent of the mean for all model outputs with the exceptions of the total demand at the turnout and the conjunctive use.

The standard error of the total demand at the turnout was 10 percent of the mean for UCAs of 34.7 ha and 30 fields. For all other combinations of UCA size and field number the standard error of the total demand was insignificant. The standard error in conjunctive use was always significant, but tended to decrease with an increase in the number of fields, and to increase with an increase in the size of the UCA.

The standard errors in model outputs under irrigation schedule #2 were similar to those for schedule #1 except for the total demand at the turnout. For the more flexible schedule #2, the standard error for the total demand ranged from 12 percent to 23 percent of the mean, tending to increase with the number of fields and decrease with the size of the UCA. (Model sensitivity to UCA size and the number of fields is discussed in more detail below.)

Therefore, with the notable exceptions of the total demand at the UCA turnout and the conjunctive use, the differences among model outputs due to different methods of UCA creation are remarkably small.

Model Sensitivity to Field Characteristics

Now that the UCA Model's sensitivity to the number of fields and the method of generating field characteristics has been determined, the model's sensitivity to individual field characteristics is investigated.

It is equally important to study the model's sensitivity to the variance of a characteristic among the fields, as it is to investigate the mean of the characteristic. Variance is introduced by the population density function and the distribution parameters used in its calibration. For example, the mean planting lag may be 9 days but may range from a minimum of 3 days to a maximum of 18 days because of the nature of the random distribution. It should be determined whether the model is sensitive to the mean value of 9 days or to the 15-day variation.

Since the model outputs were not significantly affected by the method of UCA creation or the number of fields, the results from all the runs used in the previous analyses were used to study model sensitivity to the individual field characteristics. Typically, sensitivity analyses present the change in model output as a function of the parameter under investigation. However, with 10 field characteristics and six model outputs the sensitivity matrix becomes very large, particularly when compounded by the value and variance of the characteristics. Furthermore, the combination of field characteristics describing a UCA are unique, adding another dimension to the problem.

To simplify the sensitivity analysis, the correlation between each of the 10 field characteristics and each of five model outputs (water supply, planted area, harvested area, application efficiency, and relative yield) was determined. The resulting correlations were then averaged and scored from a low of 1 to a high of 5. The outcomes are presented in Table 16.

Model sensitivity to variation in a field characteristic was determined in a similar manner, except the standard deviation of the correlation coefficients was used as a scoring indices rather than the mean value. The results are presented in Table 17. A common absolute scale was used to score the data in both Tables 16 and 17.

The overall model sensitivity to a field characteristic value or variance was computed as the average of the scores for the five model outputs. Except for the conjunctive use capacity, the model is not sensitive to the variation of field characteristics.

The model is most sensitive to the cropping pattern and least sensitive to soil type and average field area. The two soil types used for this analysis were clay loam and black cotton which may not be different enough to affect sensitivity.

Table 16. UCA Model Sensitivity (1 low, 5 high) to the Mean Field Characteristic Value.

Field Characteristic	Water Supply	Planted Area	Harvest Area	App. Eff.	Relative Yield	Overall
Access	1	2	2	1	2	1
Well	3	2	2	3	2	2
Area	2	1	1	2	1	1
Soil	1	1	1	1	2	1
Initial SWS	1	2	2	2	2	2
LCU	2	2	2	2	1	1
Conveyance Eff.	2	2	2	2	3	2
Crop	2	4	5	4	2	3
Lag	1	2	2	2	1	1
Inputs	2	1	1	2	5	2

Table 17. UCA Model Sensitivity (1 low, 5 high) to the Deviation in Field Characteristic Value.

Field Characteristic	Water Supply	Planted Area	Harvest Area	App. Eff.	Relative Yield	Overall
Access	1	1	1	1	1	1
Well	2	3	3	3	2	2
Area	2	1	1	2	1	1
Soil	1	1	1	1	2	1
Initial SWS	1	1	1	2	2	1
LCU	1	1	1	1	1	1
Conveyance Eff.	2	1	1	2	1	1
Crop	1	1	1	1	1	1
Lag	1	1	1	2	1	1
Inputs	1	1	1	1	1	1

These results suggest that the emphasis in gathering data for use in the model should focus on the mean values for the various field characteristics and not on their distributions. This greatly facilitates the use of the model since it is much easier to obtain mean values than distributed values. For example, a model user could easily estimate the average conveyance efficiency to be 80 percent, but would have more difficulty determining whether it followed a normal or beta distribution and what the distribution parameters were.

The UCA Model's sensitivity to field characteristics is also tied to the nature of the irrigation schedule and whether the model is run in the response or demand mode. Sensitivity analyses using the correlation results for different irrigation schedules show that the more rigid the schedule, the more sensitive the model is to the mean field characteristic value. As the irrigation schedule becomes more flexible, the model becomes slightly more sensitive to the deviation in field characteristics and less sensitive to mean value. When water is scarce, or the turnout capacity limiting, the nature of the model's sensitivity is similar to that for rigid irrigation schedules.

Effects of Field Numbers and UCA Size

The number of fields within a UCA corresponds to the number of independent points of demand (demand nodes) below the turnout. In an actual case, demand nodes may correspond more closely with farms than with fields. When this distinction is important, fields with similar characteristics on the same farm can be combined.

The size of a UCA increases with the number of fields. However, when studying UCA behavior it is important to consider UCA size and the number fields independently. To determine how these affect the required design capacity at the turnout and the aggregate seasonal supply and demand, multiple model runs were made, independently altering the number of fields and the UCA area.

The command area size was kept constant at 250 ha while the number of fields in the UCA varied from 30 to 500 in increments of 50. The number of fields was then held constant at 100 while the area of the UCA was set at 50, 100, 150, 250, 500, 750, 1000, 2000, and 3000 ha.

Fields were randomly generated without forcing compatibility. Conjunctive use capacity was set to zero for all fields since it is sensitive to the method of UCA creation. The remaining field characteristics were assigned the distributions for the Synthabad Example UCA.

Four irrigation schedules were studied: (1) rigid rotation (100 mm-/14 days); (2) variable depth on 14-day rotation; (3) 100-millimeter depth on a variable rotation; and (4) on-demand (variable depth and frequency).

The irrigation management efficiency was set at a constant 100 percent to limit the study to the physical aspects of the system only. Water stealing was prohibited for the same reason.

The required design capacity of the turnout was determined as the minimum capacity for a given irrigation schedule which would not result in a loss in planted area, harvested area, or crop yield. For comparison purposes, the turnout capacity is expressed in terms of flow rate per unit area (L/s/ha).

Results from the multiple simulation runs show that, for any given irrigation schedule, the required turnout design capacity per unit area is unaffected by the area of the turnout's command.

The number of fields comprising a UCA, however, can have a significant effect on the required turnout design capacity. While having no effect under fixed frequency irrigation, the number of fields can result in a 300 percent variation in the required capacity for variable frequency irrigations.

For irrigation systems operated on a demand basis, Abdellaoui (1) shows the required design capacity per unit of land area decreasing with an increase in the command area (see Figure 7). His results were generated using a constant average field size, and therefore, are due to the number of fields rather than to the size of the command area.

For the conditions simulated here, the minimum turnout design capacity for the variable frequency irrigation schedules is given by:

$$\text{Capacity} = 3.61\ N^{-0.223} \tag{30}$$

where the capacity is computed in L/s/ha and N is the number of fields. The correlation coefficient of regression (r^2) for this equation was 0.98. This curve, together with the data points used for its derivation, is presented in Figure 29.

Equation 30 implies that for an infinite number of fields, the design capacity is zero. Obviously, this is not the case. Instead, as the number of demand nodes becomes large, the design capacity for on-demand irrigation matches that required for continuous flow irrigation. This is because the fluctuation in the number of fields being irrigated simultaneously, decreases as the population of fields increases.

Figure 30 was derived by dividing the design capacity required for the different irrigation schedules by that required for continuous flow irrigation. The top horizontal line in the figure represents the capacity required for a fixed frequency variable depth schedule in which water is flowing through the turnout 50 percent of the time (i.e., 7 days on followed by 7 days off).

The design capacity for continuous flow irrigation was determined excluding the water requirement for land preparation. The seasonal irrigation requirement for continuous flow irrigation is high because of a

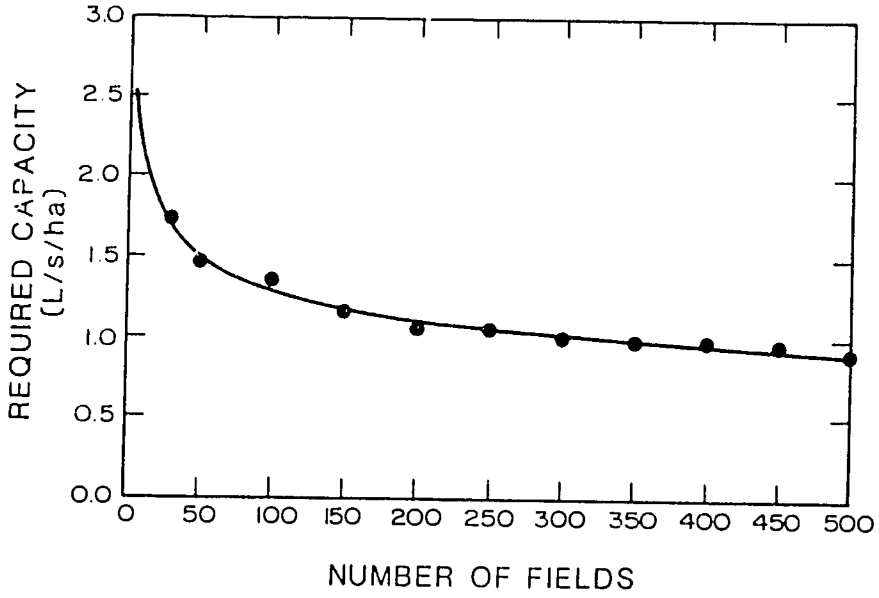

Figure 29. Required Turnout Design Capacity for On-Demand Irrigation as a Function of the Number of Fields in the Command.

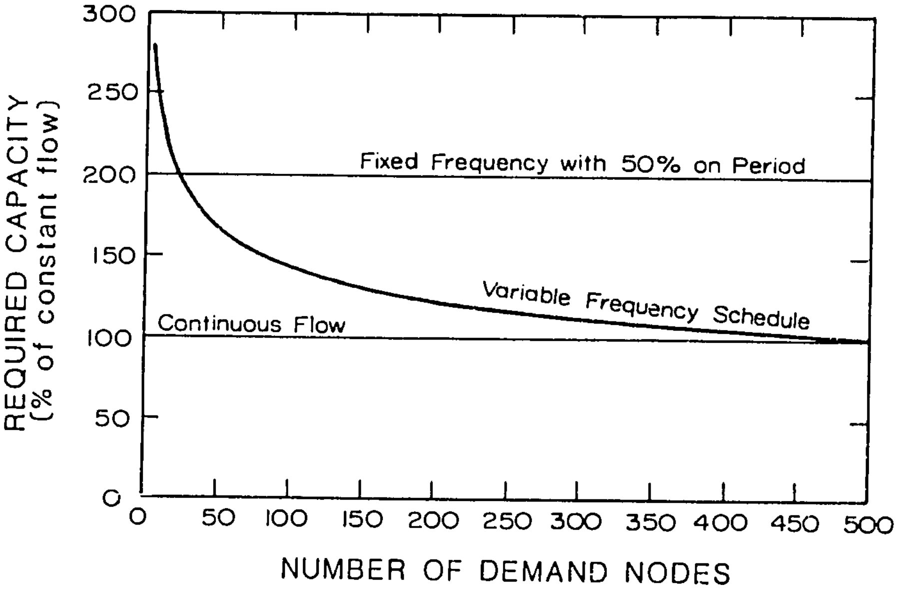

Figure 30. Required Turnout Design Capacity for Fixed Frequency and Variable Frequency Irrigation Schedules as a Percent of the Capacity Required for Continuous Flow Irrigation.

300 percent increase in evaporation from the constantly wetted soil surface. However, this does not significantly alter the design capacity required.

By presenting the required design capacity in a nondimensional manner, Figure 30 can be extended beyond the Synthabad example to other situations where field characteristics and their distributions are similar. Less sophisticated, single field models can be used to determine the required capacity for continuous flow irrigation. The requirement for variable frequency schedules could then be approximated using this figure.

Near the downstream end of an irrigation system, the design capacity should be increased to provide more flexibility to end users. It is suggested that the intersection between the line representing the design capacity for a rotation schedule and the curve for on-demand irrigation (see Figure 30) mark the point to provide increased capacity. The on-demand curve could then be used to determine the design capacity for command areas with fields less than the number represented by the intersection.

One reason on-demand irrigation schedules are not used is because of the general belief that they require greater delivery system capacities than rotation schedules. Results from this analysis, however, contradict this notion (see Figure 30). Command areas consisting of more than 25 fields require less turnout capacity with on-demand schedules than with rotation schedules with a 50 percent on period.

For on-demand irrigation, the decrease in unit design capacity with an increase in the number of fields is due to the variable frequency nature of the schedule only. This conclusion is derived from observing that there is no difference between the simulated design capacity for the fixed depth, on-demand schedule and the variable depth, on-demand schedule.

The variation among fields (planting date, crop, soil, etc.) is the reason the design capacity for on-demand irrigation changes with the number of fields. If all fields were identical, they would all need irrigation at the same time regardless of their numbers. This points to the need for a model, such as the UCA Model, which handles multiple fields and their interactions, rather than extrapolating from a single field model. It also indicates a need to determine the distribution of field characteristics when planning to investigate on-demand type irrigations.

Seasonal irrigation demand per unit land area, for a given irrigation schedule, is not affected by the number of fields or size of the UCA. Likewise, the seasonal allocation of water in response to demand is not altered by the size of the command area or the number of fields. Only the timing of supply and demand are changed by the number of fields.

This is to be expected since demand is a function of the characteristics describing a field and is not affected by the interaction among fields. If a field does not receive irrigation the first day it enters the queue, because of capacity or supply limitations at the turnout, it will express a similar demand the following day until some portion of its demand is met.

The operation of an irrigation system is not hydrologically influenced by the number of fields under its command. The laws of mass balance, rather than turnout capacity, govern the accumulation of demands throughout the system.

The seasonal water requirements for the four different irrigation schedules studied, are presented in Table 18 as percentages of the seasonal requirement for continuous flow irrigation. By comparing the columns in Table 18, it is seen that the minimum required turnout design capacity constrains demands. While not having adverse physical consequences, this may result in some fields having to wait for irrigations and some fields not receiving their full requirement. It is possible for the design capacity to meet the physical requirements of the system, but not those of the farmers.

Table 18. Seasonal Water Requirement for Different Irrigation Schedules as a Function of the Turnout Capacity.

Irrigation Schedule	Unlimited Capacity*	Design Capacity*
1) 100 mm/14-day rotation	158 percent	158 percent
2) Variable depth/14 days	60 percent	57 percent
3) 100 mm/variable frequency	49 percent	41 percent
4) Variable depth and frequency	47 percent	37 percent

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*Expressed as a percent of the seasonal irrigation requirement for continuous flow irrigation.

Apparently, flexible irrigation schedules are more efficient than rigid schedules according to the field irrigation requirement. It is interesting to note, that most of the benefit realized by on-demand schedules is due to the flexibility in irrigation timing provided by the schedule, rather than to the depth.

The potential supply efficiency (demand/supply at the turnout) is approximately 90 percent for fixed frequency schedules when the minimum design capacity is imposed. This is opposed to a potential of 100 percent for variable frequency schedules. The tendency to over supply water under fixed frequency schedules is because the supply is not synchronized with the demand for most of the irrigation season.

Water Management Alternatives Within the UCA

The management of a deficit water supply at the UCA level and at the field level are discussed below. The example Synthabad UCA was used in all the following analyses. The number of fields was increased from the original 30 to 120, but the distributions of the field characteristics were not changed. Fields were explicitly entered rather than randomly generated. The UCA size was 138.8 ha with a planned irrigated area of 119.6 ha.

Queuing System Priority and Water Allocation

Field priority within the queue is determined as a linear function of four field characteristics (relative access to the turnout, soil water status, crop value, and level of agronomic inputs) and their associated weighting factors (see Eq. 11).

The UCA Model simulates water allocation by one of three methods. The available water supply can be allocated: (1) equitably to all fields in queue; (2) to meet full demand for the highest priority fields; or (3) according to a combination of the first two. These three different methods of allocation are illustrated in Figure 14.

Field priority and the rules governing allocation are most important when there is a shortage of water. When the available water supply is distributed equally, field priority does not matter.

To study these queuing system characteristics, a deficit water supply was simulated using a 2-day on, 12-day off rotation at the UCA turnout. The turnout capacity was limited to 169 L/s. This resulted in a supply less than 40 percent of the potential demand.

The area reduction factor in response to a deficit water supply at the field level was set to zero. The reduction factor had to be low or little would have been planted or harvested with such a severely limited water supply. This suggests that in areas where farmers are very risk adverse (areas where high values for the reduction factor are applicable), only a small portion of the UCA should be planted to irrigated crops when the water supply is significantly curtailed.

For these simulations, with the area reduction factor set to zero, the planted and harvested areas were equal. The planted areas of kharif sorghum and maize were occasionally less than the planned areas. This was because the field water supply under certain conditions was insufficient to meet the land preparation water requirement at the beginning of the kharif season. The planted areas of all other crops were equal to the planned areas.

Separate model runs were made, weighting each of the four field characteristics in the priority function one at a time. For each of these simulations, the available water supply was allocated to meet the full demand for the highest priority fields. A simulation run of equitable allocation was then made for comparison. The results are summarized in Table 19 for rotation irrigation and in Table 20 for on-demand irrigation.

Table 19. Summary of Results from Comparison of Equitable Versus Prioritized Allocation Under Rotation Irrigation with a Water Shortage.

Summary Result	Potential Without Shortage	Equitable Allocation	Allocation Prioritized by:			
			Access	Stress	Crop	Inputs
Water Supply (ha m)	60.64	39.11	43.11	39.46	41.55	39.51
Harvested Area (ha)	119.6	119.6	102.4	97.2	104.4	95.2
Relative Yield	0.593	0.530	0.552	0.563	0.539	0.543
Net UCA Return (R)	361,237	323,593	289,110	279,667	289,231	258,941
Return/Hectare (R)	3,020	2,706	2,417	2,338	2,418	2,161
Return/ha m of water	5,366	7,349	5,875	6,179	6,098	5,636

Table 20. Summary of Results from Comparison of Equitable Versus Prioritized Allocation Under On-Demand Irrigation with a Water Shortage.

Summary Result	Potential Without Shortage	Equitable Allocation	Allocation Prioritized by			
			Access	Stress	Crop	Inputs
Water Supply[1]	53.58	32.89	34.80	34.27	34.20	32.94
Harvested Area[2]	119.6	119.6	100.0	96.0	102.4	95.2
Relative Yield	0.593	0.526	0.554	0.560	0.547	0.516
Net UCA Return[3]	361,237	321,284	283,248	274,306	285,858	248,041
Return[4]	3,020	2,686	2,368	2,294	2,390	2,074
Return[5]	6,073	8,679	7,110	6,958	7,310	6,442

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[1] in units of ha-m
[2] in units of ha
[3] in units of Rupees
[4] in units of Rupees/ha
[5] in units of Rupees/ha-m of water

Results listed in the potential column of the tables are for water supplies not limiting. These values are the same for rotation and on-demand irrigation except for the return per unit of water.

The total net return to the UCA from the planned 119.6-hectare irrigated area was determined as the sum of the returns from the harvested areas of each irrigated crop. When the planted area of an irrigated Kharif crop was less than the area planned, the net return from rainfed production on an area equivalent to the difference was estimated and added to the total.

The net return per harvested hectare of each crop was determined by multiplying the relative yield of the crop by the crop's potential net return. Potential net returns were derived by dividing the typical net returns for the crops grown in Maharashtra (see Table 9) by the level of agronomic inputs applied. The average level of inputs is equivalent to the relative yield value listed in the potential column of Table 19 and 20. Net returns are based on 1981 Rupees.

This approach does not account for the differences in net return per unit of land area which would result from different yields. For example, a high yielding field may reflect a greater investment in labor and agronomic inputs and would cost more to harvest than a low yielding field. However, since the variation among relative yields for this study was small, the simplified approach used is adequate.

The return per hectare meter (ha m) of irrigation water was calculated by dividing the return from irrigation by the total volume of water supplied (surface plus groundwater). The return from irrigation was estimated as the difference between the total net return and the potential return from rainfed production (35,836 Rupees).

Assuming an objective of maximizing the return per irrigated hectare, the results from this study show that water should be allocated equitably to all fields. In typical systems where allocation is a function of access to the turnout, tail-enders could realize potential yield increases of as much as a 100 percent through equitable allocation during periods of shortage. Head-enders, on the other hand, would realize slightly lower yields and would, therefore, be expected to resist an equitable allocation policy.

The results presented in Tables 19 and 20 show a greater return to land with rotation irrigation than with on-demand irrigation. This suggests that a rotation schedule should be used when there is a significant water shortage.

When the water shortage is less severe (less than 20 percent of the demand), the highest return to land is obtained by on-demand irrigation. Here fields should be prioritized first to minimize crop water stress, and then to favor the highest value crops.

If the water management objective is to maximize the return per unit volume of water, then the best results are obtained with on-demand scheduling and equitable allocation. Note, however, that maximizing the return to water may be counter to maximizing the return to land.

Reduction of Irrigated Area

When faced with a water shortage, the farmer has the option of either reducing the area he irrigates, or of deficiently irrigating the entire area. The UCA Model simulates this process by linearly reducing the irrigated area of a field whenever the ratio of the available supply to the demand is below a predetermined limit (see Figure 15).

To determine the area reduction factor which would maximize net production for the example Synthabad UCA, multiple model runs were made with reduction factors ranging from zero to one. The 14-day, variable depth irrigation schedule was imposed to concentrate the analysis on the area reduction factor. The turnout capacity was reduced from the required capacity of 169 L/s to 85 L/s to simulate a water shortage.

In kharif (rainy season), 100 percent of the area planned for irrigation should be planted, since the probability of a sufficient water supply for the season is high. For Synthabad, the primary value of irrigation is for land preparation in the preseason. If fields are planted just prior to the monsoon, the rainfall alone is nearly sufficient to meet the crop water requirements. Generally, only one irrigation is required after planting to supplement rainfall.

For the Rabi (dry) season, the water supply available for land preparation serves as a good indicator of the supply that will be available to a field later in the season. For the Synthabad case study, the area of a field planted to an irrigated crop should be reduced if the preseason supply is less than 50 percent of the demand.

Once planted, it is better not to reduce the irrigated area of a field in response to a deficit water supply. This is not only true from a net income standpoint, but also because farmers, who have already invested in high yielding variety seed, fertilizer, and labor, are reluctant to abandon irrigation on a portion of a field.

For all the situations modeled, the yield loss because of deficit irrigation was small compared with that lost from nonproductive land use. When the area reduction factor was set to zero (no reduction for a deficit supply), relative yields in response to the water supply were rarely less than 85 percent of the potential. However, when the irrigated area was reduced in response to water supplies less than 75 percent of demand, the loss in area was as much as 50 percent.

It is interesting to note that the greater a farmer's investment in inputs (seed, fertilizer, labor), the more sensitive the net return from a field is to yield loss from deficit irrigation. If a farmer invests in the necessary inputs to realize a 100 percent of the yield potential, but suffers a 20 percent yield loss because of an inadequate water supply, he will obtain only 80 percent of the potential yield. If, on the other hand, he provides enough inputs to realize only 80 percent of the yield potential, he may still obtain a yield near 80 percent with a deficit water supply. This is because enough fertilizer and other inputs have been provided to realize the production potential of the available water supply.

The trade offs between yield loss from deficit irrigation and production loss because of a reduced irrigated area, are about equal when the area is decreased for supplies less than 20 percent of demand. With surface irrigation, the irrigated area of a field would automatically be reduced with such a severely constrained supply. This would be particularly true if the flow rate was cut, rather than the length of irrigation turn, as the irrigation would be concentrated at the head of the field. Therefore, the irrigated area reduction factor is controlled by the nature of the on-field irrigation system, rather than by production economics.

An important improvement to the UCA Model would be to provide two area reduction factors in response to water supply deficits -- one for the preseason irrigated area and one for the irrigated area after planting. The portion of any field not receiving preseason irrigation could then be partitioned off for rain-fed production. Usually, the irrigated area reduction factor after planting would then be set to the lowest value permissible by the on-field irrigation system.

Irrigation Schedules

The discussion and analyses to this point have shown a higher water application efficiency (net demand/gross supply) with on-demand irrigation than with rotation irrigation. The implications of these irrigation schedules on water management efficiency (crop demand/farmer demand), however, have not been considered.

For all the simulation runs discussed, the water management efficiency has been fixed at 100 percent. In reality, water management efficiencies are less than 100 percent and vary depending on the irrigation schedule. Management efficiencies are also tied to the experience and finesse of the farmers, the reliability of the water supply, and the farmers' perception of this reliability. Thus, when comparing irrigation schedules using a simulation model, a constant water management efficiency is used to focus the analysis on the quantified differences among the schedules.

The UCA Model predicts irrigation demands based on crop water requirements which are generally different from farmer water requirements. These differences are reflected by the water management efficiency.

Differences in water requirements occur in both the timing and depth of irrigation. Keller (49) cited studies showing that farmers tend to delay irrigations an average of three days beyond the crop specified date. While delayed irrigations may cause some yield loss from crop water stress, the irrigation management efficiency is not adversely affected.

With variable depth irrigation scheduling, farmers typically apply 50 percent to 100 percent more water (provided an ample supply is available) than is required by their crops. This is equivalent to an irrigation management efficiency of 50 percent to 67 percent. Management efficiencies are forced to improve with limited water supplies.

Differences in the depth of irrigation, as determined by crop demands versus farmer demands, can be minimized using fixed depth, variable frequency irrigation schedules. Therefore, it is possible that the management efficiency of a fixed depth, variable frequency (on-demand) irrigation schedule would be greater than that of a variable depth, fixed frequency (rotation) schedule.

For the Synthabad simulations, the crop water requirement of the on-demand schedule averaged 82 percent of that for the rotation schedule. Therefore, provided the irrigation management efficiency of on-demand irrigation is greater than 82 percent of that for rotation irrigation, on-demand irrigation is favorable from an efficiency standpoint.

Unless downstream demands can be hydraulicly conveyed upstream (i.e., via a pressurized or other downstream controlled system), it is difficult for the main system to determine and meet fluctuating downstream demands. The communication of demands is perhaps the biggest limitation to implementing on-demand irrigation. Therefore, an important real time application of the UCA model would be to anticipate downstream demands.

An interesting water management option to consider is a combination approach of rotation among UCA turnouts with on-demand irrigation within the UCAs. This permits more consistent operation of the main system, thereby reducing conveyance and operational losses. Flexibility in irrigation is also provided within the UCAs.

This combination was simulated for the Synthabad Example UCA described previously. A variable volume water supply was available at the UCA turnout on a 7-day on, 7-day off rotation. Irrigation within the UCA was on a fixed depth (100 mm), variable frequency demand type schedule. The resulting water supply hydrograph for the Rabi season is presented in Figure 31.

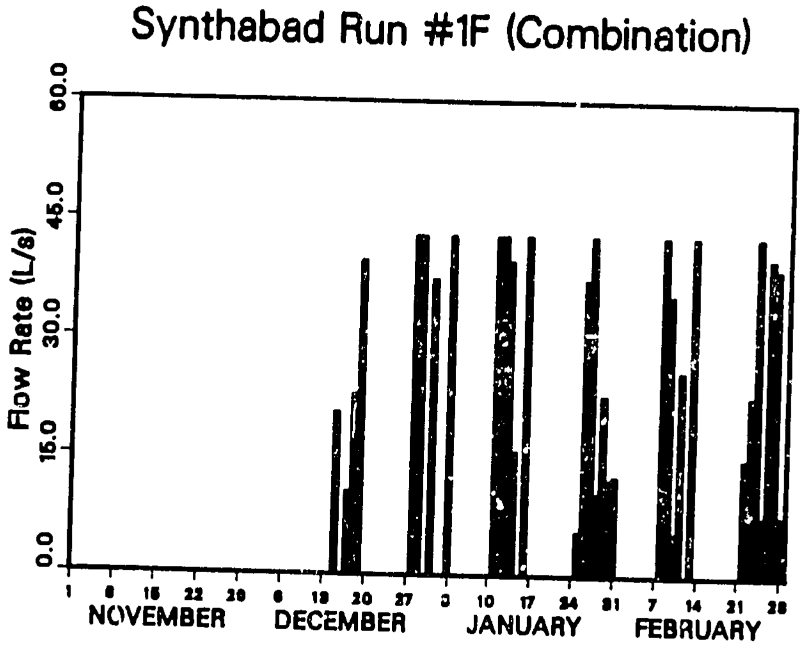

Figure 31. Rabi Segment of the Water Supply Hydrograph for the Synthabad Example UCA with a 7-Day On, 7-Day Off Rotation of the Supply at the UCA Turnout and Variable Frequency, Fixed Depth (100 mm) Irrigation Below the Turnout With No Water Stealing.

When Figure 31 is compared with Figure 26 (fixed 14-day frequency, variable depth rotation) and Figure 27 (variable frequency, fixed 100-millimeter depth on-demand irrigation) the potential advantages of a combined schedule become evident. The sporadic nature of on-demand irrigation is reduced, thus simplifying canal management. The water requirement for rotation irrigation is decreased, thereby improving water use efficiency.

For the combination irrigation schedule, the total water requirement at the UCA turnout was equivalent to an average of 310 mm per hectare as compared with 417 mm for rotation and 341 mm for on-demand. The total irrigation requirement (turnout + conjunctive use) was 366 mm for the combination schedule, 644 mm for rotation, and 393 for on-demand. See Table 21 for more comparative results.

Crop yields under the combination schedule were close to those obtained with the on-demand schedule. A slight yield reduction (1-2 percent) did result from the higher application efficiency of the combination schedule. The highest yield per unit of water applied was obtained with the combination schedule using equitable water allocation.

The implications of water stealing under the combination schedule were the same as with the on-demand schedule. Water stealing had no adverse effects within the UCA but resulted in a greater water requirement at the turnout (335 mm/ha as compared with 310 mm/ha).

The combination rotation/on-demand irrigation schedule could be used in the Synthabad without modifying the physical system. Constant flow would be maintained in the minor canals and rotated among the UCA turnouts. By reducing the turnout capacity (via the head gate) from 1.26 L/s/ha to 0.90 L/s/ha the demands could be further consolidated without affecting the UCAs. The same results could also be obtained by decreasing the on period for the turnout rotation from 7 days in 14 to 5 days. If the water supply is reliable, in time farmers will learn to adjust their demands appropriately.

Water Supply Reliability

Unreliability of the supply occurs in both its timing and amount. If water is delivered to the UCA turnouts on a regular basis but with the flow fluctuating and varying significantly from the demand, the supply is unreliable. If the flow is constant but unpredictable in its timing, again the supply is unreliable.

Sometimes, for example in run-of-the-river systems, little can be done to improve reliability. Where the water supply is controllable, however, changes in the design, operation, and management of the main system can usually be identified which will increase the reliability of the supply at the UCA turnouts.

The UCA Model can be used to determine the benefits of a more reliable water supply by simulating UCA response to supply hydrographs of varying reliability. The benefits of increased reliability can then be weighed against the costs of obtaining the increase.

One way of measuring the reliability of a water supply is by calculating the average relative difference (or error) between the given supply and a totally reliable supply. The smaller the difference, the more reliable the supply. This is similar to the relative error term used in calibrating simulation models.

This relative difference concept was used to generate supply hydrographs for studying the UCA response to varying degrees of water supply reliability. The hydrographs obtained from running the UCA Model in the demand mode for the Synthabad case study were modified to induce unreliability. The relative differences used to alter these hydrographs were randomly generated assuming a uniform distribution.

The range of variation between reliable and unreliable water supplies was derived from the warabandi hydrograph presented in Figure 4. In that example, the water supply was unpredictable 38 percent of the time (66 days out of 175). On the unpredictable days, the flow was just as likely to be zero as at full supply.

The UCA response to these unreliable supply hydrographs was simulated using the Synthabad configuration. The results for both reliable and unreliable water supplies are presented in Table 21.

Care should be taken in comparing these results for the different irrigation schedules. Since the unreliable hydrographs were randomly generated, the UCA response is also some what random. In other words, the random deviations in the supply hydrograph generated for one schedule may have been less significant than those for another.

The biggest impact due to the simulated unreliable water supplies was an 8.5 percent average loss in the overall water use efficiency. This is also reflected in the excess water supplied. If water was taken out of turn, or when a full irrigation was not needed, there would be less spillage. However, this would result in lower irrigation efficiencies at the field level, and require the farmers always to be ready to irrigate. This is equivalent to having all fields perpetually in queue.

There were no significant differences among crop yields with reliable versus unreliable water supplies; however, there was a 4 percent average loss in the harvested area with the unreliable supplies.

These simulations reflect only one degree of water supply reliability. If the water supply is unreliable because of insufficient deliveries or a different set of random events, losses in yield, harvested area, water, and water use efficiencies would be more pronounced.

Realistic simulation of an unreliable water supply is difficult without modeling the entire irrigation system from the watershed down, through the storage and delivery systems, to the UCAs. Therefore, the analysis of water supply reliability is specific to the given system, and requires either actual delivery hydrographs or the comprehensive modeling of the entire system.

Table 21. Comparison of UCA Response to a Reliable Versus an Unreliable Water Supply Under Rotation (14-Day Frequency, Variable Depth), On-Demand (Variable Frequency, 100-Millimeter Fixed Depth), and Combination (7-Day Rotation at the Turnout, On-Demand Below the Turnout) Schedules.

	Reliable Water Supply					
	Rotation		On-Demand		Combination	
	--- Water Stealing---					
	No	Yes	No	Yes	No	Yes
Turnout (mm/ha)	417	438	341	387	310	336
Groundwater (mm/ha)	27	23	52	52	56	57
Excess Supply (mm/ha)	0	0	0	0	0	0
Overall Efficiency[1] (%)	42	41	43	42	44	43
Harvest Area (% of total)	100	97	100	100	100	100

	Unreliable Water Supply					
	Rotation		On-Demand		Combination	
	--- Water Stealing---					
	No	Yes	No	Yes	No	Yes
Turnout (mm/ha)	516	504	455	462	437	325
Groundwater (mm/ha)	34	29	78	62	78	74
Excess Supply (mm/ha)	126	90	97	130	110	80
Overall Efficiency[1] (%)	33	33	34	32	35	37
Harvest Area (% of total)	94	94	97	90	100	100

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[1] This overall efficiency is the actual crop evapotranspiration divided by the total water supply (turnout+groundwater+rainfall+change in soil water).

CONCLUSIONS AND RECOMMENDATIONS

Summary

The potential benefits of irrigation cannot be derived unless the collection, storage, transmission, and delivery of water are coordinated with the temporal and spatial characteristics of the water demands at the farm level. A necessary input to the design and operation of the main system, therefore, is the behavior of the area it serves.

The main system serves as a pathway from the source of the water supply to the individual fields. At points along the system, water distribution changes from allocation among groups or blocks of irrigated fields to individual field allocations. The blocks of fields where this shift in allocation occurs demarcate the main system from what has been defined as the unit command areas (UCAs).

The UCA Model was developed to simulate the demand and response of these UCAs to the water supply at their turnouts. The demand is determined as a function of the water management scheme and of the soils, crops, and other field characteristics. The UCA response to the water supply is simulated in terms of the planted and harvested areas, irrigation efficiencies, amount of conjunctive use, and crop yields.

In the previous chapters the critical issues related to UCAs, and to the interface between them and the main delivery system, were explored. A discussion of some of the key UCA modeling concepts was also included with a review of the relevant literature incorporated throughout. The UCA Model was developed in detail by examining the various modeling methods and options as derived from some of the models in the literature.

An Indian case study, Synthabad, was developed to demonstrate the application of the UCA Model and to test the model's sensitivity to various inputs and assumptions. The UCA Model was then used, in conjunction with the Synthabad case study, to investigate various water management options and the effects of water supply reliability.

Conclusions

The outstanding contribution of this research has been the development of the UCA Model. The model has been shown to be a valuable tool for the study and improvement of irrigation system design, operation, and management.

By holding everything constant within the UCA Model, except the parameters of interest, the behavior of a UCA (in response to different water supplies, irrigation schedules, queuing system priorities, crop mixes, etc.) can be quickly and easily examined. In actual situations, where conditions vary from season to season and from year to year, such investigations would not be possible without the UCA Model or a similar tool.

Some of the conclusions derived from applying the UCA Model to the Synthabad case study are summarized below.

The UCA Model

The number of fields used in simulating a UCA influences the variation in randomly generated field characteristics and the emergence of demand. Therefore, the model user must be careful in selecting the number of fields when using random field generation and on-demand type irrigation schedules.

With the exceptions of total demand at the UCA turnout and conjunctive use, the differences among model outputs due to different methods of UCA creation are remarkably small.

The UCA Model is most sensitive to the crop type and least sensitive to the distribution of field sizes. If fields are randomly generated, UCAs of 65 fields (84 fields with forced compatibility) or more should be used to minimize the significance of differences due to different random number seeds.

The more rigid the irrigation schedule, the more sensitive the model is to the mean field characteristic values. This is also the tendency when water is scarce. As the irrigation schedule becomes more flexible, the model's sensitive to the variance in field characteristic values increases only slightly. Therefore, when gathering field data for the model, the focus should be on obtaining mean variable values rather than worrying about variable distribution.

The distribution of field characteristics can be adequately represented with the normal and empirical (with the discrete as a subset) distribution functions. Therefore, the UCA model can be simplified by including only these two distribution options.

Irrigation Schedules

The more flexible the irrigation schedule, the greater the irrigation efficiency. The conveyance efficiency, however, may decrease because of the more random nature of channel filling and draining. The irrigation scheduling efficiency may also be less with flexible schedules.

The value of on-demand type schedules lies in the flexibility of the timing of irrigation events, rather than in the flexibility of the depth of irrigation.

Fixed depth irrigations with variable frequency are more efficient than variable depth irrigations from the scheduling standpoint. The more rigid the irrigation schedule, the more localized the effects of water stealing. As irrigation schedules become more flexible (user oriented) the implications of water stealing become global.

Perhaps the major limitation of on-demand irrigation is the problem of determining downstream demands in irrigation systems without downstream control. Therefore, an important real time application of the UCA Model would be to anticipate downstream demands.

An interesting water management option to consider is a combination approach of rotation among UCA turnouts with on-demand irrigation within the UCAs. This permits more consistent operation of the main system, thereby reducing conveyance and operational losses. Also, irrigation flexibility is provided within the UCAs.

Design Capacity of Turnout

For any given irrigation schedule, the required turnout design capacity (per unit area) is unaffected by the area of its command. The number of fields comprising a UCA, however, can have a significant effect on the required turnout design capacity for variable frequency irrigations.

From the law of mass balance, the seasonal demand (per unit area) at the UCA turnout is not affected by the size of the UCA or the number of its fields.

For a large number of fields, the required system capacity for on-demand type irrigation is the same as for continuous flow irrigation.

For Synthabad UCAs with more than 25 fields, the required turnout capacity for on-demand type irrigation is less than that required for the 50 percent on time rotation. This can be used to mark the point where flexibility should be designed into rotation irrigation systems.

Allocation of Water

When the water supply is less than 80 percent of the demand, rotation irrigation should be used with equitable allocation to maximize the return to land. When water supplies are severely limited (to the point of curtailing the irrigated area) the available supply should be concentrated at the head end of the system to maximize the return to water. Such a rule, however, has obvious social limitations in its application.

Area Reduction Because of Water Shortage

Reduction in the irrigated area of a field in response to water deficits is controlled by the limitations (minimum depth of uniform irrigation) of the on-field irrigation system rather than by economics.

Generally, the area planted to an irrigated crop should be reduced according to the anticipated water shortages. However, once planted, the irrigated area of a field should not be reduced.

Reliability of the Water Supply

Unreliability in the water supply is caused by unpredictable timing of deliveries and fluctuations in the amount of the deliveries. Unreliable water supplies result in a loss of net return through lower yields (from deficit irrigation), reduction in irrigated area, increased cost for pumping supplemental water supplies, and greater labor requirements.

Recommendations

The following recommendations are presented under two general catagories: enhancements to the UCA Model and recommendations for future research.

Enhancements to the UCA Model

Computer software development is virtually an endless process. As more people use the UCA Model, further refinements will be identified. Some potential improvements recognized by the author follow:

(1) Add the capability to edit all data files without exiting the program;

(2) Add a graphics interface for the distribution of field characteristics;

(3) The field generation process should be simplified by limiting random distributions to normal and empirical (with discrete distribution as a subset);

(4) Reorder the generation of field characteristics to improve compatibility checking;

(5) Automatically check compatibility constraints for continuity;

(6) Remove the option for multiple blocks of fields within the UCA. The sensitivity analyses proved that the blocks are not important, and experience has shown that the block concept is confusing to model users;

(7) Make field size a percent of the UCA area;

(8) Dimension the model for only 250 fields;

(9) Use more of an expert system approach for system configuration (i.e., more intelligent linkage of user prompts);

(10) The irrigation management efficiency used by the model should be a function of available water supply rather than constant;

(11) Add a forage/multiple harvest crop routine;

(12) Add multiple cropping season capability to the single field simulation;

(13) Provide for optional evapotranspiration reference crops;

(14) Provide for an adjustable percolation rate tied to the water table;

(15) Reorganize the queuing subroutine so the field water balance is calculated at the beginning of the daily loop rather than at the end;

(16) Calculate the yield on the "unharvested" portions of fields (dryland production);

(17) Provide the user the option to selecting a simplified, rapid executing, on-field water budget model. (At present, only a detailed, slow running, crop-soil-water model is available);

(18) Provide graphical output of the supply and demand hydrographs;

(19) Develop a new yield model. The current model is difficult to calibrate and does not predict the effects of over irrigation; and

(20) Use two area reduction factors in response to water supply deficits -- one for the preseason irrigated area and one for the irrigated area after planting. The portion of any field not receiving preseason irrigation could then be partitioned off for rainfed production.

Future Research

These recommendations for future research include suggestions for unit command area modeling activities and for water management at the UCA level. This list is by no means exhaustive; only those ideas which have evolved from this research are presented:

(1) Actual field data should be collected for calibration and validation of the UCA Model;

(2) A groundwater model should be added to the set of irrigation system simulation models and the appropriate linkages among the models developed;

(3) For a given project (i.e., Synthabad) develop a correlation between transient variables and demand. The resulting model would not be generic, but would require much less computer memory and run much faster then the UCA Model. (The French have taken an approach similar to this, using temperature as the predictor of demands. Their program uses a continuously updated historical data set coupled with time-series forecasting.);

(4) Validate the weather simulation model developed as a part of this research;

(5) Develop a model to predict those field characteristics which are a function of farmer decisions in response to the perceived or actual water supply;

(6) Look at the difference between the aggregation of fields in a UCA and the aggregation of UCA's in a main system;

(7) Determine the optimal UCA size for an irrigation system as a whole. Investigate how channel density changes with the size of the UCAs;

(8) Study farmer demands as they vary from crop demands;

(9) Compare on-demand to rotation irrigation with a focus on the benefits of flexibility in the timing of irrigation;

(10) Investigate irrigation schedules which combine the attributes of both on-demand and rotation irrigation; and

(11) Consider social methods for the allocation of water. (This is being tested in areas of India. Where water is scarce, full supply is given to farms below 2 ha, with the scarcity rationed to larger farms.)

Other Recommendations

Research should be as concerned with the variability of results as with central tendencies. Research on crop production functions (water supply versus yield) should consider the effects due to over irrigation. World climatic data should be published in a format conducive to weather simulation.

The advent of computer models to assist irrigation system design, operation, and management opens a new era in irrigation. However, it will take time before computer assistance is readily available throughout the world. Much can be done to improve irrigation systems without the direct aid of computers. The lack of computers should not become an excuse for no action.

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Appendix A. Simulated Weather Data for Synthabad

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

JAN, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
1	JAN	1	31.4	11.2	21.3	481.	0.00	5.21
2	JAN	2	31.1	11.4	21.2	476.	0.00	5.14
3	JAN	3	30.8	11.5	21.2	472.	0.00	5.09
4	JAN	4	30.5	11.7	21.1	468.	0.00	5.04
5	JAN	5	30.3	11.8	21.1	464.	0.00	5.00
6	JAN	6	30.1	11.9	21.0	462.	0.00	4.96
7	JAN	7	30.0	12.0	21.0	459.	0.00	4.93
8	JAN	8	29.8	12.1	21.0	458.	0.00	4.91
9	JAN	9	29.7	12.2	20.9	456.	0.00	4.89
10	JAN	10	29.6	12.2	20.9	456.	0.00	4.88
11	JAN	11	29.5	12.3	20.9	455.	0.00	4.87
12	JAN	12	29.5	12.3	20.9	455.	0.00	4.87
13	JAN	13	29.4	12.3	20.9	456.	0.00	4.88
14	JAN	14	29.4	12.4	20.9	456.	0.00	4.89
15	JAN	15	29.4	12.4	20.9	458.	0.00	4.90
16	JAN	16	29.4	12.4	20.9	459.	0.00	4.92
17	JAN	17	29.4	12.4	20.9	461.	0.00	4.94
18	JAN	18	29.5	12.4	20.9	463.	0.00	4.96
19	JAN	19	29.5	12.4	21.0	465.	0.00	4.99
20	JAN	20	29.6	12.4	21.0	468.	0.00	5.02
21	JAN	21	29.7	12.4	21.0	471.	0.00	5.06
22	JAN	22	29.7	12.4	21.1	474.	0.00	5.10
23	JAN	23	29.8	12.4	21.1	477.	0.00	5.14
24	JAN	24	29.9	12.4	21.2	481.	0.00	5.18
25	JAN	25	30.1	12.4	21.2	484.	0.00	5.23
26	JAN	26	30.2	12.4	21.3	488.	0.00	5.28
27	JAN	27	30.3	12.4	21.3	492.	0.00	5.32
28	JAN	28	30.4	12.4	21.4	496.	0.00	5.38
29	JAN	29	30.6	12.4	21.5	500.	0.00	5.43
30	JAN	30	30.7	12.4	21.5	504.	0.00	5.48
31	JAN	31	30.8	12.4	21.6	508.	0.00	5.54
JAN	Averages		30.0	12.2	21.1	472.		
	Totals						0.00	157.42

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

FEB, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
32	FEB	1	31.0	12.4	21.7	512.	0.00	5.60
33	FEB	2	31.1	12.4	21.8	516.	0.00	5.65
34	FEB	3	31.3	12.4	21.9	520.	0.00	5.71
35	FEB	4	31.5	12.4	21.9	525.	0.00	5.77
36	FEB	5	31.6	12.4	22.0	529.	0.00	5.83
37	FEB	6	31.8	12.5	22.1	533.	0.00	5.89
38	FEB	7	31.9	12.5	22.2	537.	0.00	5.95
39	FEB	8	32.1	12.5	22.3	541.	0.00	6.01
40	FEB	9	32.2	12.6	22.4	545.	0.00	6.07
41	FEB	10	32.4	12.6	22.5	549.	0.00	6.13
42	FEB	11	32.5	12.7	22.6	553.	0.00	6.19
43	FEB	12	32.7	12.8	22.7	557.	0.00	6.25
44	FEB	13	32.8	12.8	22.8	561.	0.00	6.31
45	FEB	14	33.0	12.9	22.9	565.	0.00	6.37
46	FEB	15	33.1	13.0	23.1	568.	0.00	6.42
47	FEB	16	33.3	13.1	23.2	572.	0.00	6.48
48	FEB	17	33.4	13.1	23.3	575.	0.00	6.54
49	FEB	18	33.6	13.2	23.4	578.	0.00	6.59
50	FEB	19	33.7	13.3	23.5	581.	0.00	6.65
51	FEB	20	33.8	13.5	23.6	584.	0.00	6.70
52	FEB	21	34.0	13.6	23.8	587.	0.00	6.75
53	FEB	22	34.1	13.7	23.9	590.	0.00	6.80
54	FEB	23	34.2	13.8	24.0	592.	0.00	6.85
55	FEB	24	34.3	13.9	24.1	595.	0.00	6.90
56	FEB	25	34.4	14.1	24.2	597.	0.00	6.95
57	FEB	26	34.5	14.2	24.4	599.	0.00	6.99
58	FEB	27	34.6	14.4	24.5	601.	0.00	7.04
59	FEB	28	34.7	14.5	24.6	603.	0.00	7.08
FEB	Averages		33.0	13.1	23.1	563.		
	Totals						0.00	178.47

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

MAR, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
60	MAR	1	34.8	14.7	24.7	605.	0.00	7.12
61	MAR	2	34.9	14.8	24.9	606.	0.00	7.16
62	MAR	3	35.0	15.0	25.0	608.	0.00	7.20
63	MAR	4	35.1	15.1	25.1	609.	0.00	7.24
64	MAR	5	35.2	15.3	25.2	610.	0.00	7.27
65	MAR	6	35.3	15.5	25.4	611.	0.00	7.31
66	MAR	7	35.3	15.6	25.5	612.	0.00	7.34
67	MAR	8	35.4	15.8	25.6	613.	0.00	7.37
68	MAR	9	35.5	16.0	25.7	614.	0.00	7.40
69	MAR	10	35.6	16.2	25.9	615.	0.00	7.43
70	MAR	11	35.6	16.4	26.0	615.	0.00	7.45
71	MAR	12	35.7	16.5	26.1	615.	0.00	7.48
72	MAR	13	35.7	16.7	26.2	616.	0.00	7.50
73	MAR	14	35.8	16.9	26.3	616.	0.00	7.52
74	MAR	15	35.8	17.1	26.5	616.	0.00	7.54
75	MAR	16	35.9	17.3	26.6	616.	0.00	7.56
76	MAR	17	35.9	17.4	26.7	616.	0.00	7.58
77	MAR	18	36.0	17.6	26.8	616.	0.00	7.60
78	MAR	19	36.0	17.8	26.9	615.	0.00	7.62
79	MAR	20	36.1	18.0	27.0	615.	0.00	7.63
80	MAR	21	36.1	18.1	27.1	615.	0.00	7.64
81	MAR	22	36.2	18.3	27.2	614.	0.00	7.66
82	MAR	23	36.2	18.5	27.3	614.	0.00	7.67
83	MAR	24	36.2	18.6	27.4	613.	0.00	7.68
84	MAR	25	36.3	18.8	27.5	613.	0.00	7.69
85	MAR	26	36.3	19.0	27.6	613.	0.00	7.70
86	MAR	27	36.3	19.1	27.7	612.	0.00	7.71
87	MAR	28	36.3	19.3	27.8	612.	0.00	7.72
88	MAR	29	36.4	19.4	27.9	611.	0.00	7.73
89	MAR	30	36.4	19.6	28.0	611.	0.00	7.74
90	MAR	31	36.4	19.7	28.1	610.	0.00	7.75
MAR	Averages		35.8	17.2	26.5	613.		
	Totals						0.00	233.03

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

APR, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
91	APR	1	36.5	19.8	28.1	610.	0.00	7.76
92	APR	2	36.5	20.0	28.2	609.	0.00	7.76
93	APR	3	36.5	20.1	28.3	609.	0.00	7.77
94	APR	4	36.6	20.3	28.4	608.	0.00	7.78
95	APR	5	36.6	20.4	28.5	608.	0.00	7.79
96	APR	6	36.7	20.5	28.6	608.	0.00	7.81
97	APR	7	36.7	20.7	28.7	608.	0.00	7.82
98	APR	8	36.8	20.8	28.8	608.	0.00	7.83
99	APR	9	36.8	20.9	28.8	608.	0.00	7.84
100	APR	10	36.9	21.0	28.9	608.	0.00	7.86
101	APR	11	36.9	21.1	29.0	608.	0.00	7.88
102	APR	12	37.0	21.2	29.1	609.	0.00	7.90
103	APR	13	37.0	21.3	29.1	609.	0.00	7.92
104	APR	14	37.1	21.3	29.2	610.	0.00	7.94
105	APR	15	37.2	21.4	29.3	611.	17.80	7.96
106	APR	16	37.2	21.5	29.4	612.	0.00	7.99
107	APR	17	37.3	21.5	29.4	614.	0.00	8.02
108	APR	18	37.4	21.6	29.5	615.	0.00	8.05
109	APR	19	37.5	21.6	29.5	617.	0.00	8.09
110	APR	20	37.6	21.6	29.6	620.	0.00	8.13
111	APR	21	37.7	21.6	29.7	622.	0.00	8.17
112	APR	22	37.8	21.6	29.7	625.	0.00	8.22
113	APR	23	37.9	21.6	29.8	628.	0.00	8.27
114	APR	24	38.0	21.6	29.8	632.	0.00	8.32
115	APR	25	38.1	21.6	29.8	636.	0.00	8.38
116	APR	26	38.3	21.5	29.9	640.	0.00	8.45
117	APR	27	38.4	21.5	29.9	644.	0.00	8.51
118	APR	28	38.6	21.4	30.0	649.	0.00	8.59
119	APR	29	38.7	21.3	30.0	655.	0.00	8.67
120	APR	30	38.9	21.2	30.0	661.	0.00	8.75
APR	Averages		37.4	21.1	29.2	620.		
	Totals						17.80	242.24

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

MAY, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
121	MAY	1	39.1	21.0	30.1	667.	0.00	8.84
122	MAY	2	39.1	21.0	30.1	669.	0.00	8.87
123	MAY	3	39.2	21.0	30.1	671.	0.00	8.89
124	MAY	4	39.2	21.0	30.1	672.	0.00	8.92
125	MAY	5	39.3	21.0	30.1	674.	0.00	8.94
126	MAY	6	39.3	21.0	30.1	675.	0.00	8.96
127	MAY	7	39.3	21.0	30.2	676.	0.00	8.98
128	MAY	8	39.3	21.0	30.2	677.	0.00	8.99
129	MAY	9	39.4	21.0	30.2	678.	0.00	9.00
130	MAY	10	39.4	21.0	30.2	679.	0.00	9.01
131	MAY	11	39.4	21.0	30.2	679.	0.00	9.01
132	MAY	12	39.4	21.0	30.2	679.	0.00	9.02
133	MAY	13	39.3	20.9	30.1	679.	0.00	9.01
134	MAY	14	39.3	21.0	30.1	679.	0.00	9.01
135	MAY	15	39.3	21.0	30.1	678.	0.00	9.00
136	MAY	16	39.2	21.0	30.1	678.	0.00	8.98
137	MAY	17	39.1	21.0	30.1	677.	0.00	8.96
138	MAY	18	39.1	21.0	30.0	675.	0.00	8.94
139	MAY	19	39.0	21.0	30.0	673.	0.00	8.91
140	MAY	20	38.9	21.0	30.0	671.	0.00	8.87
141	MAY	21	38.8	21.1	29.9	669.	0.00	8.83
142	MAY	22	38.7	21.1	29.9	666.	0.00	8.79
143	MAY	23	38.5	21.1	29.8	663.	0.00	8.74
144	MAY	24	38.4	21.2	29.8	659.	0.00	8.68
145	MAY	25	38.2	21.2	29.7	655.	0.00	8.61
146	MAY	26	38.0	21.3	29.7	650.	0.00	8.54
147	MAY	27	37.8	21.4	29.6	645.	0.00	8.46
148	MAY	28	37.6	21.4	29.5	640.	0.00	8.38
149	MAY	29	37.4	21.5	29.4	633.	0.00	8.28
150	MAY	30	37.1	21.6	29.4	627.	17.55	8.18
151	MAY	31	36.9	21.7	29.3	619.	17.55	8.07
MAY	Averages		38.8	21.1	29.9	666.		
	Totals						35.10	272.69

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

JUN, 2001

Julian Day	Month	Day	Daily Temperature Max	Min	Avg	Solar Radiation	Rainfall	ETR
			(C)	(C)	(C)	(LY)	(mm)	(mm)
152	JUN	1	36.6	21.8	29.2	611.	0.00	7.95
153	JUN	2	36.4	21.8	29.1	607.	0.00	7.88
154	JUN	3	36.2	21.9	29.0	603.	0.00	7.81
155	JUN	4	36.0	21.9	29.0	598.	0.00	7.74
156	JUN	5	35.8	21.9	28.9	593.	0.00	7.66
157	JUN	6	35.6	22.0	28.8	588.	0.00	7.59
158	JUN	7	35.4	22.0	28.7	583.	0.00	7.51
159	JUN	8	35.2	22.0	28.6	578.	0.00	7.43
160	JUN	9	35.0	22.1	28.5	573.	0.00	7.34
161	JUN	10	34.8	22.1	28.4	567.	0.00	7.26
162	JUN	11	34.6	22.1	28.3	561.	0.00	7.17
163	JUN	12	34.3	22.1	28.2	556.	0.00	7.08
164	JUN	13	34.1	22.2	28.1	550.	0.00	6.99
165	JUN	14	33.9	22.2	28.0	544.	0.00	6.90
166	JUN	15	33.6	22.2	27.9	538.	0.00	6.81
167	JUN	16	33.4	22.2	27.8	532.	0.00	6.71
168	JUN	17	33.2	22.3	27.7	525.	0.00	6.62
169	JUN	18	32.9	22.3	27.6	519.	0.00	6.52
170	JUN	19	32.7	22.3	27.5	513.	0.00	6.42
171	JUN	20	32.4	22.3	27.4	506.	0.00	6.33
172	JUN	21	32.2	22.3	27.2	500.	0.00	6.23
173	JUN	22	31.9	22.3	27.1	493.	0.00	6.13
174	JUN	23	31.7	22.3	27.0	486.	0.00	6.03
175	JUN	24	31.4	22.3	26.9	479.	14.73	5.92
176	JUN	25	31.1	22.3	26.7	472.	14.73	5.82
177	JUN	26	30.9	22.3	26.6	466.	14.73	5.72
178	JUN	27	30.6	22.3	26.4	459.	14.73	5.62
179	JUN	28	30.3	22.3	26.3	452.	14.73	5.51
180	JUN	29	30.1	22.2	26.2	445.	14.73	5.41
181	JUN	30	29.8	22.2	26.0	438.	14.73	5.31
JUN	Averages		33.4	22.2	27.8	531.		
	Totals						103.10	201.43

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

JUL, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
182	JUL	1	29.6	22.2	25.9	431.	0.00	5.21
183	JUL	2	29.3	22.2	25.8	424.	0.00	5.11
184	JUL	3	29.1	22.2	25.7	417.	0.00	5.02
185	JUL	4	28.9	22.2	25.6	410.	0.00	4.92
186	JUL	5	28.7	22.2	25.5	403.	0.00	4.83
187	JUL	6	28.5	22.3	25.4	396.	0.00	4.74
188	JUL	7	28.3	22.3	25.3	390.	0.00	4.65
189	JUL	8	28.1	22.3	25.2	383.	0.00	4.56
190	JUL	9	27.9	22.3	25.1	377.	0.00	4.48
191	JUL	10	27.8	22.3	25.0	371.	0.00	4.39
192	JUL	11	27.6	22.3	25.0	365.	0.00	4.31
193	JUL	12	27.4	22.3	24.9	359.	0.00	4.24
194	JUL	13	27.3	22.3	24.8	353.	0.00	4.16
195	JUL	14	27.1	22.3	24.7	347.	0.00	4.09
196	JUL	15	27.0	22.3	24.7	342.	0.00	4.02
197	JUL	16	26.9	22.3	24.6	337.	0.00	3.96
198	JUL	17	26.8	22.3	24.6	333.	0.00	3.90
199	JUL	18	26.7	22.4	24.5	328.	0.00	3.84
200	JUL	19	26.6	22.4	24.5	324.	0.00	3.79
201	JUL	20	26.5	22.4	24.4	320.	15.57	3.74
202	JUL	21	26.4	22.4	24.4	317.	15.57	3.70
203	JUL	22	26.3	22.4	24.3	314.	15.57	3.66
204	JUL	23	26.3	22.4	24.3	311.	15.57	3.63
205	JUL	24	26.2	22.4	24.3	309.	15.57	3.60
206	JUL	25	26.2	22.4	24.3	307.	15.57	3.58
207	JUL	26	26.2	22.4	24.3	306.	15.57	3.57
208	JUL	27	26.1	22.4	24.3	305.	15.57	3.56
209	JUL	28	26.1	22.4	24.3	305.	15.57	3.55
210	JUL	29	26.2	22.4	24.3	305.	15.57	3.56
211	JUL	30	26.2	22.4	24.3	306.	15.57	3.57
212	JUL	31	26.2	22.4	24.3	308.	15.57	3.59
JUL	Averages		27.2	22.3	24.8	349.		
	Totals						186.90	127.52

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

AUG, 2001

Julian Day	Month Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
213	AUG 1	26.3	22.4	24.3	310.	15.13	3.61
214	AUG 2	26.3	22.4	24.3	309.	15.13	3.61
215	AUG 3	26.3	22.4	24.3	310.	15.13	3.61
216	AUG 4	26.3	22.3	24.3	310.	15.13	3.61
217	AUG 5	26.3	22.3	24.3	311.	15.13	3.62
218	AUG 6	26.3	22.3	24.3	312.	15.13	3.64
219	AUG 7	26.3	22.3	24.3	314.	15.13	3.65
220	AUG 8	26.3	22.2	24.3	315.	0.00	3.67
221	AUG 9	26.3	22.2	24.3	318.	0.00	3.70
222	AUG 10	26.4	22.2	24.3	320.	0.00	3.73
223	AUG 11	26.4	22.1	24.3	323.	0.00	3.76
224	AUG 12	26.5	22.1	24.3	326.	0.00	3.80
225	AUG 13	26.5	22.1	24.3	330.	0.00	3.84
226	AUG 14	26.6	22.0	24.3	333.	0.00	3.89
227	AUG 15	26.7	22.0	24.3	338.	0.00	3.94
228	AUG 16	26.8	21.9	24.3	342.	0.00	3.99
229	AUG 17	26.9	21.9	24.4	347.	0.00	4.05
230	AUG 18	27.0	21.8	24.4	353.	0.00	4.12
231	AUG 19	27.1	21.7	24.4	358.	0.00	4.19
232	AUG 20	27.2	21.7	24.4	364.	0.00	4.26
233	AUG 21	27.4	21.6	24.5	371.	0.00	4.34
234	AUG 22	27.5	21.5	24.5	378.	0.00	4.42
235	AUG 23	27.7	21.4	24.5	385.	0.00	4.51
236	AUG 24	27.8	21.3	24.6	392.	0.00	4.60
237	AUG 25	28.0	21.2	24.6	400.	0.00	4.70
238	AUG 26	28.2	21.1	24.6	409.	0.00	4.80
239	AUG 27	28.4	21.0	24.7	417.	0.00	4.91
240	AUG 28	28.6	20.8	24.7	426.	0.00	5.02
241	AUG 29	28.9	20.7	24.8	436.	0.00	5.13
242	AUG 30	29.1	20.5	24.8	446.	0.00	5.26
243	AUG 31	29.4	20.4	24.9	456.	0.00	5.38
AUG	Averages	27.1	21.7	24.4	357.		
	Totals					105.90	129.36

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

SEP, 2001

Julian Day	Month	Day	Daily Temperature			Solar Radiation	Rainfall	ETR
			Max (C)	Min (C)	Avg (C)	(LY)	(mm)	(mm)
244	SEP	1	29.7	20.2	24.9	466.	15.88	5.51
245	SEP	2	29.8	20.1	25.0	473.	15.88	5.59
246	SEP	3	30.0	19.9	25.0	479.	15.88	5.67
247	SEP	4	30.2	19.8	25.0	485.	15.88	5.75
248	SEP	5	30.4	19.7	25.0	491.	15.88	5.82
249	SEP	6	30.5	19.6	25.1	497.	15.88	5.90
250	SEP	7	30.7	19.4	25.1	503.	15.88	5.97
251	SEP	8	30.9	19.3	25.1	508.	15.88	6.03
252	SEP	9	31.0	19.2	25.1	513.	0.00	6.09
253	SEP	10	31.2	19.1	25.1	518.	0.00	6.15
254	SEP	11	31.3	19.0	25.2	522.	0.00	6.21
255	SEP	12	31.5	18.9	25.2	526.	0.00	6.25
256	SEP	13	31.6	18.8	25.2	529.	0.00	6.30
257	SEP	14	31.7	18.7	25.2	532.	0.00	6.34
258	SEP	15	31.8	18.6	25.2	535.	0.00	6.37
259	SEP	16	31.9	18.5	25.2	537.	0.00	6.39
260	SEP	17	32.0	18.5	25.2	538.	0.00	6.41
261	SEP	18	32.1	18.4	25.2	539.	0.00	6.42
262	SEP	19	32.1	18.4	25.2	539.	0.00	6.43
263	SEP	20	32.2	18.3	25.3	539.	0.00	6.42
264	SEP	21	32.2	18.3	25.3	538.	0.00	6.41
265	SEP	22	32.2	18.3	25.3	536.	0.00	6.39
266	SEP	23	32.1	18.4	25.3	533.	0.00	6.36
267	SEP	24	32.1	18.4	25.2	530.	0.00	6.32
268	SEP	25	32.0	18.5	25.2	526.	0.00	6.26
269	SEP	26	31.9	18.5	25.2	521.	0.00	6.20
270	SEP	27	31.8	18.6	25.2	514.	0.00	6.12
271	SEP	28	31.6	18.8	25.2	507.	0.00	6.04
272	SEP	29	31.5	18.9	25.2	499.	0.00	5.94
273	SEP	30	31.2	19.1	25.2	490.	0.00	5.82
SEP	Averages		31.4	18.9	25.2	516.		
	Totals						127.00	183.89

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

OCT, 2001

Julian Day	Month	Day	Daily Temperature Max	Min	Avg	Solar Radiation	Rainfall	ETR
			(C)	(C)	(C)	(LY)	(mm)	(mm)
274	OCT	1	31.0	19.3	25.1	479.	15.32	5.70
275	OCT	2	31.0	19.3	25.1	478.	15.32	5.68
276	OCT	3	31.0	19.3	25.1	476.	15.32	5.66
277	OCT	4	31.0	19.3	25.2	475.	15.32	5.64
278	OCT	5	31.0	19.3	25.2	473.	15.32	5.62
279	OCT	6	31.0	19.3	25.2	471.	15.32	5.61
280	OCT	7	31.0	19.3	25.2	470.	0.00	5.59
281	OCT	8	31.1	19.3	25.2	469.	0.00	5.57
282	OCT	9	31.1	19.3	25.2	467.	0.00	5.56
283	OCT	10	31.1	19.2	25.2	466.	0.00	5.54
284	OCT	11	31.1	19.2	25.2	465.	0.00	5.53
285	OCT	12	31.1	19.2	25.2	464.	0.00	5.52
286	OCT	13	31.2	19.2	25.2	464.	0.00	5.51
287	OCT	14	31.2	19.1	25.2	463.	0.00	5.51
288	OCT	15	31.2	19.1	25.2	463.	0.00	5.51
289	OCT	16	31.3	19.0	25.2	463.	0.00	5.51
290	OCT	17	31.4	19.0	25.2	464.	0.00	5.51
291	OCT	18	31.4	18.9	25.2	464.	0.00	5.52
292	OCT	19	31.5	18.8	25.2	465.	0.00	5.53
293	OCT	20	31.6	18.7	25.2	467.	0.00	5.55
294	OCT	21	31.7	18.6	25.2	469.	0.00	5.57
295	OCT	22	31.8	18.5	25.2	471.	0.00	5.60
296	OCT	23	32.0	18.3	25.2	474.	0.00	5.63
297	OCT	24	32.1	18.2	25.1	477.	0.00	5.67
298	OCT	25	32.3	18.0	25.1	481.	0.00	5.71
299	OCT	26	32.5	17.8	25.1	485.	0.00	5.77
300	OCT	27	32.7	17.6	25.1	490.	0.00	5.82
301	OCT	28	32.9	17.4	25.1	495.	0.00	5.89
302	OCT	29	33.2	17.1	25.1	502.	0.00	5.96
303	OCT	30	33.5	16.8	25.1	509.	0.00	6.04
304	OCT	31	33.8	16.5	25.1	516.	0.00	6.13
OCT	Averages		31.7	18.6	25.2	475.		
	Totals						91.90	175.18

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

NOV, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
305	NOV	1	34.2	16.1	25.1	525.	12.37	6.23
306	NOV	2	34.2	15.9	25.1	526.	12.37	6.24
307	NOV	3	34.3	15.7	25.0	528.	12.37	6.25
308	NOV	4	34.4	15.5	25.0	529.	0.00	6.26
309	NOV	5	34.5	15.3	24.9	530.	0.00	6.26
310	NOV	6	34.5	15.2	24.8	531.	0.00	6.27
311	NOV	7	34.6	15.0	24.8	532.	0.00	6.27
312	NOV	8	34.6	14.8	24.7	533.	0.00	6.26
313	NOV	9	34.6	14.6	24.6	534.	0.00	6.26
314	NOV	10	34.6	14.4	24.5	534.	0.00	6.25
315	NOV	11	34.6	14.2	24.4	534.	0.00	6.24
316	NOV	12	34.6	14.0	24.3	534.	0.00	6.23
317	NOV	13	34.6	13.8	24.2	534.	0.00	6.21
318	NOV	14	34.6	13.6	24.1	534.	0.00	6.19
319	NOV	15	34.5	13.4	24.0	533.	0.00	6.16
320	NOV	16	34.4	13.2	23.8	532.	0.00	6.14
321	NOV	17	34.3	13.1	23.7	531.	0.00	6.10
322	NOV	18	34.2	12.9	23.6	530.	0.00	6.06
323	NOV	19	34.1	12.7	23.4	528.	0.00	6.02
324	NOV	20	33.9	12.6	23.3	526.	0.00	5.98
325	NOV	21	33.7	12.5	23.1	523.	0.00	5.92
326	NOV	22	33.5	12.3	22.9	520.	0.00	5.87
327	NOV	23	33.3	12.2	22.8	517.	0.00	5.80
328	NOV	24	33.0	12.1	22.6	513.	0.00	5.73
329	NOV	25	32.7	12.0	22.4	509.	0.00	5.66
330	NOV	26	32.4	12.0	22.2	504.	0.00	5.57
331	NOV	27	32.0	11.9	22.0	498.	0.00	5.49
332	NOV	28	31.6	11.9	21.8	492.	0.00	5.39
333	NOV	29	31.2	11.9	21.5	486.	0.00	5.29
334	NOV	30	30.8	11.9	21.3	478.	0.00	5.18
NOV	Averages		33.8	13.6	23.7	522.		
	Totals						37.10	179.80

Simulated Climatic Data

Synthabad, India mean climatic data. (Based on data for Pune, India.)

DEC, 2001

Julian Day	Month	Day	Daily Temperature Max (C)	Min (C)	Avg (C)	Solar Radiation (LY)	Rainfall (mm)	ETR (mm)
335	DEC	1	30.3	11.9	21.1	470.	0.00	5.06
336	DEC	2	30.1	11.8	21.0	467.	0.00	5.01
337	DEC	3	29.9	11.8	20.9	464.	0.00	4.97
338	DEC	4	29.7	11.8	20.8	461.	0.00	4.92
339	DEC	5	29.6	11.8	20.7	458.	0.00	4.88
340	DEC	6	29.4	11.7	20.6	456.	0.00	4.84
341	DEC	7	29.3	11.7	20.5	453.	0.00	4.80
342	DEC	8	29.2	11.7	20.4	450.	0.00	4.77
343	DEC	9	29.0	11.7	20.4	448.	0.00	4.73
344	DEC	10	28.9	11.7	20.3	446.	0.00	4.70
345	DEC	11	28.8	11.7	20.3	444.	0.00	4.67
346	DEC	12	28.7	11.7	20.2	442.	0.00	4.65
347	DEC	13	28.7	11.7	20.2	440.	0.00	4.63
348	DEC	14	28.6	11.7	20.2	439.	0.00	4.61
349	DEC	15	28.6	11.7	20.1	438.	0.00	4.60
350	DEC	16	28.5	11.7	20.1	437.	0.00	4.59
351	DEC	17	28.5	11.7	20.1	437.	0.00	4.59
352	DEC	18	28.6	11.7	20.1	437.	0.00	4.59
353	DEC	19	28.6	11.7	20.2	437.	0.00	4.60
354	DEC	20	28.7	11.7	20.2	438.	0.00	4.61
355	DEC	21	28.8	11.7	20.2	439.	0.00	4.63
356	DEC	22	28.9	11.7	20.3	441.	0.00	4.65
357	DEC	23	29.0	11.7	20.4	443.	0.00	4.68
358	DEC	24	29.2	11.6	20.4	446.	0.00	4.72
359	DEC	25	29.4	11.6	20.5	449.	0.00	4.77
360	DEC	26	29.7	11.6	20.6	453.	0.00	4.82
361	DEC	27	29.9	11.5	20.7	458.	0.00	4.88
362	DEC	28	30.3	11.4	20.8	463.	0.00	4.95
363	DEC	29	30.6	11.4	21.0	468.	0.00	5.03
364	DEC	30	31.0	11.3	21.1	474.	0.00	5.11
365	DEC	31	31.4	11.2	21.3	481.	0.00	5.21
DEC	Averages		29.4	11.7	20.5	451.		
	Totals						0.00	148.27

Appendix B. UCA Model Output for a Single Field Study

```
Synthabad Case Study -- Single Field Analysis Using Mean Climatic Data

        The elevation of the site =   559 m
        The latitude of the site  = 18.83 degrees
        The longitude of the site = 73.85 degrees


The soil texture/name is Clay loam

    Layer number                          1        2
    Initial soil water (mm)            36.5    693.5
    Thickness of section ( m)          0.10     1.90
    Saturated storage (mm)             48.6    923.4
    Field capacity (mm)                36.5    693.5
    Wilting point (mm)                 17.6    334.4
    Available water (mm)               18.9    359.1

    The initial depth of ponded water is   0.0 mm

    The infiltration rate is 100.0 mm/day
    The percolation rate is 100.0 mm

    Model #1 is used for evaporation from the soil surface.

                 E=EP/(1.5**(TWT-1.0)

    The minimum soil water content in the top soil layer due to atmospheric
    drying is 88.0 mm/ m or   8.8 mm.


Crop:    HYV Sorghum

        Growth Stage          Month Day  Julian  Days After
                                          Day    Beginning

        Planting               JUN   14   166        0
        Emergence              JUN   18   170        5
        Initial Growth         JUL    3   185       20
        Full Cover             AUG    7   220       55
        Mid-season             SEP   16   260       95
        Physiologic Maturity   OCT   16   290      125


Fixed Frequency Irrigations

        Irrigation  Month Day  Julian   Depth
          Number                Day     (mm)

            1        JUL   12   194     12.44
            2        AUG   23   236     47.43
            3        SEP   20   264     53.88
            4        OCT    4   278     25.37
```

```
HYV Sorghum

S E A S O N   S U M M A R Y

Reference crop evapotranspiration = 634.04 mm
Seasonal potential evaporation    = 287.03 mm
Seasonal actual evaporation       = 135.67 mm
Seasonal potential transpiration  = 347.01 mm
Seasonal actual transpiration     = 347.01 mm
Seasonal deep percolation         = 303.42 mm
Seasonal runoff                   =   0.00 mm
Seasonal water                    = 753.92 mm
Seasonal irrigation water         = 139.12 mm
Seasonal precipitation            = 614.80 mm
Beginning soil water storage      = 730.00 mm
Ending soil water storage         = 697.82 mm
Beginning surface water storage   =   0.00 mm
Ending surface water storage      =   0.00 mm


  STAGE               JULIAN     DATE          C O N S U M P T I V E   U S E             PPT     WIRR    DEEP    RUN    POND    TOTAL
                       DAY    MONTH  DAY   ETP      TP       T       EP       E                          PERC    OFF   WATER     SW
Beginning of Season    166     JUN   14
                                                                                                                         0.00   730.00
Planting               166     JUN   14    0.00     0.00     0.00     0.00     0.00     0.00     0.00    0.00    0.00
                                                                                                                         0.00     0.00
Emergence              170     JUN   18   33.57     0.00     0.00    33.57    17.67     0.00     0.00    0.00    0.00
                                                                                                                         0.00   712.33
Initial Growth         185     JUL    3   85.78     3.25     3.25    82.53    46.43   103.10     0.00   40.10    0.00
                                                                                                                         0.00   725.64
Full Cover             220     AUG    7  137.54    55.83    55.83    81.72    38.91   292.80    12.44  199.71    0.00
                                                                                                                         0.00   736.43
Mid-season             260     SEP   16  200.35   168.87   168.87    31.48    12.00   127.00    47.43   39.00    0.00
                                                                                                                         0.00   690.99
Physiologic Maturity   290     OCT   16  176.80   119.06   119.06    57.74    20.67    91.90    79.26   24.60    0.00
                                                                                                                         0.00   697.82

The predicted yield = 5.00 ton/ha or 100.0 percent of the potential yield.
```

Appendix C. UCA Model Output for a Multiple Field Study

```
UCA Model Version: January 26, 1986


Site Name/Run Description: Example Synthabad UCA; 7 day on, 7 day off water supply; no water stealing

Unit Command Area: Typical Synthabad UCA

Year of Run/Simulation: 2001

         The elevaton of the UCA =  559. m
         The latitude of the UCA =  18.83 degrees
         The longitude of the UCA =  73.85 degrees

There are 10 different cropping patterns and 2 different soil types in the UCA.

The UCA consists of  30 fields divided into  1 blocks.

The size of the UCA is   34.7 ha


Description of the queuing system:

A prioritized queue was in affect with weighting factors of:
         100.00   for the relative access of a field to the turnout;
           0.00   for the degree of water stress;
           0.00   for the crop priority; and
           0.00   for the relative level of agronomic inputs.

The water supply at the UCA turnout was allocated to meet full demand
for those fields first in the queue.

The maximum number of hours of irrigation per day was 24.0 hr.

The turnout capacity of the UCA turnout is    43. L/s.


Irrigation schedule within the UCA:

Block   Irrigation Frequency (days)  Allowable   Net Depth of
Number   Schedule   or Demand Type   Depletion  Irrigation (mm)
...............................................................

  1      Rotation        14              0          1000

The on-field irrigation management efficiency was 100. %

The farmers demanded full irrigation for  50. % of the area of their fields.

If the water delivery to a field was less than  75.% of the gross demand
the irrigated area of the field was reduced.

The minimum net depth of irrigation was  50. mm and the maximum was 100. mm.
```

```
                         UCA WATER USE ANALYSIS


Total water demand at the UCA turnout  516. mm (    18. ha m)
Total water supplied at the UCA turnout  417. mm (    14. ha m,  80.8 % of demand)

Distribution of supply: mean  427. mm/field    st. dev.  174. mm/field

Conjunctive use of groundwater:   27. mm (   0.94 ha m   90. hr of pumping/well

Water use per harvested hectare  (Total harvested area =  30.4 ha):

                Transpiration  372. mm
                Evaporation    126. mm
               (Percolation    157. mm)

                Total CU       498. mm
               (Total plus DP  655. mm)

Water supply per harvested hectare:

                UCA turnout      476. mm
                GW pumping        31. mm
                Rainfall         804. mm
                Excess supply      0.
                Change in SWS   -114. mm

                Total Supply    1198. mm

Calculated overall efficiency (CU/Supply)  41.6 %

Given mean conveyance efficiency  79.9 %

Calculated average on-field efficiency (CU/Field Supply)  45.2 %

Calculated average on-field irr app eff (net demand/gross irr supply) for growing season # 1  92.2 %
Calculated average on-field irr app eff (net demand/gross irr supply) for growing season # 2  93.1 %


Irrigation Demand and Supply by Crop:

                                Net                    Gross
Crop                 Growing  Demand  % of Total   Supply  % of Total  Supply
                     Seacon    (mm)     Demand      (mm)     Supply   Eff. (%)
------------------------------------------------------------------------------

HYV Sorghum             1      362.      22.6       439.      22.9      82.5
HYV Corn                1      335.       3.0       508.       3.8      66.0
Pearl Millet            1      275.       4.9       379.       5.6      72.5
Pulses                  1      249.       2.2       304.       2.3      82.0
Chili Pepper            1      367.       3.3       412.       3.1      89.0
HYV Sorghum             2      743.       6.6       749.       5.6      99.3
HYV Wheat               2      483.      38.8       568.      38.1      85.1
Gram                    2      330.       5.9       397.       5.9      83.2
Sunflower               2      478.      12.8       569.      12.7      84.0
```

STATISTICAL ANALYSIS OF FIELD DATA

Typical Synthabad UCA

Number of fields in the UCA 30 Total UCA area 34.7 ha

Average field size 1.16 ha (Standard deviation = 0.60)

Mean relative distance of fields from the UCA turnout 56. (St.Dev. = 16.5)

Number of wells in the UCA 4 Total well capacity 19.3 lps
Average well capacity 4.82 lps (Standard deviation = 3.49 L/s)
Average well capacity per field 0.64 L/s)

Average on-field linear coef of irr uniformity 77.3 % (St.Dev. = 7.58)

Average conveyance efficiency from the turnout to the field 79.9 % (St.Dev. = 10.10)

Soil Type	% of Fields	% of UCA Area
1	53.3	51.6
2	46.7	48.4

Crop Pattern	% of Fields	% of UCA Area
1	23.3	21.0
2	3.3	4.9
3	6.7	6.6
4	3.3	2.0
5	3.3	1.4
6	30.0	31.4
7	3.3	7.8
8	6.7	5.8
9	10.0	6.6
10	10.0	12.4

Mean planting lag 9. days (Standard deviation = 3.4)

Mean level of agronomic inputs 59.4 % (Standard deviation = 6.2)

CROSS CORRELATION ANALYSIS OF UCA FIELDS

Variable:

1 Relative distance from field to UCA water supply
2 Well capacity
3 Field size
4 Soil type
5 Ending soil water
6 On-field linear coef of irr uniformity
7 Conveyance efficiency from turnout to field
8 Cropping pattern
9 Planting lag
10 Relative level of agronomic inputs
11 Water supply from UCA turnout to field
12 Planted area for cropping season #1
13 Harvested area for cropping season #1
14 On-field irrigation app eff for cropping season #1
15 Relative yield for cropping season #1
16 Planted area for cropping season #2
17 Harvested area for cropping season #2
18 On-field irrigation app eff for cropping season #2
19 Relative yield for cropping season #2

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	1.00																		
2	0.43	1.00																	
3	0.45	0.67	1.00																
4	0.21	-0.02	0.07	1.00															
5	-0.10	-0.75	-0.38	0.53	1.00														
6	-0.10	0.11	-0.03	0.02	-0.16	1.00													
7	-0.93	-0.54	-0.63	-0.23	0.15	0.17	1.00												
8	0.13	0.20	0.08	-0.06	-0.21	-0.12	-0.15	1.00											
9	0.31	0.47	0.80	0.13	-0.16	-0.12	-0.46	-0.16	1.00										
10	-0.02	-0.16	-0.07	0.33	0.40	-0.04	-0.01	-0.09	0.14	1.00									
11	-0.11	0.10	-0.12	0.05	0.09	0.05	0.11	-0.29	0.12	0.12	1.00								
12	0.01	-0.29	-0.16	0.05	0.28	0.16	0.05	-0.87	-0.07	0.14	-0.03	1.00							
13	0.01	-0.29	-0.16	0.05	0.28	0.16	0.05	-0.87	-0.07	0.14	-0.03	1.00	1.00						
14	-0.29	0.25	0.09	-0.25	-0.40	-0.11	0.25	0.73	0.03	-0.17	-0.04	-0.86	-0.86	1.00					
15	0.05	-0.10	-0.03	0.33	0.35	0.06	-0.07	0.12	0.13	0.96	0.12	-0.05	-0.05	-0.05	1.00				
16	-0.13	0.36	0.06	0.00	-0.30	0.00	0.08	0.54	0.09	-0.06	0.53	-0.82	-0.82	0.70	0.10	1.00			
17	-0.13	0.36	0.06	0.00	-0.30	0.00	0.08	0.54	0.09	-0.06	0.53	-0.82	-0.82	0.70	0.10	1.00	1.00		
18	-0.12	-0.23	-0.07	0.11	0.12	0.20	0.14	-0.45	-0.20	-0.03	-0.58	0.66	0.66	-0.56	-0.16	-0.81	-0.81	1.00	
19	0.07	-0.22	-0.07	0.31	0.46	0.01	-0.06	-0.23	0.14	0.95	0.00	0.35	0.35	-0.34	0.87	-0.32	-0.32	0.15	1.00

```
UCA CROP ANALYSIS


Crop:              HYV Sorghum          Growing season # 1

Number of fields planned for crop =    7

Crop area (hectares): Planned   7.3    Planted   7.3    Harvested   7.3

Mean planting date: JUN 16    (Std. Dev. =  3.7 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 0.94    Std. Dev. 0.034

Relative yield (including reduction factor and agronomic inputs): Mean  54.2    Std. Dev.  6.9


Crop:              HYV Corn             Growing season # 1

Number of fields planned for crop =    1

Crop area (hectares): Planned   1.7    Planted   1.7    Harvested   1.7

Mean planting date: JUN 24    (Std. Dev. =  0.0 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 1.00    Std. Dev. 0.000

Relative yield (including reduction factor and agronomic inputs): Mean  58.0    Std. Dev.  0.0


Crop:              Pearl Millet         Growing season # 1

Number of fields planned for crop =    2

Crop area (hectares): Planned   2.3    Planted   2.3    Harvested   2.3

Mean planting date: JUN 21    (Std. Dev. =  7.1 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 0.98    Std. Dev. 0.021

Relative yield (including reduction factor and agronomic inputs): Mean  63.4    Std. Dev.  9.1
```

```
UCA CROP ANALYSIS

Crop:               Pulses                Growing season # 1
Number of fields planned for crop =    1
Crop area (hectares): Planned   0.5    Planted   0.5    Harvested   0.5
Mean planting date: JUN 11    (Std. Dev. =  0.0 days)
Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0
Yield reduction factor due to irr uniformity: Mean 1.00    Std. Dev. 0.000
Relative yield (including reduction factor and agronomic inputs): Mean  72.9    Std. Dev.  0.0

Crop:               Chili Pepper          Growing season # 1
Number of fields planned for crop =    1
Crop area (hectares): Planned   0.7    Planted   0.7    Harvested   0.7
Mean planting date: JUN  6    (Std. Dev. =  0.0 days)
Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0
Yield reduction factor due to irr uniformity: Mean 0.98    Std. Dev. 0.000
Relative yield (including reduction factor and agronomic inputs): Mean  59.9    Std. Dev.  0.0

Crop:               HYV Sorghum           Growing season # 2
Number of fields planned for crop =    1
Crop area (hectares): Planned   2.7    Planted   2.7    Harvested   2.7
Mean planting date: OCT 18    (Std. Dev. =  0.0 days)
Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0
Yield reduction factor due to irr uniformity: Mean 0.93    Std. Dev. 0.000
Relative yield (including reduction factor and agronomic inputs): Mean  48.5    Std. Dev.  0.0
```

```
UCA CROP ANALYSIS


Croo:              HYV Wheat            Growing season # 2

Number of fields planned for crop =    9

Crop area (hectares): Planned  10.9    Planted  10.9    Harvested  10.9

Mean planting date: OCT 30    (Std. Dev. =  4.2 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 0.95    Std. Dev. 0.024

Relative yield (including reduction factor and agronomic inputs): Mean  57.3    Std. Dev.  5.3


Crop:              Gram                 Growing season # 2

Number of fields planned for crop =    2

Crop area (hectares): Planned   2.0    Planted   2.0    Harvested   2.0

Mean planting date: OCT 29    (Std. Dev. =  0.7 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 0.93    Std. Dev. 0.025

Relative yield (including reduction factor and agronomic inputs): Mean  55.8    Std. Dev.  5.4


Crop:              Sunflower            Growing season # 2

Number of fields planned for crop =    3

Crop area (hectares): Planned   2.3    Planted   2.3    Harvested   2.3

Mean planting date: OCT 24    (Std. Dev. =  1.5 days)

Relative yield (water potential only): Mean 100.0    Std. Dev.  0.0

Yield reduction factor due to irr uniformity: Mean 0.94    Std. Dev. 0.033

Relative yield (including reduction factor and agronomic inputs): Mean  53.2    Std. Dev.  3.7
```

WATER MANAGEMENT SYNTHESIS PROJECT REPORTS

WMS 1	Irrigation Projects Document Review Executive Summary Appendix A: The Indian Subcontinent Appendix B: East Asia Appendix C: Near East and Africa Appendix D: Central and South America
WMS 2	Nepal/USAID: Irrigation Development Options and Investment Strategies for the 1980's
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