PN-AAZ-736

CLASSIFICATION OF GRAVITY IRRIGATION SYSTEMS AND THEIR OPERATION

WATER MANAGEMENT SYNTHESIS PROJECT

WMS REPORT 78

CLASSIFICATION OF GRAVITY IRRIGATION SYSTEMS AND THEIR OPERATION

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This paper was prepared at Cornell University for the Water Managment Synthesis II Project, USAID Contract DAN-~~1427~~-C-00-2086, to the Consortium for International Development. 4127

March 1988

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EXECUTIVE SUMMARY

The need for a more systematic way of classifying irrigation systems has been voiced by many professionals in irrigation development. Without such unifying classification systems or typologies, the knowledge generated by research cannot be easily applied across systems, and the systematic analysis of irrigation regions is hampered.

There are three main issues that the development of useful irrigation typologies must confront. The first is to determine which perspective to take (sociological, economic, physical, operational) and the purpose of the typology. The second issue is how to deal with the tremendous spatial and temporal diversity found both within and between systems, while the third is the continuous rather than discrete nature of irrigation classifications.

This paper has two main goals. The first is to develop a general purpose typology based on physical attributes, which national and international irrigation agencies can use for irrigation 'demographics'. The method used to develop this typology is to first create an inventory of all of the physical attributes that affect the operation of the irrigation system. Once this background is presented, the most general and significant classifications are identified and discussed. The final typology is then constructed using the classifications of cropping system, physical area, water source, extent of irrigation, and topography.

The second goal of the paper is to propose a typology that describes how gravity systems are operated. After addressing the major issues in the operational strategy, which included the water delivery method, the time frame and the response to water shortages, a simple operational typology is created using the attributes of degree of responsiveness, schedule, and operational procedure.

Chapter 1

ISSUES IN IRRIGATION TYPOLOGY DEVELOPMENT

Scientific investigation can be broadly separated into systematics (clarifying relationships among phenomena and arranging them in a meaningful order) and functional studies (discovering the laws governing the behavior of phenomena). Work in the area of systematics is a prerequisite to the development of a sound scientific method because it directly affects the investigator's ability to effectively interpret data in order to generate quality conclusions. Systematics, of which typologies are an essential part, tries to, as Plato said "cut nature at the joints" so that uniformities are evident in the phenomena to be described and explained. (McKelvey, 1982)

The history of science indicates that the functional side of most disciplines (i.e., an understanding of the laws and principles governing phenomena) did not make rapid progress until basic taxonomic work was completed. Chemistry did not make much progress until Mendeleev worked out the periodic chart of the elements, and biology would still be in its infancy if taxonomic studies had not laid the groundwork for functional research. In each science, the classification systems described the structure and relationships of the important objects to one another and to similar objects. This allowed general statements to be made about classes of objects (Sokal, 1979).

The general classification scheme produced by these systematists has been the platform on which succeeding functional studies were based. As the diversity of the phenomena being studied increased, this taxonomic groundwork became even more important (McKelvey, 1982).

Although the classification systems mentioned above were very extensive in their scope, such systems do not have to be universal to be of use. A range of classification systems directed toward specific functional purposes were widely used in most sciences, and they are often precursors to more universal classification systems.

In recent years, a number of irrigation professionals have expressed the need for a more systematic method to classify gravity irrigation systems, but as yet no serious effort is complete (Small, 1985). The resulting lack of coherence in irrigation studies prompted one researcher to call much of such work "a heap of ostensibly unrelated facts" (Chambers, 1986). The study of irrigation systems can be likened to a giant picture puzzle being constructed by investigators all over the world. Nobody has access to the work of everyone, yet each researcher needs and wants to know what has already been done, which parts are causing problems, and which research needs to be replicated. The lack of a coherent classification system seriously undermines efforts to communicate this information.

Because of the complex nature of irrigation, the prospect of one universal irrigation classification system seems remote at this point in time. Unlike biological organisms, irrigation systems have no "genes" to pass on to their off-spring and thus irrigation classifications cannot rely on this kind of organizing principle. But, the fact that a universal taxonomy is unlikely does not eliminate the possibility of systematic classification in irrigation. A wide range of functional classifications, with more limited purposes, can greatly assist much of irrigation science. The term 'typology', was chosen for this paper because of its more functional connotation, as opposed to 'taxonomy', which has a more universal meaning.

DIFFICULTIES IN TYPOLOGY DEVELOPMENT

There are a number of major issues to be considered when developing typologies for irrigation systems. The first question that the researcher must resolve is that of perspective. Economists, sociologists, and engineers will each describe a system using different criteria. Their choices will depend on the specific purpose for which the typology is to be used. This raises serious questions about the feasibility of a general classification that will satisfy the needs of all disciplines.

A second issue is the tremendous diversity found among systems throughout the world. No two irrigation systems are exactly alike, and each results from a unique combination of cultural, historical, economic, political, and environmental forces. Not only is there a tremendous diversity among systems, but also within the system itself. In large systems spatial differences in soils, customs, organization, etc. often lead to a variety of water distribution methods within the system, allowing possible classification in more than one category. This diversity is further compounded by the fact that irrigation systems are dynamic and evolve over time.

A third major difficulty in typology development is the continuous rather than discrete nature of irrigation characteristics. For example, how does one determine the point at which a system ceases to be small and becomes large? Subjective decisions about such dividing points must be made in order to come up with useful "types".

Bearing these difficulties in mind, the key questions that a systematist must answer are:

1) How many attributes are needed to adequately characterize a system?

2) How similar must systems be to be classified together?

Answers to these questions are clouded by the fact that those that appear to be similar when few attributes are considered may end up being different if many attributes are used. Ideally, the fewer the attributes needed to characterize a system the better. Unfortunately, to be analytically useful, classifications may have to use many characteristics.

Although there may not be nearly as many kinds or types as there are, say of biological organisms, irrigation systems are much larger and more complex phenomena and probably have a greater number of attributes per kind. Sells (1964) suggests that as many as 500 attributes may be needed to adequately characterize a social organization. Irrigation systems are social and technical organizations and may require even more. There is always the possibility that each system is really unique and any classification will be artificially imposed.

Despite this possibility, experience suggests that classification is not an impossible endeavor. Even though irrigation systems do differ, they are also similar. To the extent that they are similar, the use of effective management practices or other improvements in one system may be transferable to others. Classification of similar systems into types will allow us to form generalizations about the group. These in turn may be used to determine when a particular practice may be transferable in part or in total to another categorically similar system.

THE CONTRIBUTION OF TYPOLOGIES TO THE STUDY OF IRRIGATION SYSTEMS

The development of typologies can benefit the study of irrigation systems in a

number of ways:

1) Allow researchers to do irrigation "demographics" of a specific region so that research priorities can be established based on the relative importance of the different types of systems. By irrigation "demographics" we mean the systematic study of irrigation systems that describes the density, distribution, and vital characteristics of irrigation in an area. It appears that, in most countries intimate knowledge of what exactly is going on in the irrigation sector is not available. Not only is information missing, but when it does get collected, there is no suitable way to organize it. The lack of a coherent typology may be a significant reason why information is not collected and organized.

2) Help in the development of information retrieval systems. Data stemming from functional studies can be organized into useable sets of classes. Thus comparisons of similar systems can be made.

3) Enable planners and managers to be aware of the range of available options for system design and operation, and give focus to operational options in specific categories of systems.

4)Provide a framework in which to describe and understand the diversity of irrigation systems and their operation. This framework can also facilitate the discovery, development, and teaching of management principles.

RESEARCH FOCUS OF THIS PAPER

Organization of all of the as yet uncharted irrigation systems throughout the world, using all possible perspectives, cannot be accomplished in a single research work. Although we have tried to use a multidisciplinary perspective in some of our analysis, there is a marked engineering bias in this paper, because we are engineers. The underlying focus of our typologies is the physical factors that affect the operation of the water distribution system.

Throughout the report, 'operation' refers to the activities associated with controlling water in the canal system, and the 'operators' are those people responsible for those activities. This is based on the assumption that, whether the system is indigenous or government run, at each hydraulic level there must be some person or persons responsible for controlling the water flow to some degree. Without someone responsible, irrigation projects usually deteriorate quickly because they tend to be high entropy systems. This inherently hierarchical nature is manifested in the structure of the irrigation organization.

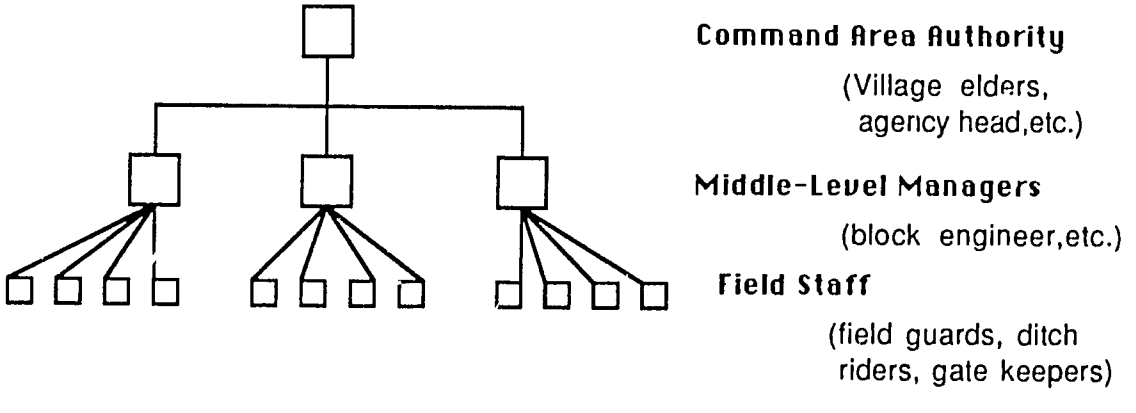


Figure 1: A Generic Irrigation Organization.

The operators have to have a system perspective if water flows are to be

properly distributed.

We have two goals in mind in this report. The first is to develop a general physical classification system for the purpose of assisting national and international irrigation agencies to do irrigation demographics. The second goal is to begin the construction of a typology to be employed by researchers conducting functional studies to improve system operation. Others interested in constructing different typologies will, however, find much of this material useful.

The development of a general classification system as well as an operational typology requires the study of a large number of gravity irrigation systems. Our research was based on extensive published materials available at Cornell University, augmented by many discussions with researchers who had first hand experience in a variety of irrigation systems.

The secondary source material, although fairly comprehensive, was limited in usefulness because each study focused on a different aspect of an irrigation system. Very few detailed accounts of the actual operation of irrigation systems exist, and this makes it difficult to construct conclusive typologies.

One caveat before we proceed. Although the following classifications focus on the physical attributes of systems, we must be careful to avoid the physical determinism this suggests. Physical variables are not the only influential factors in a system. Attention must always be given to the social, economic and organizational variables, which have an equal, if not more significant influence in the irrigation system.

Chapter 2

CONSTRUCTING A GENERAL TYPOLOGY BASED ON PHYSICAL ATTRIBUTES

In this section a general classification system for gravity irrigation is developed using physical variables as the criteria. The strategy pursued is to first identify in a system inventory all the relevant physical variables that affect operation and then decide on the most important general variables for the final typology. To make a simple analogy, this strategy is similar to trying to classify cars by first identifying all the parts that can differ (i.e., steering wheel, brakes etc.) and then deciding on some general characteristics that are the most significant for classification (size, color, fuel etc.)

INVENTORY OF PHYSICAL VARIABLES AFFECTING IRRIGATION OPERATION

The purpose of this inventory is to list and organize all the physical factors that affect the operation of a gravity irrigation system. Numbered nodes are distinct variables that can directly affect the operation of a system. Lettered nodes list attributes of the variable that vary in degree (i.e., the intensity of rainfall).

The question that was kept in mind while creating this tree was, "Can the factor or quality significantly affect the operation of a gravity irrigation system?" Some attributes that influence irrigation in various ways, such as aspects of soil

fertility, were left out because of their minimal influence, in general, on the actual operation of a system.

The inventory is divided into 'natural' factors and 'manmade' factors. This is meant to help differentiate those variables that are more or less 'given' in an irrigation systems from those that are more heavily influenced by human intervention.

INVENTORY OF PHYSICAL VARIABLES AFFECTING IRRIGATION OPERATION

A1. Natural Factors:

Water Parameters

1.1 Rainfall
- a. Intensity
- b. Duration
- c. Timing
- d. Spatial variability

1.2 Evapotranspiration
- a. Temperature
- b. Wind
- c. Solar radiation
- d. Relative humidity
- e. Crop and stage of growth
- f. Moisture availability

1.3 Stream Flow Characteristics
- a. Quantity
- b. Variability

1.4 Aquifer Characteristics
- a. Quantity
- b. Yield
- c. Depth

1.5 Water Quality
- a. Salinity
- b. Chemical levels
- c. Silt content
- d. Temperature

Land Parameters

1.6 Soils
- 1.6.1 Mechanical Properties
  - a. Building properties
  - b. Erosivity
- 1.6.2 Water Transmitting Properties
  - a. Percolation rate
  - b. Infiltration rate
  - c. Spatial variability
- 1.6.3 Water Retention Properties
  - a. Texture
  - b. Structure
  - c. Depth
  - d. Spatial variability
- 1.6.4 Salinity and Alkalinity

1.7 Topography
- a. Slope
- b. Variability
- c. Landform characteristics
- d. Altitude

1.8 Watershed Characteristics
- 1.8.1 Size
- 1.8.2 Shape
- 1.8.3 Other land uses

1.9 Health Factors in the Environment

A2. Manmade Factors

Cropping Parameters

2.0 Crop Type
- a. Water demand
- b. Stress sensitivity
- c. Yield response curve
- d. Crop season
- e. Perennial vs. annual
- f. Farming practices (e.g., direct seeding vs. transplanting)

2.1 Cropping Patterns
- 2.1.1 Single Cropping Patterns
  - a. Monoculture
  - b. Rotations

2.1.2 Multiple Cropping Patterns
a.Sequential
Double
Triple
Quadruple
b. Intercropping
Mixed
Row
Strip
Relay

Water Acquisition Factors

2.2 Run of the River and Springs
2.2.1 Head Diversion (weir or barrage)
a. permanent
b. temporary
2.2.2 Lowlift Pump

2.3 Reservoirs and Tanks
2.3.1 Main Reservoir
2.3.2 Distributed Reservoirs

2.4 Groundwater
2.4.1 Well Characteristics
a. depth
b. size
2.4.2 Water Lifting Device
Positive displacement pumps
Variable displacement pumps
Indigenous water lifts

2.5 Conjunctive Use
2.5.1 Surface + Groundwater
2.5.2 Surface + Drainage
2.5.3 Surface + Surface

2.6 Reuse of Drainage Water

Water Distribution Factors

2.7 Scale of the System
2.7.1 Command area
2.7.2 Travel time for flows
2.7.3 Number of Bifurcations and Control Points
2.7.4 Number of Irrigators

2.8 Canal Characteristics
2.8.1 Shape and Size of Cross Section
2.8.2 Slope of Canal
2.8.3 Lining
Masonry surface
Covered membrane
Earthen
2.8.4 Density of Canals(length/ha)
2.8.5 Storage Capacity

2.9 Control Structures

2.9.2 Bifurcations, Divisions
Proportional, fixed
Adjustable, differential
a. Continuous
b. Discrete

2.9.3 Drop Structures
a. Permanent
b. Temporary

2.9.4 Cross Regulators
a. Fixed
b. Adjustable

2.9.5 Sediment Traps

2.9.6 Culverts, Siphons

2.9.7 Outlets
Fixed (fixed weir,orifice, syphon)
Open/Closed (shuttergates)
Stepwise (stoplogs)
Gradual (gated orifice or moveable weir)
Automatic (Neyrpic gates)
a. upstream control
b. downstream control

Water Application Factors

3.0 Field Methods
- 3.0.1 Border Strip
- 3.0.2 Wild Flooding or Water Spreading
- 3.0.3 Furrows
- 3.0.4 Basin
- 3.0.5 Surge

3.1 Drainage
- 3.1.1 Surface
- 3.1.2 Subsurface
- 3.1.3 Wells

Information Factors

3.2 Data Collection Means

3.2.1 Flow Measuring Structures

- Flumes
  - Parshall
  - Cut throat
  - Trapezoidal
  - H Flume
- Weirs
  - Crump
  - Broad crested
  - Sharp crested
- Orifices
- Other Means of Estimating Flow

3.2.2 Weather Measuring Instruments
- Rainguage
- Open Pan Evaporator
- Thermometer
- Barometer

3.2.3 Soil Moisture Measurements
- Plant indicators
- Porous blocks
- Tensiometer
- Feel method

3.2.4 Other Observations
- a. Planting dates
- b. Water in drains
- c. Crop growth stage
- d. Field preparation data

3.3 Data Transfer Means
- 3.3.1 Roads
- 3.3.2 Radio
- 3.3.3 Telephones
  - a. Frequency of regular data transmission
  - b. Frequency of emergency data transmission
- 3.3.4 Word of mouth
  - a. Formal
  - b. Informal

3.4 Data Handling Equipment
- 3.4.1 Computer
- 3.4.2 Manual Files

SURVEY OF SOME CURRENT CLASSIFICATIONS

As one can see from the inventory, there are a large number of attributes that could be used to describe an irrigation system. We are unaware of any systematic attempt to organize attribute lists such as this one, to classify systems. However, there are a number of relatively simple classifications, created ad hoc largely for the purpose of sector reviews. These classifications generally exhibit little coherence among themselves, but we briefly review them as examples of how irrigation professionals currently classify systems. This literature gives a good indication of the kind of information that is actually available for classifications. One of the major constraints to any typological effort is that in order to be immediately useful it must only require information that is easily available. As we shall see later, in some situations, available information may not be sufficient for any typology to be used.

In this brief survey we will confine ourselves to Water Management Synthesis II publications, because they give a good overview of what actually exists in the general literature. The publications chosen were ones where specific classifications were highlighted in the analysis. In most cases, the specific definitions of the classifications are given as stated in the document. In many cases, no exact definition was given.

Water Management Synthesis Reports

Report #1: Indian Subcontinent:

There are brief references to small, medium, and large systems, as well as tubewells and low lift pump systems. No definitions are given.

Report #3: Bangladesh:

The report refers to small, minor, medium, and large systems. A large system is defined as one with 1,000 - 100,000 acres and a single source. The other sizes are not specified. A distinction is also made between wet season and year round irrigation. The types of systems are defined as:

a) Gravity-fed canal system

b) Low lift pumps

c) Deep tubewells

d) Shallow tubewells

e) Hand pumps

f) Traditional methods

Report#5: Thailand:

References are made to reservoir, tanks, and lowlift pump systems. The tank system is defined as one with a capacity of .1 MCM to 40 MCM.

Report #7: General Asian Overview:

Reasonably specific definitions of scale are given:

a) Large: > 10,000 ha

b) Medium: 1,000 - 10,000 ha

c) Small: 100 - 1,000 ha

d) Very Small: <100 ha

For groundwater systems, large wells are defined as having > 40 lps and small wells < 40 lps. A small pumping plant is defined as <120 lps.

Report #14: Peru

There are references to public vs. private, and small vs. large, and distinctions are made among between coastal, sierra, mountain valley and alta selva (high forest) systems.

Report # 26: The Sahel

References to small vs. large scale, community vs. authority managed, and total vs. supplemental systems.

Report #35: India

References are made to major, minor and medium systems, as well as groundwater and hill area projects. Government department responsibility is determined by the surface area of the systems. The irrigation department is responsible for systems >40 ha, the agricultural department for systems <40ha, and the planning commission is only concerned with systems >2,000 ha.

In describing AID funded projects, attributes included were:

a) Scale

b) Cropping intensity (two season, *kharif*, *rabi*)

c) Storage (freeboard, max. height of dam, design flood)

d) Main canal length

e) Number of structures

f) Lining

g) Siltation rate

h) Age of the reservoir

Report #37: African Overview

The basic differentiation is between large scale (>500 ha) and small-scale (<200ha). There was no medium scale mentioned. Small scale categories included:

a) Runoff farming

b) River flood plains (wet season, dry season, non-season)

c) Channel commanded areas

d) Mongrove/costal

e) Private vs. public

f) Geographical region (desert, semi-desert,dry savanna, humid savanna, humid tropical, high tropical, and subtropical plateau)

Report #40: Kenya

Small scale systems are defined as those less than 500ha, owned and operated by local users. Systems are also differentiated by their organizational system and by whether their purpose was drought relief.

Report #42: Egypt

The main distinction is between Old lands and Old-new lands. This distinction was determined by differences in soil type, on-farm management, drainage and salinity characteristics, and methods of distribution.

Report #51: Mauritania

System types are:

a) Calabash labor intensive: hand carried from well or river.

b) Flood irrigation: depressional irrigation when water table recedes after rainy season.

c) Floodland irrigation: water used from small dams built to trap runoff.

d) Recession irrigation: uses residual soil moisture from floods.

Differences in scale noted are:

a) Small village perimeter

b) Large-scale perimeter

c) Private small-scale perimeter

Report #63: Research in Africa

This report makes the main distinction between independent and public irrigation. Independent systems are categorized with the descriptors large, small, NGO sponsored, and private commercial schemes. The small-scale schemes are further divided into clan-based vs. bureaucratic management. Descriptions are provided of each scheme's origin, goals, technology, ownership of water, structures, and the functions of the water user associations.

REVIEW OF GENERAL CLASSIFICATIONS

The point that this brief review makes is that irrigation science clearly lacks the ability to unambiguously describe systems. Even within the WMS project, researchers have made little effort to standardize the definitions that are used in classifications (large, small, etc.) among and even within countries. This is understandable because the focus of the documents reviewed had other specific purposes that weren't adversely affected by the lack of a coherent classification system. However this makes comparing and contrasting experiences from different areas very difficult.

It is important to recognize that there is often a local terminology or method of classification that may not be readily grasped by the casual observer, although it will be well understood by the irrigation people within the country. For example, tubewells in Bangladesh are often referred to as deep or shallow. To much of the world these terms would seem to refer to the depth of the well. In Bangladesh, however, these terms commonly describe the capacity of the well: a deep well generally having a capacity of about 5 cfs, while shallow tubewells have a capacity of 1 or 2 cfs or less. These terms may also be used to indicate the type of pumps in use.

Local terms are commonly used to depict complex agroclimatic conditions. Again in Bangladesh, rice crops are grown in the *Boro, Aus* , or *Aman* seasons. Bangladeshies intuitively understand these terms to imply rather specific sets of environmental conditions, cropping practices, water availability, and the like. In Indonesia, the scale of an irrigation systems is usually defined as technical, semi-technical, or simple. These terms roughly relate to large,

medium, and small, respectively used in most of the world. The complexity or sophistication of the technology is only very generally related to these Indonesian terms. Methods for rotation of irrigation water distribution in a given country are often known by terms that have very specific meanings. In India *warabundi* and *sagepoly* refer to water distribution techniques with well defined meanings to irrigation engineers.

Country specific terms such as those mentioned above are often clearly defined when used internally by the irrigation establishments. Readers of irrigation literature, however, may find it a little confusing, and it places many barriers to effectively applying lessons learned in one system to other similar systems.

Our literature review did help us find some common variables that can be used to produce a useful irrigation typology. The variables listed below were chosen for two major reasons. They are either extremely important in the operation of an irrigation system by itself, or they are good general classifications that encompass a large number of specific variables listed in the inventory.

1) Cropping System

2) Scale

3) Water Supply

4) Extent of Irrigation

5) Topography

6) Climatic Type

7) Soil Type

8) Structural System

9) Age

Note that we confined ourselves to physical variables. Although these were the most prevalent in the literature, a number of social and economic variables are also commonly used. The most common distinction is between private vs. government, which is probably more important than most physical descriptors.

The main purpose of the following section is to propose a general typology that can be used for 'irrigation system demographics'. In order to do this, we first review the variables listed above, and then choose the categories that appear to be the most appropriate for the typology.

Cropping System: Paddy-Based vs Non-Paddy-Based

The cropping system is a central component of the irrigation enterprise, and most other factors are influenced by crop demands. There are many ways to distinguish cropping systems (both temporal and spatial). One example of a temporal distinction is that between annual and perennial crops, but the most general and perhaps most useful is between paddy-based and non-paddy-based cropping systems. This differentiation is made because paddy irrigation is significantly different from other forms of irrigation.

a) Paddy fields are ponded so that the root zone is continuously saturated, while non-rice crops require an unsaturated soil.

b) Paddy rice, especially high-yielding varieties, are very sensitive to water stress with yield responses that resemble step functions. Since yields can be so dramatically affected by the water supply, system operation must be much more careful and err on the side of too much water.

c) There is a different definition for over irrigation. In paddy, neither percolation

nor evaporation are significantly affected by extra water. Physical factors for paddy that determine over irrigation, unlike other crops, are dike height and plant submergence.

d) It is best suited and thus more likely to be in a continuous operational mode. Distribution can be from paddy to paddy, and this tends to equalize distribution.

e) Water is used for weed control in paddy.

f) Paddy requires considerably more water than most other crops.

Besides the physical distinction (which have significant operational and organizational ramifications), there are other reasons to make paddy-based cultivation a distinct category. Paddy rice dominates irrigated agriculture in much of Asia and is the most important food crop in many countries. Additionally, it has been the focus of most of the research done in irrigation.

The actual division between paddy and non-paddy based systems can be complicated where cropping is mixed, and paddy is grown in only one season. Nevertheless, paddy demands will tend to determine how the system is operated because of its stress sensitivity, and even a small percentage of paddy can qualify the system as paddy-based.

The cropping system includes all of the parameters in 1.9 and 2.0 of the system inventory. We have tried to reduce these to the most significant. The paddy vs. non-paddy distinction, however, has implications for many of the other natural and manmade parameters.

Scale

There are three aspects of scale that are important: the physical area of the system, the number of levels, and the number of irrigators.

1) Physical Area

The operation of a system is directly affected by the physical area that it encompasses. For example, one of the consequences of an increase in area is that the travel time of the water flow increases. This may become very important in systems such as 100 km long Indian systems, where travel times can be 5-10 days. This restricts the responsiveness of the water distribution system and necessitates more long-term planning.

In large systems, communication among operators and irrigators is frequently more difficult simply because the distances are so large. Responsive operating strategies are difficult to enact and systems tend to operate more rigidly.

An increase in physical size also usually means a concomitant increase in the size of the irrigation organization, which has "always proved to be the single most important variable influencing the choice of an organizational structure". (Bottrall, 1981) The larger the organization, the greater the need for coordination and 'agency' involvement in the system operation. Additionally, as the system gets larger, heterogeneity of its rainfall, soils, cropping patterns and even climate in mountainous regions, also increases, and this can introduce significant operational complexities.

As we saw from the literature review, there are many ways to describe physical area ranging from 'very small' to 'very large'. The most common

distinction is between small, medium, and large systems, which are assigned specific meanings depending on the country.

2) Number of Levels

Levels in a system can be defined from both physical and organizational standpoints. We are concerned with the levels of operation defined by the physical division of flow. A canal remains at the same level as long as the offtakes do not reduce its flow by more than 40 percent. All of the offtake canals are part of the next level. If the bifurcation divides the flow evenly , subsystems are created. Most systems vary between one and four levels, which range from the main canal to the field channels.

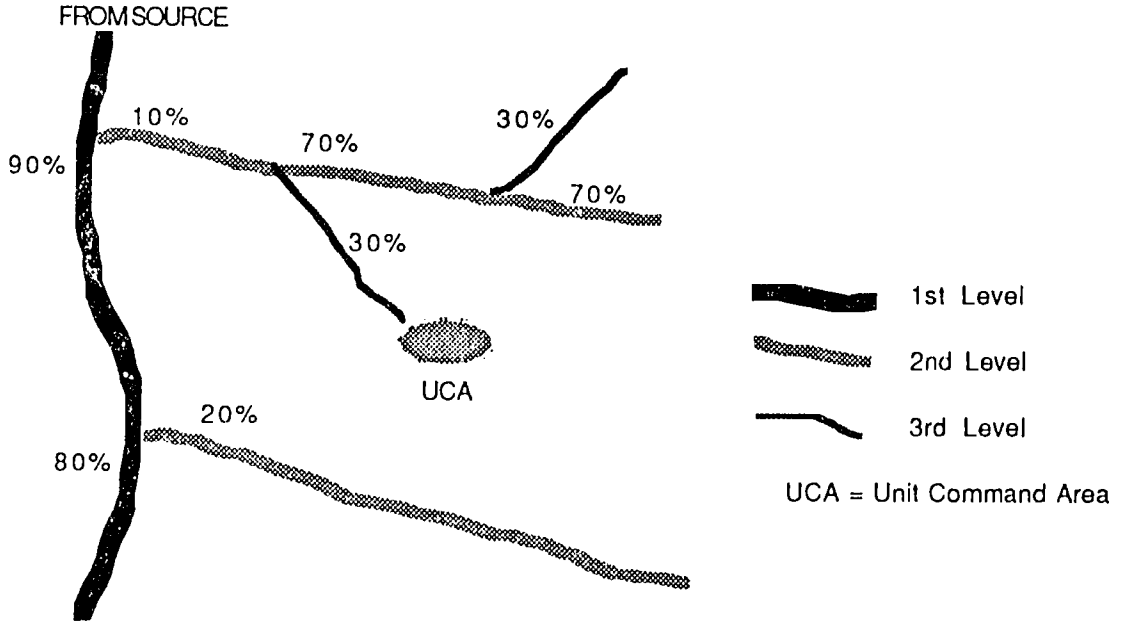


Figure 2: Illustration of Water Flows in a Three-Level System.

There is some correlation between levels and size, which is shown below:

Area	Typical Levels	Examples
Under 100 ha	2-3	Goinre system in Burkina Faso
100-10,000 ha	3-5	Chhuto Mouja in Nepal
10,000+	5+	Gal Oya in Sri Lanka

Unfortunately this correlation is rough. Some large systems have only two levels because their command area is long and extended, and there are small, intensely cultivated systems with four levels.

3) Number of Irrigators

One essential aspect of scale that the above categories do not address is the number of irrigation units or farmers in the system. A system in Colorado with only 100 farmers may have the same area and number of levels as an Indian system with 10,000 farmers, but system operation will be very different. Another level of complexity is added when there is variability in farm sizes, crops, and cropping practices.

As complexity increases so do the demands on management to ensure that different and dispersed activities are working together smoothly to achieve the

allocation objectives. This requires effective communication and coordination. There is often an increased need for conflict resolution and involvement in other political factors that greatly complicate the life of the operators.

Water Supply

Water supply is a highly significant variable. The important aspects are the type of source and its supply characteristics.

Type of Source

The most common distinction is the type of water source:

a) Reservoir or tank

b) Run-of-the-River

c) Groundwater

d) Conjunctive

Within these four categories, there are further distinctions such as whether a run-of-the-river system is dependent on gravity or lowlift devices, the type of reservoir (large, tank, distributed), and the type of well (shallow, deep etc.). Information about the type of source is usually readily available and can be used to predict technologies in use and water supply characteristics. In general, reservoirs and groundwater sources are more stable than run-of-the-river, but many management factors also significantly influence stability. In trying to predict how water is managed based on technologies used, it is important to recognize that although certain technologies present difficulties for operation (such as pump systems requiring a reliable supply of power and spare parts), their effects lie not in the technologies themselves, but in the cost and variability of the supply. If pumped water is managed more carefully by farmers it is

because such water is usually more costly. In gravity-fed hill irrigation systems in Nepal, for example, where much effort must be expended by users to get and maintain a supply of water, it is managed as carefully as in any pump system (Yoder and Martin, 1987).

Supply Characteristics

In order to adequately describe the water supply, there are three attributes that must be considered - the average amount of available water in relation to the demand and the temporal and spatial variability in the supply. Figure 3 is a typical water supply situation.

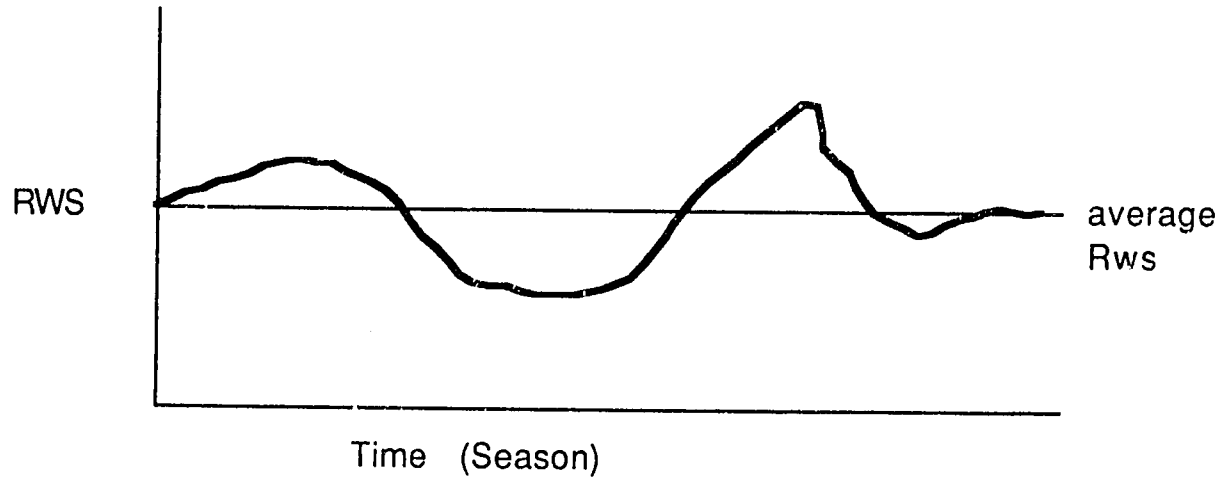


Figure 3: Graph of Relative Water Supply over One Season.

Relative Water Supply

The amount of water available relative to the irrigation demand (RWS) has a significant effect on system operation. We define RWS as supply at the head of

the system divided by the demand as determined by evapotranspiration (ET), seepage, and percolation.

RWS = Supply/Demand

RWS = Irrigation water + Precipitation / ET + Seepage + Percolation

The amount of pressure users put on the operators and the social tension in the system is inversely related to RWS (Keller, 1986). As discussed in Chapter 3, the operating strategy of a system with a low RWS will be more likely to include intensively controlled rotations. We designate three ranges for RWS.

< 1 : Low RWS. The water supply is below actual requirements. This will usually require strict control and higher degrees of management.

1 - 2 : Medium RWS. A variety of operational strategies can be successfully employed. Moderate amounts of management effort are needed.

>2 : High RWS. More likely to have farmer controlled (demand) schedules. Greatest flexibility in operation.

Temporal and Spatial Stability of the Supply

Other attributes of the water source that directly influence operation are temporal and spatial stability. There are a number of ways to describe this attribute. One way to quantify temporal variability is to put limits on some of the statistical measures. High variation in the supply can be defined as a coefficient of variation (standard deviation/mean RWS) of more than 25 percent. Low

variation is then a coefficient of variation below 25 percent. The operational implication is that supplies with high variation will be more difficult to use effectively than ones with low variation. Supplies with high variation will require more management effort, which may adversely affect the timeliness and adequacy of the irrigation supply for system users.

This characterization can be further refined by recognizing that supplies greater than a certain level do not affect operation. Thus, we are interested in the variation in supply within a certain range and could ignore RWS of, say, 3.

Even with this refinement, our description of RWS may not adequately characterize all situations. For example:

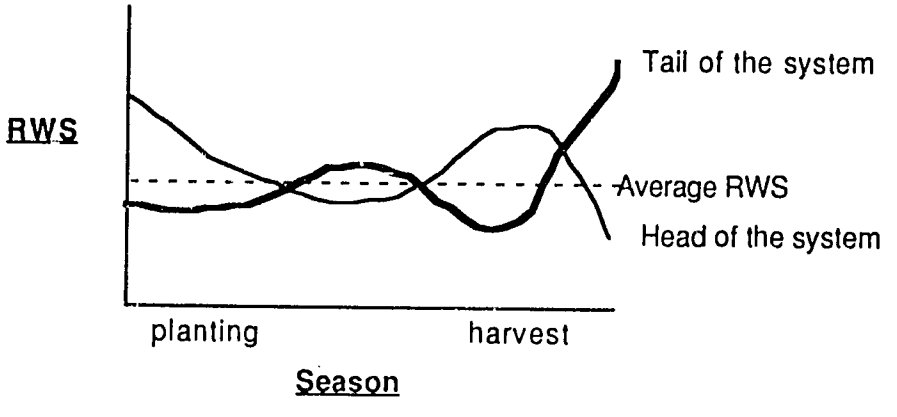


Figure 4: Differences in RWS Variation.

The two supply curves have the same mean and variation, but actual field condition are quite different. One way of dealing with this is to calculate RWS during critical crop periods. This calculation results in indicators such as the Stress Day Index.

The position of the farmer or system in the overall command area of the source can also affect its water stability. This is based on the simple fact that unlike fixed land and mineral resources, water flows. Thus, at any location and time the status of this resource is highly dependent on occurrences at other points in the water system. The location of an irrigator in a system determines to a significant degree the stability of supply. For example, given the river area below (Figure 5):

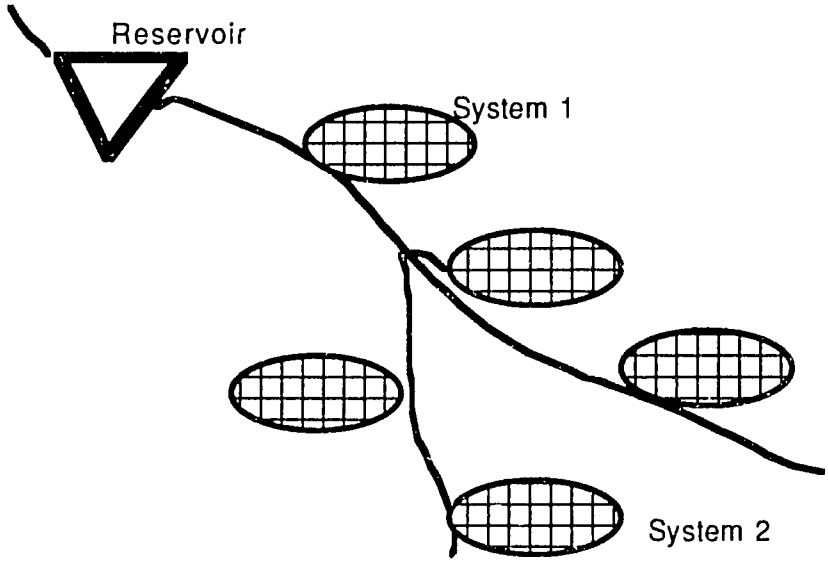


Figure 5. Example of the Importance of System Position.

System 1 is likely to have a more stable supply than system 2 because it is closer to the source. In a similar manner, this applies to position in a watershed.

Further, the position of the system in relation to the water supply may also determine the primary operational concern. If acquisition is difficult, no matter what the state of the rest of the system, it will be next to impossible to produce a plentiful crop. This condition can serve to unify users.

The main problem with using temporal and spatial aspects of the water supply to characterize systems is in coming up with useful classifications. At this point, the data needed for such classifications are very difficult to obtain, and no classifications are currently in use.

Extent of Irrigation

Two broad types of irrigation capability can be catagorized: irrigation to supplement natural rainfall and irrigation to provide all or almost all of the crop water needs (Levine, 1982). Although this classification is not found in the inventory, it does encompass soil, climatic, and cropping system parameters in a way that is very useful.

Supplemental irrigation is usually less expensive and spreads investment cost over a larger number of people than complete irrigation systems. Supplemental irrigation is often practiced in subhumid areas, where soils have poor water retentive properties, at the beginning or end of a wet season, and often with lower value crops.

Complete irrigation may be required because of the climate and the crop. It is also used to reduce risk by stabilizing year-to-year variation in agricultural production and to increase the potential magnitude of that output. Complete irrigation may also encourage the adoption of high-value crops and more productive technologies.

Topography: Mountain vs. Plain Irrigation

Mountain systems are easily distinguished from plain irrigation because:

a) Mountain systems are generally small in scale (less than 100 ha).

b) The topographical setting of mountain systems makes transportation of inputs and outputs difficult, and thus these systems are generally more remote and outside of governmental spheres of influence. As a result, most mountain systems are indigenously initiated and user operated, removed from commercial markets, and economically and politically isolated.

c) The topography may make many operational activities, such as frequent opening and closing of gates and canal maintenance, difficult.

d) Water acquisition is generally a major focus in mountain systems. Canal construction can be difficult, and flash floods from mountain runoff often wash out the acquisition structures and canals. The need to secure a reliable water supply is a strong incentive to users for unification and is a promoter of equity.

e) The mountain environment has distinct hydrological conditions and constraints. Drainage, for example, is rarely a problem, but erosion because of high water velocities appears to be an ubiquitous problem. Seepage losses are almost always greater than on the plains.

f) Finally, mountain irrigation usually requires a greater investment in field preparation, especially in land leveling, terracing, etc.

Climatic Zones

Irrigation systems are operated in a wide variety of agroecological

environments that affect irrigation practices. Distinguishing major types of climates and associated characteristics is an initial step in the classification of systems. These classifications encompass many of the water and land parameters listed in the inventory.

Arid Climate: (Annual rainfall < 250mm, ET/rainfall > 1, and dry season > 6 months) Usually crops cannot be grown without supplemental irrigation in arid climates, and most systems rely entirely on irrigation water. Rains are infrequent, often very intense, and completely unpredictable. The climate favors very high evapotranspiration rates because the solar radiation values are very high and air humidity is low.

Semiarid Climate: (Annual rainfall = 250 - 500mm, ET/rainfall > 1, and dry season 4 to 5 months) Semiarid regions have an even more variable climate than that of arid regions, and thus it is difficult to reduce the classification to a single climatological group. In semiarid regions, rainfall deficiencies cause requirements for crop irrigation during at least part of the growing season. Supplemental irrigation is thus quite important for a viable agriculture, and dry land farming is restricted to a few drought resistant species. Major recognized climatological entities that have distinctive temperature and precipitation patterns are savanna, mediterranean, and steppe climates.

Subhumid Climate: (Annual rainfall = 500 - 750 mm, ET/rainfall = 1, and dry season 1 to 3 months) Subhumid climates are widespread throughout both hemispheres. Precipitation patterns differ little from those of humid climates, but total rainfall is lower. Solar radiation values are generally higher,

indicating that evaporation may be considerable. In many cases, there is one marked, dry period in which irrigation is often needed. In other cases, although the average rainfall is high throughout the year, there are frequent drought periods that can upset the water balance of crops.

Humid Climate: (Annual rainfall > 750mm, ET/rainfall >1, and no dry season) Humid climates are those for which precipitation equals or exceeds the evaporative demand of the atmosphere for most periods of the year. Common reasons for irrigation in this climate are soil conditions, such as shallow sandy soils, and as a risk minimization strategy. Extensive cloud cover reduces incident solar radiation and decreases evaporation.

The main usef of these classifications is that they give some idea of the rainfall, ET patterns and possible crops, and thus the likelihood of the necessity of supplemental or complete irrigation systems. However, climatic type is often too general to be of much help and may even be deceptive. We still need to know the exact quantity of precipitation and evapotranspiration, as well as the temporal variation in these factors. For example, the Punjab in Pakistan is an arid climate, but irrigation systems are fed by rivers that start in a humid climate, and thus supplies are much more predictable than would be expected. The definition of arid, semiarid, etc. may also be a problem because there are a number of different criteria that could be used, and the same system might be classified differently by separate researchers (e.g., using the number of dry months rather than total precipitation to define 'arid').

Environmental Type : Another way of more broadly describing the climate as it affects irrigation is to look at the environment. Several characteristics of the water supply and cropping system that directly affect operators were chosen to construct a simple four-cell typology.

Water Supply	Cropping System: Low Diversity	Cropping System: High Diversity
Static	I	II
Dynamic	III	IV

Figure 6: Environmental Types Using Cropping and Water Supply Descriptors

Diversity Axes: These refer to the degree of spatial diversity in factors that affect the cropping parameters, such as the degree of soil variability, and the number of crops and cropping patterns used. This results in either a homogeneous or heterogeneous cropping system.

Stability Axes: These refer to the temporal changes, primarily in the water parameters. A high degree of fluctuation in water supply and demand contribute to a more dynamic environment, whereas a predictable, stable water supply creates a static environment.

Classifications of various environments and the effect of associated characteristics on system operation are shown below.

Type	*Example*	*Effect on System Operation*
I	An arid environment with monoculture.	Only minor information problems. Can design long-range operation and implement without major alterations.
II	Variety of cropping patterns in system, but with a predictable water supply	Similar problems to type 1 but a higher degree of uncertainty in implementation because of complexity.
III	Homogeneous crops but highly variable water supply	Difficulty in planning and executing operational plans.
IV	Diverse cropping patterns and unpredictable water supply and demand	Major information problems, tentative sets of strategies that can have major alterations in their execution.

Soil Type

There are a number of ways to classify soils that are irrigated, ranging from the overly simple (favorable, unfavorable) to the detailed USDA/SCS classification system.

Soil properties that affect operation of irrigation systems include:

a) Mechanical Properties: Highly erosive soils limit the rate at which water can be applied to or discharged from the field and restrict options for canal design. Poor building properties of the soil indirectly affect system operation by creating maintenance problems and structural complications.

b) Water Retention Properties: The amount of water available to plants in the soil profile is a function of the texture, structure, and rooting depth. These play a major role in determining the frequency with which water must be applied to most crops other than rice. Retentive soils such as clays or loams, with a high organic matter content, give a certain amount of flexibility to system operation because of soil buffering capacity. Well drained sandy soils, on the other hand, require more frequent and careful management.

c) Water Transmitting Properties: These properties can affect both the supply of and demand for water in the system. The speed with which water moves into and through the soil profile will determine the rate of water application, and this in turn places constraints on the scheduling of irrigation turns. The determination of safe intake rates for soils is one of the most important considerations in the planning of operational schedules for most non-paddy crops. Low infiltration can be very good for crops such as rice but can pose some problems in furrow systems because of the timing requirements.

One of the most problematic aspects of soil description is the extreme variability in soil physical properties that can occur in even small irrigation systems. For example, within the command area of a single distributary of the Gal Oya system, a four-fold difference in soil water availability was found due to differences in soil characteristics. (Zolezzi, 1986) At this point, a viable soil classification system for use in irrigation typologies is unlikely.

Structural System

There are two structural aspects of an irrigation system that are easily described: the canals and the control structures. Canals can vary by lining (concrete, earthen), which influences seepage and permissible water velocity, as well as by size (including freeboard). Continuous systems require much smaller canals than those with rotational schedules.

Control structures in a system exist on a continuum between adjustable and non-adjustable. Only limited changes can be make with non-adjustable structures, while adjustable structures accommodate a wide variety of flow situations. This continuum and its respective characteristics are shown below.

Non-Adjustable ----------			**Adjustable**
Fixed Controls	On-off controls	Stepwise adjusted	Gradually adjusted
Minimum canal freeboard			Maximum canal freeboard
Proportional Division			Differential Division
Low operational complexity			High Operational Complexity

To a certain extent, there is also a correlation between rigid and responsive operating strategies, and non-adjustable, adjustable controls respectively. The main problem with using structures as a classification variable is in developing suitable categories. We propose three simple classifications: low, medium and high control structural systems.

Type	Characteristics
Low Control	No controls or fixed control with no measuring structures.
Medium Control	On-off and stepwise adjusted controls with some measuring devices.
High Control	Gradually adjusted control structures with many measuring devices.

This classification system has two main deficiencies. First, within a system there can be a variety of structural types used (e.g., adjustable for the main level and fixed for the field level), and there does not appear to be any simple way to describe these hybrid systems. Second, it does not take into account the density of control structures, which may be an even better measure of extent of control than the type of structure.

Age

The question of how to distinguish among various ages of systems (i.e., old vs. new) is also not simple. However, it is clear that the length of time a system has been in operation is a significant determinant of the level of performance. As with any technical system, the operators and farmers gradually learn how to operate the system at its potential. The time frame of this learning curve can be from a few months to many years, depending on the complexity of the system and the history of irrigation in the region. Along with the learning process, modifications in the design are gradually made to fit the priorities and goals of

the people involved. This is to be expected because no design is ideally matched to the conditions in which it operates.

The physical condition of the system deteriorates over time, and this detrimentally affects system operation. Additionally, the external environment may change dramatically as transportation infrastructure is built, markets are developed and inputs become more available, and this in turn will affect system operation. Thus systems that vary in age are usually not readily comparable. They have different knowledge bases, institutional and operational capacities, and often differ physically because of adaptive change.

Arguments have been made that in the early years of a newly established irrigation settlement scheme, there are strong reasons for the close supervision of farmers' irrigation practices, because many may have no experience with irrigation(Bottrall, 1981). This implies the need for more centralization in new government projects and gradual decentralization as the skills of the farmer and operators increase. To complicate things further, the development of large irrigation systems can take years, even decades. No large government system in India has ever been completed, and some have been under construction for over 30 years.

The question of how age affects system operation raises some interesting issues. If the system has been established for a long time, external conditions may have changed so dramatically that many of the design assumptions are no longer valid. For example, the 'duty' concept for distributing water is part of the historical legacy in Sri Lanka and India. Although it may have been suited to the original conditions of homogeneous crops and water abundance, it is quite unworkable in the present situation of scarce water supplies, variable soils, and 'dry' and paddy crop mixtures (Bottrall, 1981).

TYPOLOGY FOR GENERAL IRRIGATION DEMOGRAPHICS

Now that we have listed the physical attributes of an irrigation system and discussed the most important classifications that encompass these attributes, we are ready to construct a general classification system or typology. As pointed out in the first chapter, there are three major issues in the development of a typology:

(A) The objectives to be served by a particular classification system,

(B) The descriptive basis upon which a system is founded, and,

(C) The methodologies employed to establish and validate a system

Each of these issues will be addressed in subsequent sections:

(A) The first issue is important because researchers attempting to develop typologies should not view their development, in and of itself , as an end. Rather, they should view the typology as a tool to increase their ability to interpret, predict, or control some facet of irrigation.

The researcher has to initially chose between two objectives. He/she can elect to develop a system that has utility for a specific purpose, or the investigator can devise a more universal system with a variety of applications. For example, a classification of plants based on growth form will not reflect the natural taxa, but it might be useful for specific landscaping purposes, even if it does not assist the advancement of evolutionary biology. Conversely, a classification of irrigation systems by maintenance requirements may be useful for agency

planning but may not help clarify the theoretical issues of water use efficiency. Irrigation systems cannot be classified like animals and plants because there is no principle of "propinquity of descent" by which to guide the classification. Although one universal classification system is thus unlikely, there is a lot of room for more specific typologies.

For the purpose of this chapter, we chose the objective of identifying major system "types" so that research activities can be designed for priority systems, and representative sites for management research can be more accurately selected. This typology or ones like it could become a basic tool used by irrigation institutions in their process of determining research priorities. If an agency could establish that one kind of system (i.e., small, supplemental, paddy-based) is dominant in an area of interest, research efforts could be tailored to specific problems faced by that type.

(B) The descriptive basis of the typology involves addressing two fundamental questions:

1) How many attributes are needed to adequately characterize a system?

2) How similar do systems have to be to be classed together?

It should be made clear that any general typology will have its limitations. There will undoubtedly be exceptions that don't 'fit', and there will be many applications for which it will not be appropriate. It is certain, however, that almost any classification system is better than the state of confusion that exists now. Even if the current typology is crude, it can be refined over time.

As to the question of exceptions, every typology has them. Even in the well-developed science of biological systematics, there are still many organisms that do not readily fit into any of the current classifications. The important question is whether the classification captures a significant portion of the irrigation

systems in question. There will always be systems in the fringes, but these will probably not warrant abandoning the classification system.

The complications of spatial and temporal diversity as well as the continuous nature of irrigation systems also must be dealt with in the classification system. There has been a lot of debate in irrigation circles about how to divide various attributes into manageable categories. Is 'small' less that 50 ha or is it less than 500 ha.? The point we would like to stress is that it doesn't really matter what dividing points are chosen as long as they are consistently used. The divisions we have made below are open to change depending on the user's situation.

We chose five major physical attributes as the core of our general typology. These were based on a survey of irrigation professionals(Appendix) and a review of the literature. We feel that any analytically useful typology must include at least the following physical attributes:

1) Cropping System: Paddy Based, Non-paddy Based
2) Physical Area: Large, Medium, Small
3) Water Source: Reservoir, Run-of-the-River, Groundwater, Conjunctive
4) Extent of Irrigation: Supplemental, Complete
5) Topography: Mountain, Plain

These attributes are mapped out in a tree diagram in Figure 7. A first impression might be that the typology is too complex. Even with only five attributes, there are almost fifty possible system types. However, further inspection shows that in any particular region only a few of the possible types will be represented. We should emphasize that even though this typology includes only physical attributes, there are other equally important social attributes that we did not use.

(C) Validation of this typology is the next step. The methodology of validation will have to include an iterative process of actual application to a real region and refinement of the specific classifications. The typology must be tailored to the specific purpose of the user and the context in which it is used.

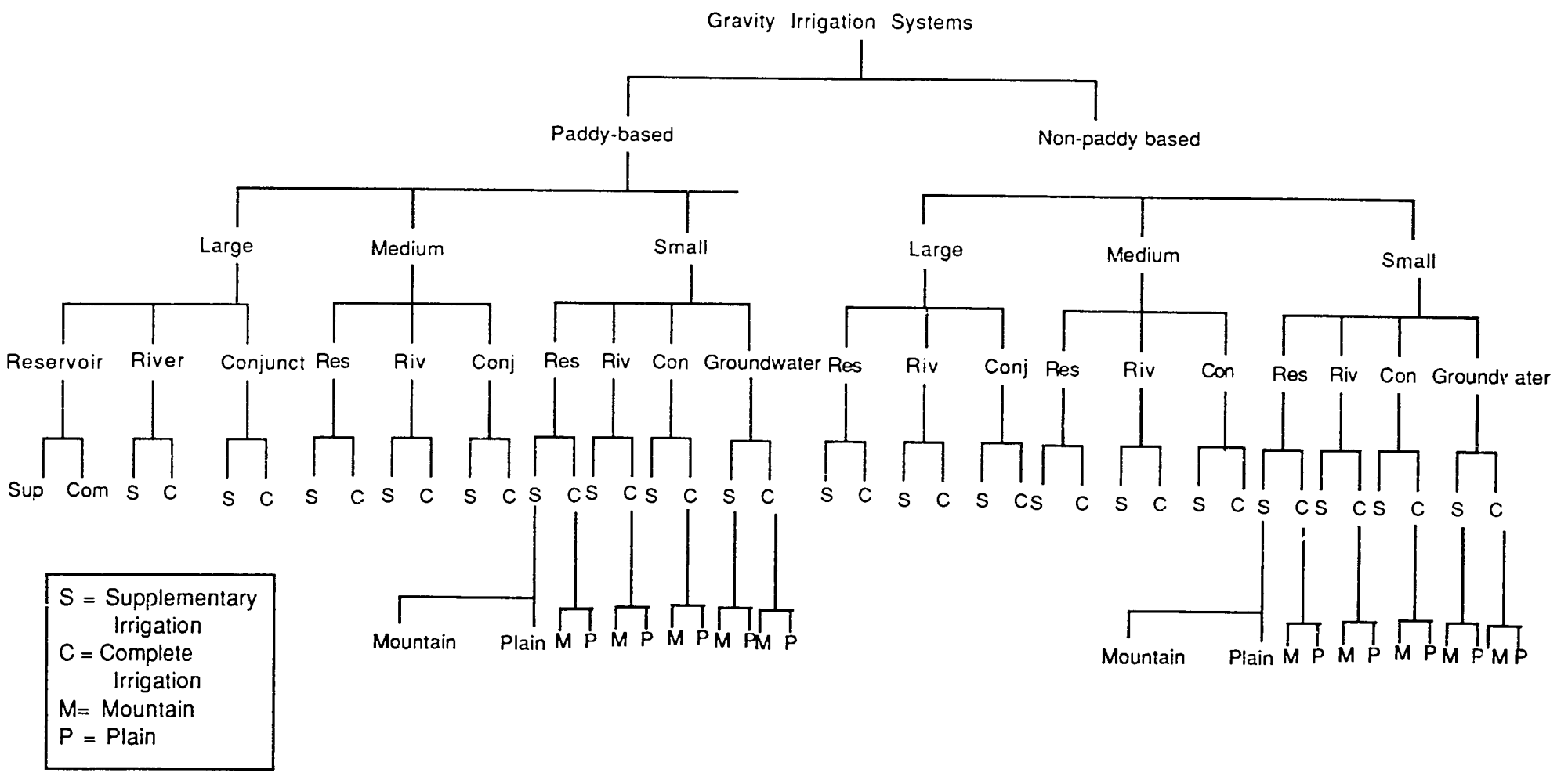


Figure 7: Typological Tree for General Irrigation Demographics.

Chapter 3

THE DEVELOPMENT OF AN OPERATIONAL TYPOLOGY

The purpose of this section is to go beyond the general approach and develop a a typology that can be used in functional studies focused on system operation. This typology will help clarify the different ways a system can be operated and aid in identifing systems with analogous operational conditions. By operation we mean the activities associated with distributing water in a gravity irrigation system. The strategies used to distribute this water are influenced by a wide diversity of factors. These include the physical, the organizational and the social systems, as well as the economic environment. Because of the enormous complexity, we will constantly be faced with the dilemma of either providing too much detail or oversimplifying the situation. A gross conceptual model is illustrated below:

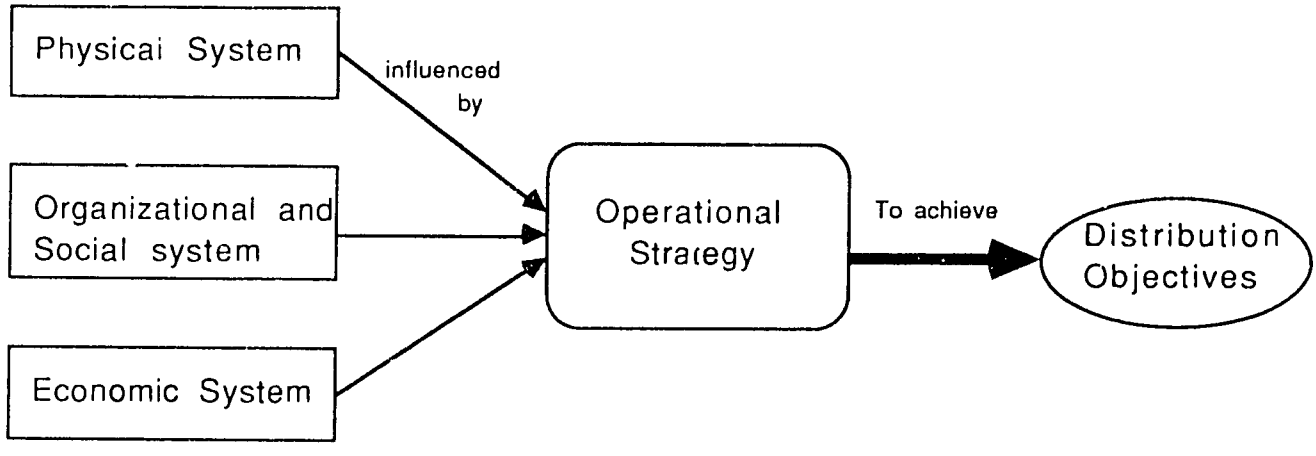


Figure 8: Factors that Influence Operational Strategy.

WATER DISTRIBUTION OBJECTIVES

The operational strategy is the means that irrigation organizations use to achieve their distribution objectives. These objectives can vary significantly among systems and system users and can markedly affect operational strategies. It is important to note that we mainly take the point of view of the operators in distinguishing the distribution objectives from the system objectives, which can include sociopolitical, geopolitica,l and commercial concerns. The distribution objectives from the system operator point of view include maximizing:

1) Equity: This objective is often realized through water rights and can be defined:

a. By land area

b. Per farmer

c. By production potential

d. By share

2) Utility as defined in relation to:

a. Labor use

b. Land use

c. Water use

d. Importance of the crop

The two primary objectives are subject to the following constraints:

1) Minimizing conflict among members and groups affected by the system.

2) Long-term, environmental stability.

Equity, in general, is the most fundamental of distribution objectives. In its simple forms it results in proportional division among users, which is relatively easy to accomplish. Equity considerations can, however, result in very complicated procedures (Maas and Anderson, 1986).

Utility (maximizing output in relation to some limiting factor), on the other hand, is almost always more difficult to operationalize because it requires greater quantities of information and the physical and organizational infrastructure to optimally respond to changing conditions.

The above objectives may be stated outright, but people who operate the system (agency personnel or hired canal tenders) but often have unstated objectives that affect system operation. These include:

A) Minimizing pressure on themselves. (i.e., bowing to political clout, threats of losing ones job and even physical intimidation).

B) Maximizing illegal income (i.e., bribery), including indirect bribes (promotions etc.).

Farmers, on the other hand, are primarily interested in decreasing risk while increasing their income. Chambers (1986) argues that from the farmer's point of view, the irrigation water supply is 'good' if it meets the following four criteria.

1) Adequate: What quantities the farmer regards as adequate may depend on other aspects of the supply and may include 'overwatering' and building up of

buffer stocks in the field.

2) Predictable: Farmers need to know how much and when the water is coming so that agricultural activities can be optimized.

3) Timely for the Crops: The irrigation supply should meet the water requirements of the crops, especially during stress sensitive periods.

4) Convenient: Farmers want to obtain water with a minimum of trouble and time. This means minimizing red-tape, conflicts,and making the water flows manageable and available at convenient times. (eg., not during the night or during festivals).

Besides these criteria, we would add that farmers are also concerned with

5) Low Cost: Farmers want water at the lowest possible cost. They are usually willing to pay more if service improves.

It can be argued that if a supply is predictable, the farmers will adjust their resources to optimize the inputs of capital and labor. Once predictability has been achieved, timeliness and adequacy goals can realistically be pursued.

Allocation

The objectives of a water distribution system are usually translated into, or are derived from, some sort of water rights. These rights can be associated with either a specific amount of water per user, a fixed percentage of the water supply, or a specified duration of access to flow in the delivery system. After considering the available water resources, these rights are translated into specific operational rules that determine under what conditions rights are exercised, as well as the day-to-day operational procedures. The rules and rights can be extremely simple (take whatever is wanted) or very complex (i.e., the rules in the Valencia system, Maas and Anderson, 1986). The process used to

determine to allocation rules is shown below:

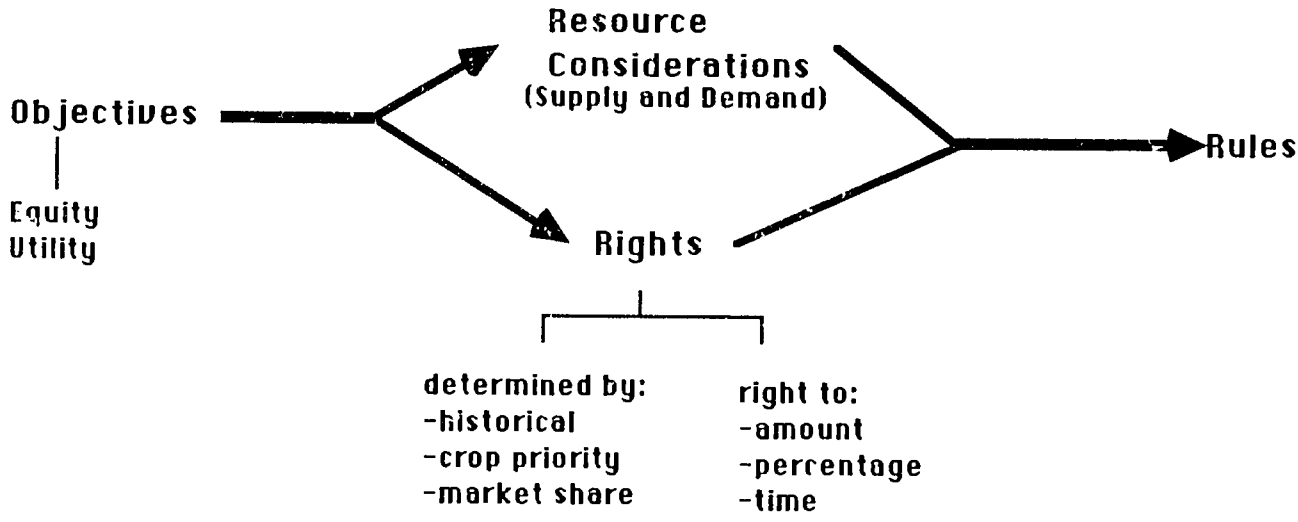


Figure 9: Determination of Allocation Rules

Specific water rights may have existed prior to the construction of the system and the identification of specific objectives, but they are still usually based on equity and/or utility issues.

OPERATIONAL STRATEGIES AS DETERMINED BY SYSTEM CHARACTERISTICS AND CAPACITY

We can visualize the attributes of an irrigation system as being divided into given characteristics and system capacity. An operational strategy harmonizes these two. To a certain extent both the requirements and the capacity can be altered.

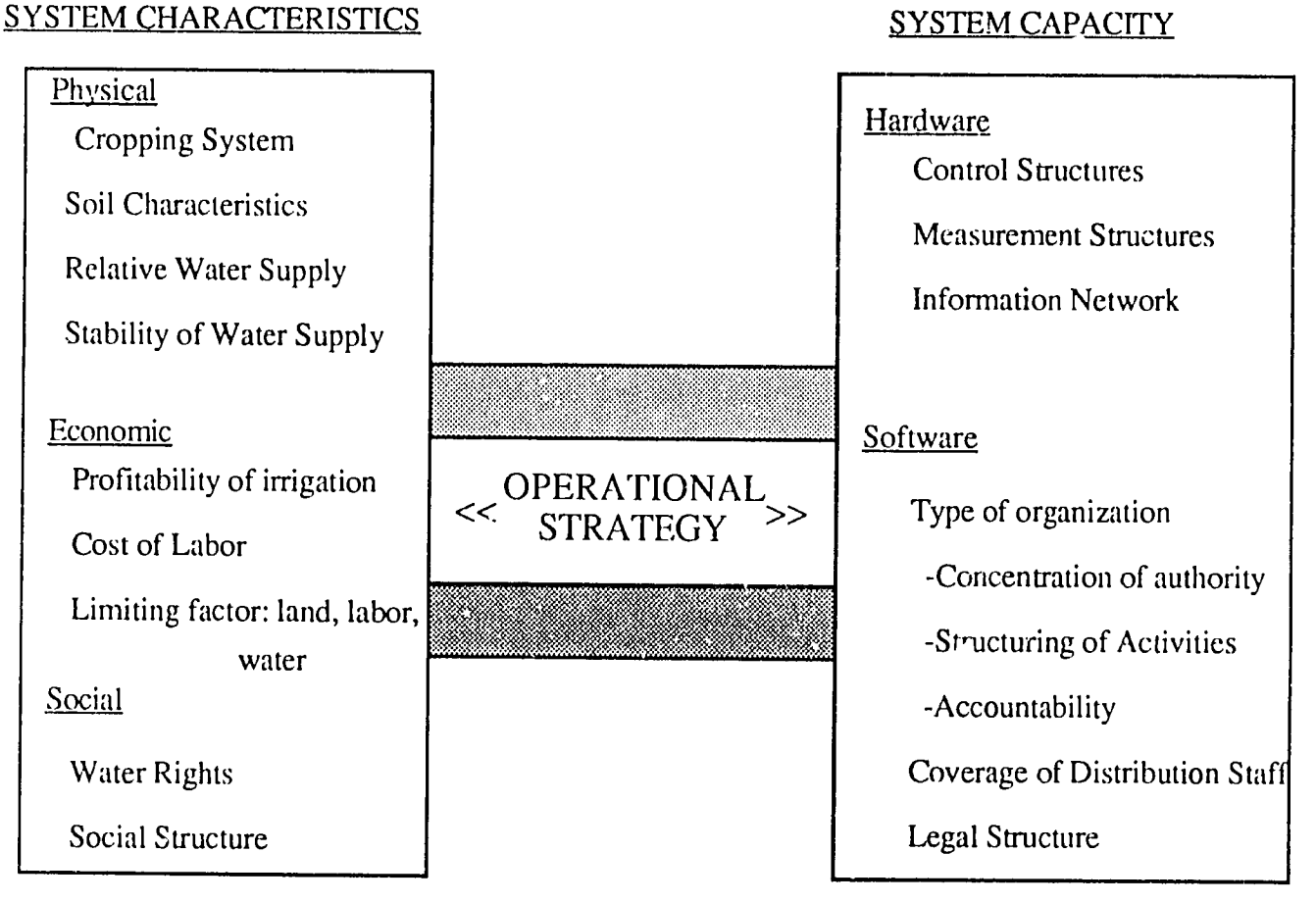


Figure 10. Operational Strategies as Determined by System Characteristics and Capacity.

System capacity includes both quantity and quality aspects. These are illustrated below:

Hardware

Quantity	*Quality*
No. of control structures (space - dense)	Type of control structure (wooden slats -automatic gates)
No. of measurement structures	Type of measurement structures
Penetration of canals	Type of canal lining
Information systems	Ease of use and relevance

Software

Quantity	*Quality*
Number of staff	Training and motivation
Organizational structure	Type of linkages Accountability

A gauge of the extent of system capacity is also useful. We can distinguish:

1) Used Capacity: The infrastructure that is used in a typical day of operation.

2) Reserve Capacity: The capacity used under unusual conditions (i.e., during a ten-year drought).

3) Excess Capacity: Superfluous capacity. This is often the result of poor planning or a change in operation. (e.g., in many systems the

measuring structures are never used because they are not required for operation).

To a certain extent hardware and software components can substitute for each other. In the case of extra capacity, a one-time investment in infrastructure (physical and organizational) but must be followed by recurrent investments in capacity utilization.

Intuitively, it seems that there must be compatibilities between the system requirements and system capacity. However, this is quite difficult to establish and at least one study that tried to correlate the physical and social environment with the way systems are operated, could make no significant conclusions because of the variability in these factors. (Uphoff and Esman,1974). It is clear, however, that one prerequisite to discovering these compatibilities is a thorough understanding of the operational strategy.

METHODS OF WATER DELIVERY

Probably the most important aspect of the operational strategy is the method of water delivery used in the system. There is considerable confusion in the literature about how to describe different operational schedules. As a result, the same terms are often used in reference to very different types of operation. In this section we will first outline the basic kinds of water delivery methods (intermittent and continuous) and then clarify some confusing issues.

Intermittent Delivery

The three components of an intermittent flow are:

1) Flow Rate (q)
2) Frequency (i)
3) Duration (d)

The flowrate and duration are often multiplied to determine the amount of water delivered. This component may be the most relevant piece of information from the farmer's point of view (Figure 11).

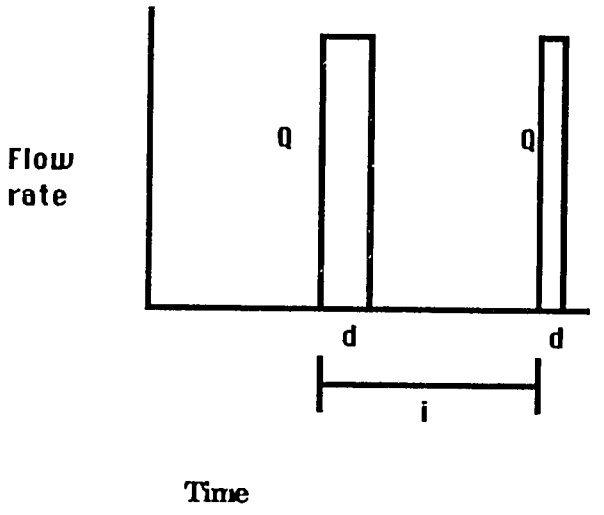


Figure 11. Schematic Representation of Intermittent Delivery (Source: Horst, 1983).

Changing irrigation requirements during the growing season can be met by altering one or more of the three variables, q, i, and d. In devising a schedule, the basic options for each variable are:

1) Fixed - the variable does not change during the time period considered.

2) Varied - the variable changes to a lesser or greater extent over time.

A variety of intermittent schedules are illustrated in figures 12 and 13.

Continuous Delivery

In the case of continuous delivery, only the flow rate is an issue because the frequency and duration are irrelevant. The flow rate can, however, be either fixed or varied. From an operator's point of view, the various strategies to meet changing water demands are illustrated in Figure 14.

Consequences of Choosing Fixed or Varied Components

From a system level point of view, the simplest delivery schedules are those that include changes in only one component. The consequence of varying the duration is odd delivery times. This commonly occurs in rotation systems when farmers take as long as they want once their turn arrives.

Keeping the rate and duration constant while varying the frequency is perhaps the easiest schedule to operate because the whole system or subsystem can be adjusted for one flow rate. The system is closed for longer or shorter periods of time to meet variability in irrigation requirements and rainfall (Horst, 1983).

	Freq	Rate	Duration
Type 1	V	V	V
Type 2	V	V	F
Type 3	F	V	V
Type 4	V	F	V

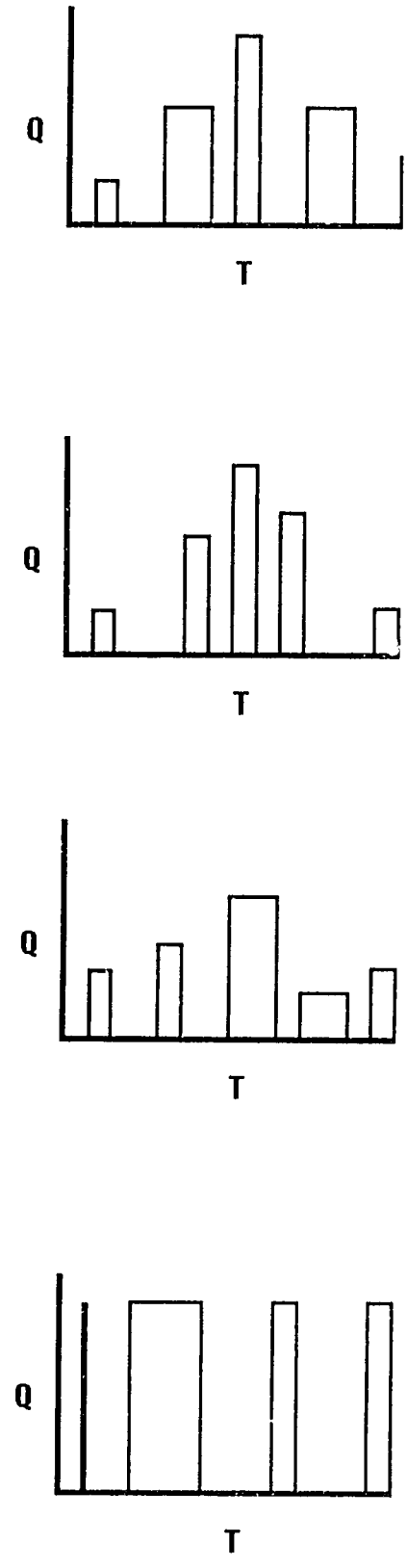


Figure 12. Varying Intermittent Schedules (**V= Varied Flow, F= Fixed Flow**)

	Freq	Rate	Duration
Type 5	F	V	F
Type 6	F	F	V
Type 7	V	F	F
Type 8	F	F	F

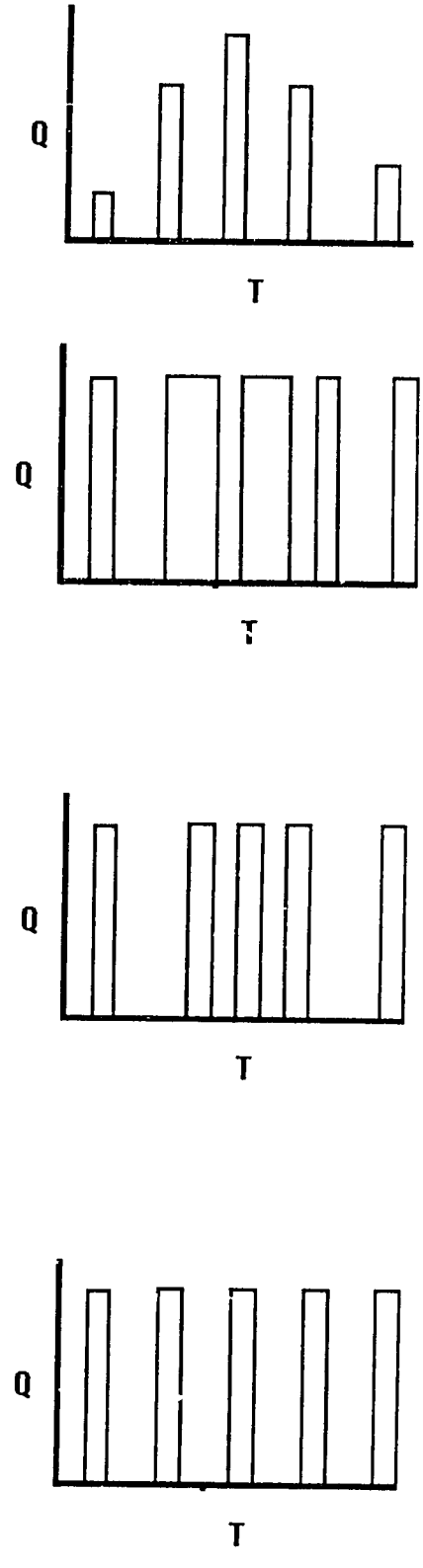


Figure 13. Varying Intermittent Schedules (**V= Varied Flow, F= Fixed Flow**)

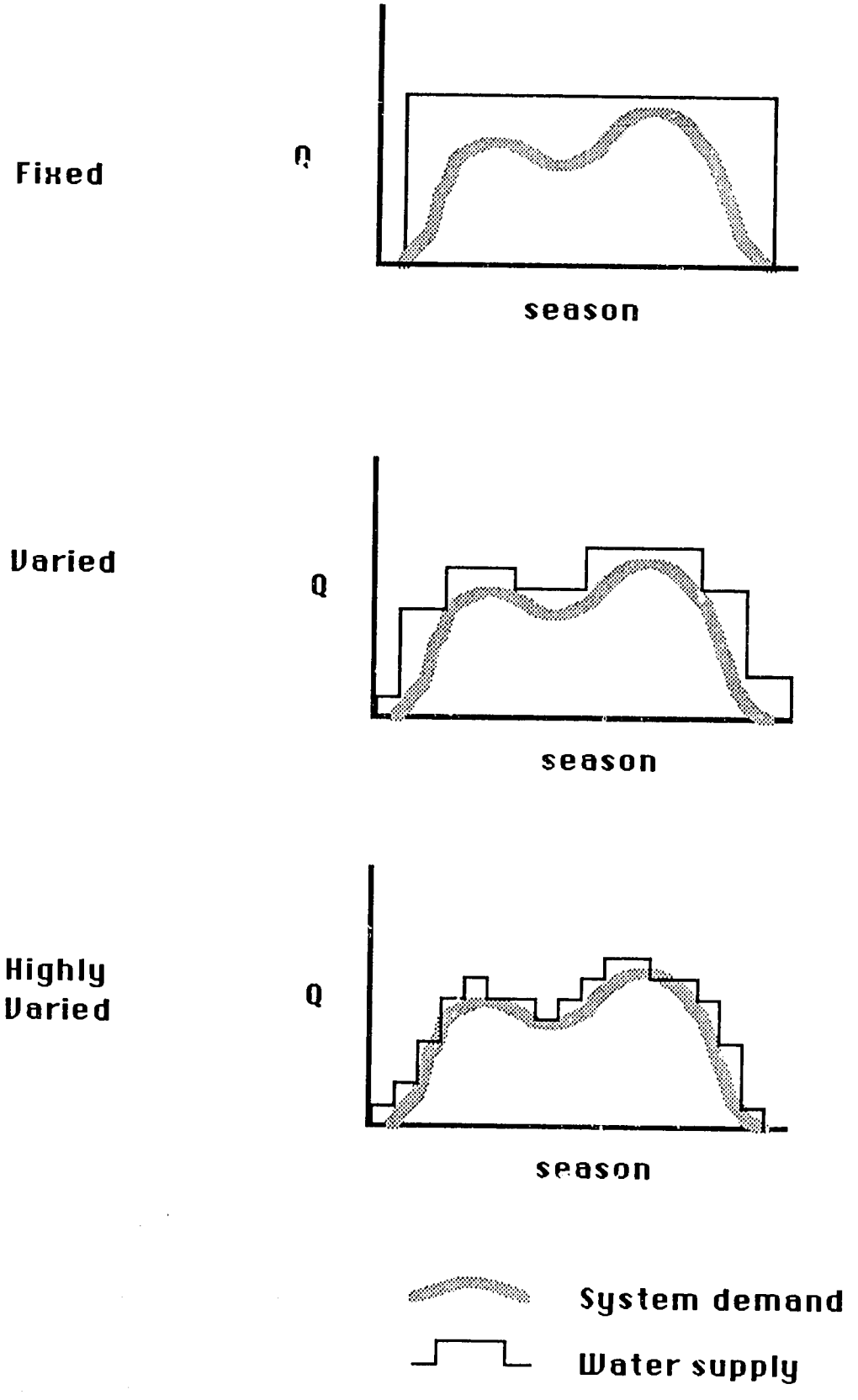

Fixed
Q
season
Varied
Q
season
Highly
Varied
Q
season
System demand
Water supply

Figure 14. Fixed and Varied Continuous Delivery.

The most difficult scheduling component for operators to vary is rate. This requires readjustment of control structures for every change and the use of measuring structures, which results in more complicated operational procedures and a greater need for skilled operators. In schedules where two components are varied, similar situations exists. The easiest schedule for operators to carry out is one where the rate is fixed because this does not require continual readjustment of the control structures.

The relative complexity of different schedules and their effect on control structures are listed below:

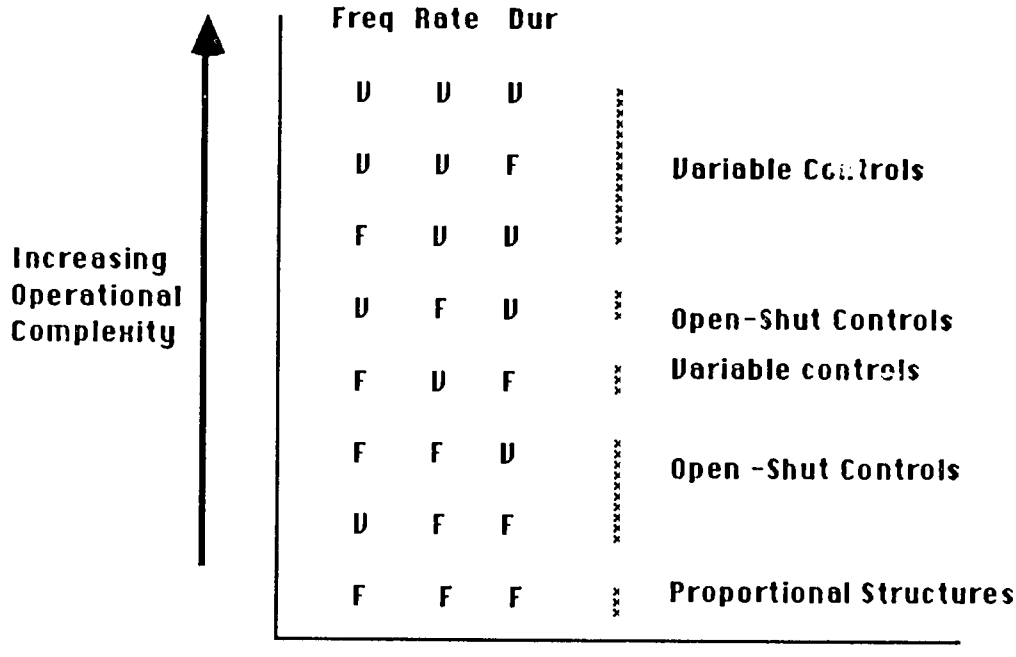


Figure 15. Control Structures Associated with Various Intermittent Schedules.

It is important to recognize that the various operational schedules are not inherently good or bad. A good schedule is one which fits the conditions in which it must operate. Thus, even if a fixed schedule of operation may at first seem inefficient because not all the distributed water is used by plants, the organizational and social environment may be such that other schedules would not be effective.

FACTORS THAT ARE PART OF A SCHEDULE DESCRIPTION

Time Frame

An operational strategy can be viewed from a number of time frames including:

1) The Long Term: The evolutionary nature of all systems inevitably implies change over the long term as operators and users respond to varying demands and environmental conditions. In this time frame, factors such as salinity, waterlogging, and the expansion of the command area become pressing issues. Although many of the modifications that occur in a system are due to factors external to the system (often political and economic in nature, and thus difficult to include in an operational strategy), some changes may be predictable.

As in any new irrigation system, operators and users go through a learning process adapting to the system's demands and constraints. It may be possible to include this phase in a characterization of long-term operational strategy.

2)Annual and Interseasonal: Many factors that influence operation, such as reservoir water levels and cropping patterns, can change on an annual or

seasonal basis. This is especially true when there are wet and dry seasons, each of which can have differing water demands and crops.

3) Intraseasonal: The day-to-day operation of a system can be extremely dynamic and it is at this level that changes in operational strategy are most apparent. The operational strategies used in this period are the ones that we have focused on.

Uses of Irrigation Water

Operational strategies primarily address how water entering the canal system is distributed and used. However, an irrigation system uses water for a wide variety of purposes, and it is useful to list these purposes.

The primary purpose of the water is to fulfill the needs of growing crops, but in the process the water is used up not only for ET of the crop but also for (Bos, Repogle, and Clemmons, 1984):

- Consumption by non-irrigated vegetation (weeds, trees)
- Evaporation
- Seepage from canals
- Tailwater runoff
- Deep percolation

Secondary purposes of irrigation water include:

1) Salinity control - leaching of salts through the soil profile
2) Land preparation - only at the beginning of the season
3) Weed control

4) 'Management ease'

5) Domestic uses

6) Fish ponds and animal watering holes

When irrigation systems are laid out, designers usually focus only on the primary purpose of providing crop water needs. The initial design must, however, support all the other uses. If they are not considered, impossible demands can be made on system capacity because those needs may be more important to users than crop requirements. For example, water for land preparation is vital to most rice cultivation, and if the canals are too small or the supply too limited, the system will suffer. (Murray-Rust, 1983). Further, if water is used for domestic purposes, the system may require year round operation.

System Level

An important clarification to make when describing schedules is to identify the system level to which the description applies. The schedule classifications presented earlier describe the flow in a given level of a system, but many schemes have different types of schedules for each of their hydraulic levels. For example, the main system may be in a continuous flow mode, whereas at the farm-level fixed rotations are used.

It is important to understand how each level of the system operates because they are all interconnected. Hybrid schedules are especially difficult to classify. We show one of these in Figure 16 , an illustration of a three-level system with various continuous and rotational schedule options.

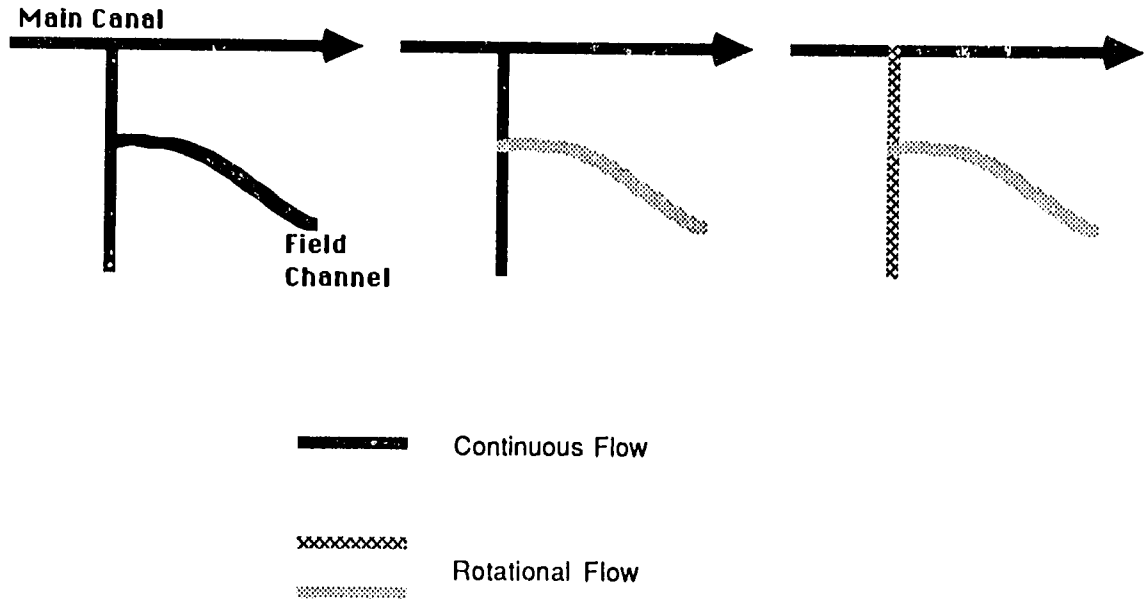


Figure 16. Flow Options in a Three-Level System.

Definition of Varied Flow

The most important clarification in developing a classification system is defining what is meant by 'varied' and 'fixed' flow. Few systems have truly 'fixed' duration, rate, or frequency because hydraulics,climatic changes, and operational activities invariably result is some variation. A judgement must be made as to what constitutes 'fixed'. 'Varied' is even more difficult to define. The three most important issues are:

1) Who determines the variation?

2) What kind of variation is it?

3) When and why is the variation occurring?

1)To illustrate the issues involved in figuring out who determines variation, consider a typical canal with five off takes. A canal authority (either an agency or group of irrigation elders) and farmers or farmer groups are the actors.

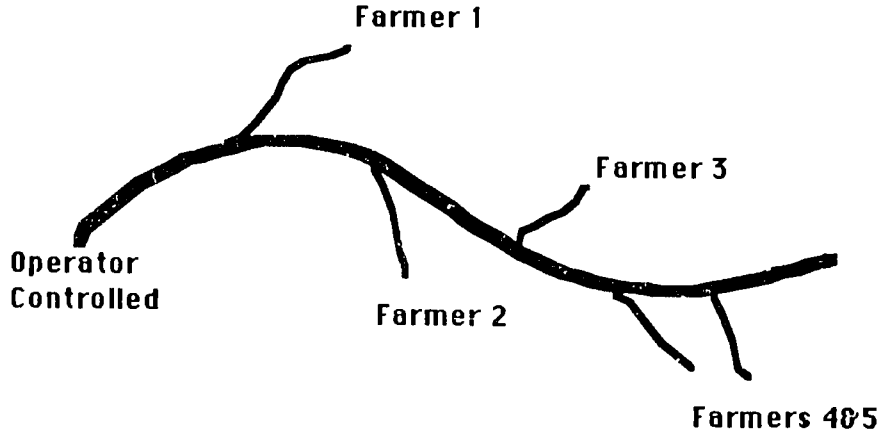


Figure 17 : Illustration of Schedule Variation

There are three ways in which variation can occur in this situation:

A - Farmer controlled: The farmer or farmers' group decides what the variation should be.This often occurs in smaller systems when there is abundant water.

B - Joint control: Farmers and the operators negotiate to decide on variation. This is probably the most common type, and there are numerous ways this can be accomplished (i.e., contract, market, consultation) (Chambers,1980).

C - Operator controlled: Operators impose variations after only minimal consultation with farmers. Occurs under very rigid

strategies or where there is a information system in place. Imposed variation may also be the result of a change in natural conditions, such as reduced water supply.

When more than two components are varied, each of these variations can be controlled in a different way. One can have a system where the rate is varied by the farmer, but the duration is imposed by the agency.

The question of who controls the water flow is correlated with the Relative Water Supply. When the variations are determined by the off takes, systems tend to have higher RWSs. As water becomes more scarce, there is a tendency for control over the water flow to shift to higher levels in the system. During times of relative water abundance, many systems relax their control of rotations in favor of a laissez faire demand schedule, whereas in times of water scarcity there is a marked tendency to impose fixed rotations.

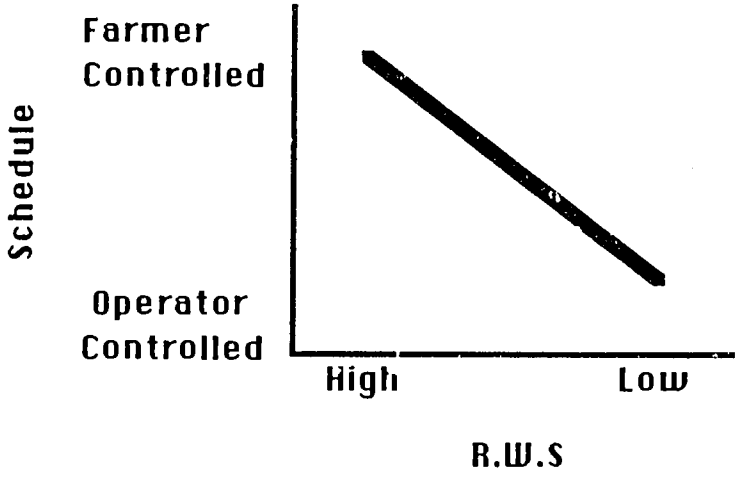


Figure 18: Shifts in Control of Flow with Changes in RWS.

2) Degree and type of flow change determine the <u>kind</u> of variation. Variation in

each schedule component is limited to a range of possibilities (eg., +/- 30 percent). These ranges are not important if they do not restrict the farmer or operator from doing basically what he or she wants, but can become a significant constraint if they do (e.g., if the canals can't deliver the desired flow rate, a farmer may have to irrigate all night). The effect of the restrictions will depend on the irrigation methods used, the crops grown, and the size of the holdings. We can however make a distinction between

Restricted Variation: Limits in variation restrict what the operators can do.

Unrestricted Variation: No constraints limit the operator in most circumstances.

The variation can also be *continuous* or *discrete*, full supply or no supply.

3) The most important clarification is when and why do the variations occur. There are two basic reasons why adjustments in water flow are made:

A) Changes in water demand. This can be due to the crop growth stage, rainfall, and to a limited extent ET.

B) Changes in water supply. This generally means water shortages but in some cases is due to water abundance. Rainfall is the main factor affecting supply.

At this point we introduce the concept of responsive vs. rigid operational strategies. The basic issue is the amount of information used to adjust flows during the system operation.

A responsive operational strategy is one that varies the water flows in response to changes in water supply and demand. A prerequisite for a responsive strategy is a system with the capacity to be flexible. This capacity will be addressed later.

A rigid operating strategy is one that does not change the pattern of water flows in response to changes in supply or demand. All the decisions are made prior to the season, and no new information is collected.

It is important to emphasize that the operational strategies are described from the operator's point of view. The issue of concern is how the water flows in the system are altered in response to information received from the operators. A continuous, full supply schedule may be very 'rigid' from an operator's point of view but be 'responsive' from the farmer's since water can be taken when necessary.

Demand systems that supply water at the request of farmers (like those in the western USA) are highly responsive because their water flows continually change as information is received from the field. The *warabundi* system, on the other hand, is an extremely rigid system because it rarely alters its operating procedures.

Between rigid and responsive there is a continuum of schedules. One way of thinking about this range is to consider:

Response Time. The time it takes for the operators to respond to a change in the water supply or demand. With responsive strategy, operators would react immediately whereas a rigid strategy would not allow any response. One way to quantify this would be to observe what happens after a certain change and measure response time. Thus, highly responsive could be 1 day, medium would be 2 to 4, and low response might be more than 5 days.

Information Use. The type and quantity of information used by operators tells something about how the system is operated (Figure 19). If information is used

to alter water flows to better match supply and demand and thus optimize production, operators are trying to operate the system responsively. If no information is used or the information is used only to check that schedules are followed. the system is pursuing a rigid operating strategy. This difference has been called administrative vs. managed operation, respectively.

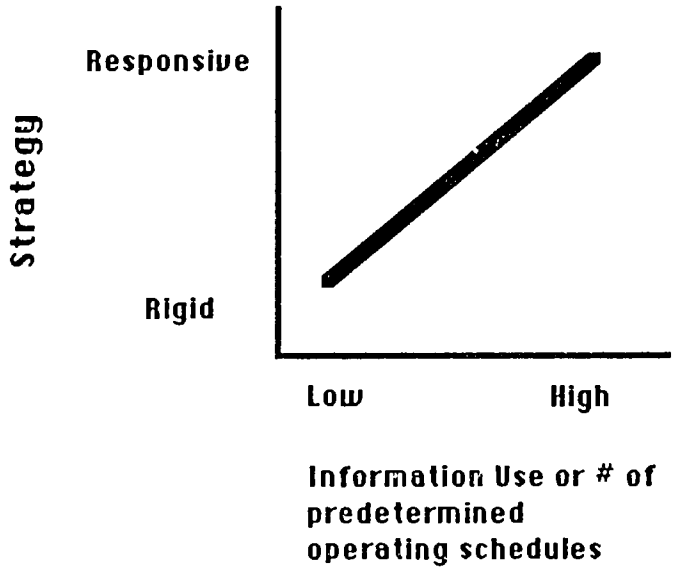


Figure 19: Correlation of Rigid and Responsive Strategies to Information Use

Water Shortages

It is instructive to outline a variety of responses to water shortages. Before doing this, we must recognize that water scarcity is a relative term. It will connote a different condition to a farmer growing acres of high-value market crops trying to maximize profits, than to one growing subsistence foods. It is also important to distinguish between nominal and real scarcity (Bromley, 1982). Nominal scarcity refers to a situation in which water is apparently scarce, but the scarcity derives from the particular way in which the water is

managed or in which the fields are leveled. Real scarcity refers to cases where even with 'good' management practices, supplies to not meet demand.

There are basically three ways in which system operators respond to water shortages.

1) Reduce the amount of land that is serviced by the system. This can be done according to crop priorities or farm priorities (time of settlement, location).

2) Reduce the amount of water that is supplied to each land area.

3) Try to find new sources of water.

Three case studies illustrate each of the responses.

Valencia System in Spain

The supply procedures used in this system are elaborately codified for drought situations. When the supply is abundant, water generally flows continuously, and a demand schedule is used. As the water supply dwindles, turns are instituted between and down the length of distributaries. At the next level of water scarcity, the irrigation interval is lengthened. At the next level, time limits are imposed on each hectare and finally, if water is extremely scarce, certain lands without special rights receive no water (Maas and Anderson, 1986).

From this description, it is clear that as the RWS decreases, control over the flow moves from the farmers to the operators. It is also clear that Valencia has a very responsive operating strategy, which has the capacity to change operating schedules to meet at least four levels of water supply.

UPRIS in the Philippines

In the three systems studied by Valera(1984) in the Central Luzon Province in the Philippines, water is distributed according to a schedule determined by the irrigation agency prior to the beginning of the season. The operators respond to coming water shortages by reducing the amount of land supplied by the system. This system has a fairly rigid operating strategy. There is no capacity or effort made to alter operating procedures in the face of reduced water supplies.

South Korea

In a system studied by Wade(1980), operators responded to water shortages by concentrating attention on providing farmers with alternative means of obtaining water, such as small portable pumps, or arranging for the purchase of water from private tubewells. There was an increased concern with water releases from the reservoir, but not with the distribution of water throughout the area. The operating procedure is quite rigid, but many of the distribution decisions remain under farmers control.

A SIMPLE OPERATIONAL TYPOLOGY

The issues outlined earlier must be carefully kept in mind as we propose a simple typology to describe how various gravity-fed systems are operated (Figure 20). The question we must first answer is which attributes are appropriate for an operational typology. We choose three: the schedule, the degree of

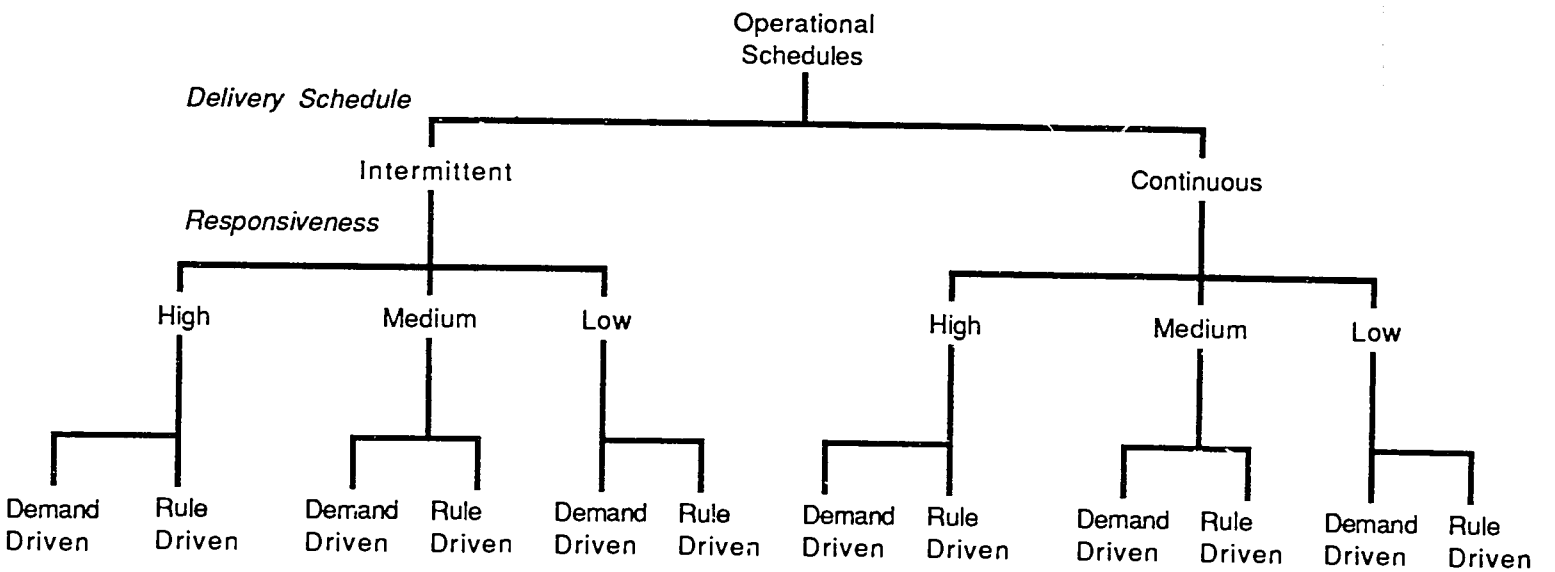


Figure 20: A Simple Operational Typology for Gravity-Fed Irrigation Systems.

responsiveness, and the type of operational procedures that influence system response. Under the schedule variable, a distinction is made between intermittent and continuous flow. Specific kinds of intermittent flow were omitted because important aspects are covered by the degree of responsiveness. By system responsiveness, we mean the time it takes for a system to respond to significant changes in the water demand or supply (i.e., rainfall, water shortage, increasing crop demands). There is an inherently subjective aspect to this description (what is a significant change?), but we can quantify it somewhat by defining:

High responsiveness as a response that occurrs in less than 24 hrs.
Medium responsiveness as a response that occurrs in 2 to 4 days.
Low responsiveness as a response that occurs in more than five days.

In order for this classification to be less ambiguous we need to define from whose perspective responsiveness is being viewed and on what specific criteria it is based. It is quite possible that head and tail sections of a system will experience very different levels of 'responsiveness'. One way of dealing with these questions is to identify one factor (rainfall or farmer demand) and measure it in the middle of the system.

The next distinction is that of demand driven vs. rule driven procedures. The notion behind this is that the operators can respond in an ad hoc manner directly to the demands of the system users or they can operate according to a predetermined set of rules. Rules are commonly set before the season begins using information that is available. A rule driven schedule would not respond to an unpredictable change like too much or too little rainfall. This distinction corresponds to the 'managed' vs. 'administered' systems mentioned in other

irrigation literature. A rule driven procedure can be highly responsive if a lot of information is available and the envionment is very predicatable, then preset rules will match actual conditions. Conversely, demand driven procedures can cause low responsiveness if the operators are unable to change flows very quickly.

The operational typology is shown in Figure 20 is based on a number of assumptions:

1) The time frame for response is short term.

2) Because each level of a system may be operated differently, the classifications are limited only to the first and second level of the system for comparison purposes.

3) Definitions are formulated from the operators' perspective, not the farmers'.

4) The typology is focused on gravity rather then lift systems

Operational strategies exist in a complex physical, organizational, and economic milieu. Not every operational strategy is ideally suited to every kind of environment. If the system objectives are to be optimized, there must be a compatibility between the operational strategy and the environment in which it works.

Chapter 4

CONCLUDING REMARKS

The two sections of this paper may initially seem disconnected, but they are logically part of the same iterative process. The initial purpose of the project was to study the operation of gravity systems, but it soon became clear that it would be futile to talk about operation without being able to distinguish among various systems. This led to the development of the general typology, which is a logical precursor to the operational typology presented in Chapter Three.

The general system typology has the potential to became an important tool in the decision-making process of national and international irrigation agencies. If the categories can be refined and validated, the typology promises to be a major factor in organizing irrigation research and will greatly facilitate the transfer and application of knowledge. For example if we collected all the case studies of medium-scale, non-paddy, conjunctive systems, we would be much more capable of making useful prescriptive statements directed toward new or planned projects.

The issues addressed in the development of the operational strategy in Chapter Three will become increasingly important as more emphasis is given to improving the operation and management of existing systems. These issues must be addressed and our language clarified if we are going to make significant improvements in system operation. The potential for system operators to share knowledge is enormous. As water increasingly becomes the scarce factor in irrigated agriculture, our ability to describe operational strategies and their context will be essential to improved water management.

The next stage in this research effort is the validation and refinement of the typologies. These typologies are meant to serve as models to organize thoughts and are open to modification. This paper will be successful if it gives irrigation researchers a starting point with which to create their own typologies.

APPENDIX

SURVEY TO RANK OPERATIONAL ATTRIBUTES

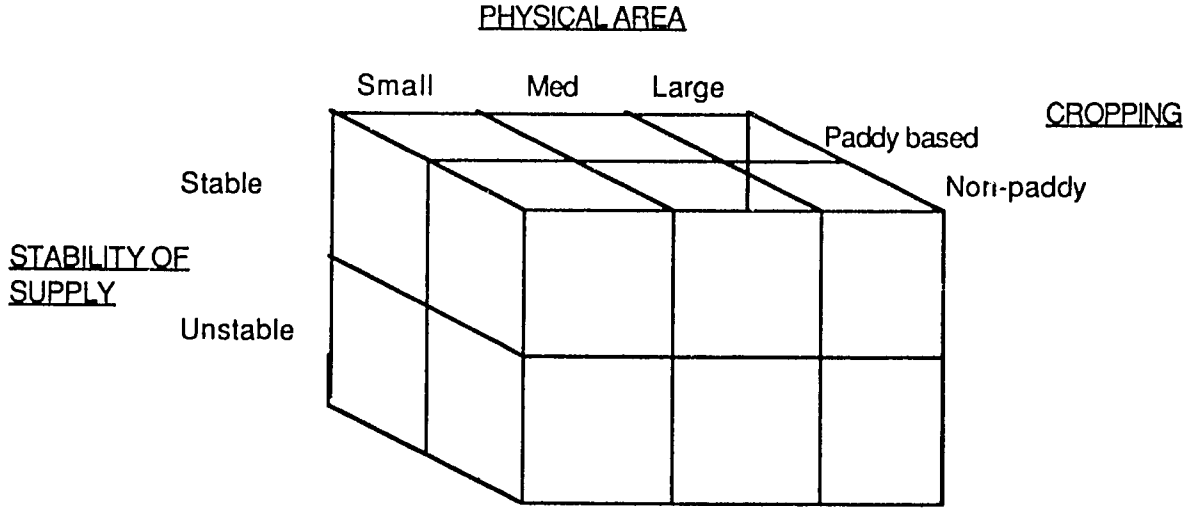
Typology of Physical Characteristics for Canal Irrigation Operation

Previous attempts at developing useful typologies have often faltered because of the many obstacles to such an endeavor. Not only is there a tremendous diversity of canal irrigation systems, but there is also a myriad of perspectives from which they can be viewed. The question is further complicated by spatial and temporal variations found in most systems, and the continuous rather than discrete nature of irrigation classifications.

Despite these formidable difficulties the project has continued based on the belief that some ordering is possible - given the objective of understanding canal irrigation operation. A typology hopefully can help illuminate the operational implications of various sets of physical characteristics. It may thus be useful for addressing the questions of scheduling, rigid vs. responsive operating strategies, communication needs, and management intensity.

Because of the large number of characteristics that affect irrigation operation there is a need to limit the typology to a few variables or else it becomes too difficult to use. (most people cannot deal with 15th dimensional space). In order to do this we need to identify the most important characteristics.

To these ends we ask you to rank at least the top four out of all the following system characteristics according to the importance of their influence on the operation of the distribution system. We have already done some selecting of characteristics, but please feel free to add characteristics and/or change the way they are defined. The question to be kept in mind is " Does this characteristic generally influence operation more or less than the other characteristics? We realize that it is difficult to choose the most important characteristics from a list of variables that all are important. A common thought will probably be "It depends". We are hoping,however, that if there is some consensus we can devise a simple typology that may illuminate some of the operational implications mentioned earlier. One example is illustrated below:



PLEASE RANK THE FOUR MOST IMPORTANT PHYSICAL CHARACTERISTICS ON THE BASIS OF THEIR INFLUENCE IN CANAL OPERATION. (1 - 4)

Physical System Characteristics	Rank
a) Paddy based vs Non-paddy based cropping	_____
b) Age (i.e Old vs New)	_____
c)Physical area	_____
d)Number of irrigation units/irrigators	_____
e) Climatic Type (i.e Arid,Semi-Arid,Semi-Humid,Humid Temperate vs Tropical Wet season, No wet season)	_____
f)Supplemental vs complete irrigation	_____
g) Topography (i.e. Mountain vs Plain)	_____
h) Soil type (i.e. difficult - problem free)	_____
i)Adjustable vs Non-adjustable structures	_____
j)Density and type of canals	_____
k)Density and type of measurement structures	_____
l) Relative Water Supply(supply/demand for water)	_____
m) Stability of the water supply	_____
n) Technology of acquisition	_____
o) Continuity of irrigation area	_____
p) Others _____	_____
_____	_____

For the top four choices from the previous page can you propose simple ways to differentiate or distinguish different types. For example:

Characteristic: *Physical Area*

Different Types: *Small, Large*

Specific Differentiation: *Small is < 1000 ha, Large is > 1000 ha.*

1) **Most important characteristic:**

2) **Second most important characteristic:**

3) **Third most important characteristic:**

4) **Fourth most important characteristic:**

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