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MULTICRITERION APPROACH TO THE EVALUATION OF IRRIGATION SYSTEMS PERFORMANCE

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ABSTRACT

Multicriterion Approach to the Evaluation of Irrigation Systems Performance

In recent years the importance and the lack of comprehensive methodologies for measuring the performance of existing irrigation schemes has been widely expressed. The objective of this study is to develop a systematic procedure by which some use can be made of the large quantities of data, already routinely collected in irrigation schemes, for the purpose of their regular seasonal evaluation. Consideration is confined to the performance of the main irrigation system of small-holder, canal-fed irrigation schemes of the developing countries. A generalized conceptual framework has been developed for a methodology by which the performance criteria for any irrigation system can be identified and combined together into a single index which measures the overall performance of the system.

Six criteria have been identified as adequate for characterizing the important features of the performance of any irrigation system. These are; *adequacy*, *equity*, *water losses*, *water user convenience*, *cost* and *durability*. New methods for characterizing each of *adequacy*, *equity* and *water user convenience* have been developed and tested using data from the Gezira scheme, Sudan. Characterization of *adequacy*, *equity* and *water losses* involves the development of a soil moisture simulation model and characterization of the *water user convenience* involves the use of the concept of the fuzzy set theory.

Identification of the criteria to be used in evaluating any particular system(s) and evaluating the trade-offs between them requires the participation of the decision-maker in the system(s) to be evaluated. This is achieved through the use of the multi-attribute utility theory. It has been applied with a group of Sudanese officials in order to derive their utility functions. The utility function reflects the decision-maker's strength of preferences over different achievement levels of each objective and his trade-offs between different objectives. The derived utility functions are reported and their usefulness is discussed.

The methodology developed provides a useful tool for measuring the performance of irrigation systems, comparing the performance of different systems and assessing improvement in performance resulting from rehabilitation investments.

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LIST OF ABBREVIATIONS AND IMPORTANT SYMBOLS

ADE	Assistant Division Engineer.
A_i	Area of crop i in hectares.
A_{ij}	Area of crop i in period j in hectares.
ASCE	American Society of Civil Engineers.
A_r	Area under the stress intensity-duration curve.
ARC	Agricultural Research Corporation, Wad Medani, Sudan.
$A \cup B$	A union B.
$A \cap B$	A intersection B.
BI	Block Inspector.
CCP	Central Clay Plains.
Cu	Christiansen coefficient (a measure of equity)
C_v	Coefficient of variation (a measure of equity).
C_{wc}	Uniformity coefficient (a measure of equity).
c(i,j)	Concord index.
DE	Division Engineer.
DI	Diversity index which measures the diversity of opinions of different people.
DIF.(A,Z_i)	The difference between the fuzzy sets A and Z_i.
DVG.	A fuzzy measure of the diversity of opinions of different people.
D_{ij}	Root depth of crop i in day j in mm.
d(i,j)	Discord index.
ETa	Actual evapotranspiration.
EI, E_i	Irrigation efficiency.
ETm	Maximum evapotranspiration.
ETo	Potential evapotranspiration.
Ep	Pattern efficiency (a measure of equity).
ESP	Exchangeable Sodium Percentage.
e_c	Conveyance efficiency.
FAO	Food and Agricultural Organization of the United Nations.
FC	Field Capacity.
FOP	Field Outlet Pipe.
F_{non}	A measure of equity equals to the ratio of the variance to the square root of the mean.
$f(\phi)$	Soil moisture availability function.
GARS	Gezira Agricultural Research Station, Wad Medani Sudan.

GDP	Gross Domestic Product.
HR	Hydraulics Research limited, Wallingford, England.
HRS	Hydraulics Research Station, Wad Medani, Sudan.
IAI	Irrigation Adequacy Index.
ICID	International Commission on Irrigation and Drainage.
IE	Irrigation efficiency.
IIMI	International Irrigation Management Institute.
ILRI	International Institute for Land Reclamation and Improvement, Wagingen, the Netherlands.
I_2	Inter-quartile ratio (a measure of equity).
K_c	Crop factor or crop coefficient.
K_{ij}	Sensitivity of crop i in period j for water stress.
Ls	Sudanese pounds.
LWC	Land and Water Charge (a charge taken from the farmers in the Gezira scheme for government services).
MAUT	Multi-Attribute Utility Theory.
MOFEP	Ministry of Finance and Economic Planning, Sudan.
MOI	Ministry OF Irrigation, Sudan.
O&M	Operation, Maintenance and minor repairs.
P	Fraction of the total soil moisture which can be depleted without ETm becomes less than ETo.
PWP	Permeant Welting Point.
R_j	Irrigation adequacy in period j.
Sa	Soil moisture storage capacity in mm/m.
SGB	Sudan Gezira Board, Barakat, Sudan.
SL	Stress level.
SMD	Sudan Meteorological Department.
SI_i	Social indifference curve number i (it represent the preferences of the society).
TC	Transformation Curve (represents the boundary of the feasible region in the graphical solution of multiobjective planning problems).
T_{ij}	Trade-offs between objectives i and j.
$u_i(x_i)$	Utility function of attribute x_i.
U(X)	Overall utility function.
V_j	Soil moisture storage in the root zone on day j in cubic meters.
WDP	Water Delivery Performance (a measure of adequacy).

W_{ij}	Surrogate worth trade-off function.
W_j	Relative importance of period j.
w_j	Relative weight of period j.
β_i	Relative weight of crop i.
$\mu(x_i)$	Degree of membership of the element x_i in the fuzzy set A (called support of x_i in A).
ϕ	Soil moisture level above the permanent welting point.

CHAPTER 1

INTRODUCTION

1.1. Prelude:

Irrigation developments have been and are expected to continue to be a major component in the national development plans of many developing countries. They have been identified as one of the major engines for accelerating the development of these countries. This is not only because of the importance of irrigation in securing and increasing food production, but also as a tool for creating opportunities of decent life for their rural population. This view is supported by the willingness of donor and lending agencies to finance irrigation projects and by the large sums of money committed to them by the national governments in developing countries. According to the World Bank estimates, up to the year 1980, $15 billions were invested in irrigation in developing countries (Carruthers, 1986, pp.265). The Asian Development Bank, for example, from its commission in 1960 up to 1988, has channelled $3 billions to irrigation. This amounts to 12% of all the bank's approved loans in this period (Kobayashi, 1989).

Despite the high priority enjoyed by irrigation in the development strategies of many developing nations and the substantial part of these nations' limited financial resources invested in it, in recent years there has been an increasing concern and steadily expanding body of literature about the performance of existing irrigation systems. The performance of large number of the gravity-flow canal systems, which are the most common in developing countries, is said to be below expectations (Wade, 1982, pp.8). The dissatisfaction with the performance of existing systems is also evident from the fact that, in recent years, rehabilitation and betterment have become increasingly more attractive than investing in new systems. In the 1977 United Nations water conference, for instance, the FAO estimated that in the period from 1975 to 1990, in developing countries, 45 out of the 92 million hectares irrigated at that time would have to be rehabilitated (costing $ 22 billions at 1975 prices) as compared with only 22 millions hectares potential for new construction (FAO, 1977).

Although these figures may be outdated now and usually reliable estimates like these are difficult to obtain, they reflect the sheer size of the problem and the popularity of rehabilitation can easily be seen from the frequency of conferences dealing with the subject in recent years (Weare, 1989).

The general concern about the performance of existing irrigation systems and the large sums of money injected in the rehabilitation of some of them has generated wide realization of the importance and general neglect of the regular monitoring and evaluation of the performance of these systems. Lenton (1986, pp.50), for example, stated that:

> "*One of the extraordinary characteristics of irrigation systems management is that, despite the fact that large irrigation projects generate revenues far in excess of the largest business corporations, there is virtually no information on the extent to which these irrigation systems are achieving performance objectives...*"

A team from the International Institute for Land Reclamation and Improvement (ILRI) Netherlands, evaluated 12 African irrigation systems situated in six different countries (ILRI, 1985). Some of the main conclusions from these evaluations stated that: "*The results of most irrigation projects fall below pre-project expectations ...*" and that: "*... The valuable management instrument of* *monitoring and evaluation are not used to full advantage.*". Based on these conclusions, one of the main recommendations stresses the importance of taking systematic monitoring and evaluation as an integral part of any irrigation system.

On the other hand, in many large-scale irrigation systems, particularly those controlled by governments, enormous quantities of data on water levels and discharges at various levels in the canalization system is regularly collected. Virtually no use is made of these data. It may remain locked in cupboards without even being checked. This study is based on the premise that the reason for not using these data for performance evaluation despite the realization of its importance comes a from lack of systematic methodologies by which this performance can be measured.

Performance evaluation methodologies are urgently needed by financing agencies and irrigation departments. If such methodologies exist then different design approaches and/or management policy alternatives can be evaluated, the performance of two or more systems, or that of the same system over time, can be compared and investments on reforms (i.e. rehabilitation of physical structures and/or upgrading of management techniques) can be decided on. Several "*management strategies*" have been advocated by the research community as useful for improving the performance of irrigation systems (Lenton, 1986). These include, for example, farmer participation and water scheduling. Performance evaluation methodologies are needed to test the usefulness of these *strategies* in field conditions. The availability of performance standards is equally required by those who are involved in the management of irrigation. With clear performance standards managers can be guided in the direction in which they must strive for improvement and can have clear priorities for actions.

In recent years the need for performance evaluation methodologies has been recognized by many researchers. The literature review in the next chapter shows that it is now generally agreed that adequate evaluation requires the use of a *set* of criteria to describe the system behaviour with respect to a *set* of characteristics. Several such criteria have been proposed. In our view, however, some work still needs to be done in this subject. Firstly, the definition of some of the proposed criteria is very general. For example, important criteria have been offered without precise definitions of their meanings or methodologies for measuring their achievement levels. Sometimes several criteria are proposed for characterizing the same aspect of the system performance. Secondly, although it has been recognized that different priorities should be assigned to each of these criteria depending on the physical, economic, social and environmental setting in which the irrigation systems are operating, no work has been done in order to evaluate the trade-offs between these criteria.

1.2. The Objective and Scope of the Study:

This study is meant to be part of the overall efforts towards the improvement of the performance of existing irrigation systems. Its broad objective is to develop a methodology by which one can measure how these systems are performing in relation to expectations. It is hoped that this can be achieved through the use of the type of data already routinely collected in these systems. The site-specific and the multidisciplinary nature of the irrigation systems make it difficult to develop an evaluation methodology which is applicable to any system and covers all the aspects of the performance. For this reason, in this study, we set out first to establish a general conceptual framework for a standard approach which can be followed in evaluating any irrigation system regardless of its size, geographical location, technical type, socio-economic or environmental setting. The development of a specific evaluation procedure based on this framework, however, requires: 1) specification of the type of systems to be evaluated, 2) definition of the system boundaries, and 3) specification of the purpose of the evaluation. At this stage certain restrictions are imposed on the scope of the study and the focus is concentrated on the performance of medium and large-scale, small-holder, government-controlled, canal-fed irrigation systems. Canal-fed irrigation systems are by far the most common in developing countries. Among these, the government-controlled small-holders systems impose special management challenges because of the numerous, often conflicting, benefits anticipated from these system by the different parties involved in them.

At this stage it may be necessary to define what we exactly mean by "*irrigation system*", i.e. define the boundaries of the system, and define the aspects of the performance we are looking for.

The allocation of responsibility of the water distribution and application in irrigation schemes differs from one place to the other. But generally, with the exception of schemes which are communally or privately owned and which are usually smaller in size, the water control task in medium and large scale small-holder schemes is shared between two parties. A government supply organization (usually the irrigation department or its equivalent) and water users. The government supply organization runs the main distribution system up to and including some point in the canalization network. Below this point the water management responsibility is handed over to the water user who may be an individual farmer, a farmer organization or an agricultural organization (Chambers, 1980). In this study, by "*irrigation system*" it is referred to the part of the scheme in which the water control is conducted by a government supply organization and is taken to consist of:

1) Physical facilities, such as: dam or pumping plant, network of canals and their associated structures, roads and communication facilities.
2) Management structure including personnel.
3) Operation rules, i.e. set of rules set out to govern the way in which the physical and management facilities should be operated.

As concerning the aspects of the irrigation system to be considered in the evaluation, attention in this study is confined to one aspect of the system performance. Irrigation schemes are usually expected to serve various broad objectives. Examples of these are: foreign exchange earning, security of food production and improving the income of the rural population. Many of these broad objectives are expected from the irrigation scheme as a whole including the farming system and their achievement is largely determined at the planning stage in decisions concerning, for example, the area to be irrigated, the sizes of the land holdings and the types of crops and cropping intensities. If the evaluation is aiming at improvement in performance then, once the irrigation system is built, all the potential for improvement lies in the hands of the system manager and all of which can be achieved through water control measures. It is this water control which is the central focus of this study.

It is perhaps useful also to state the purpose of the evaluation in mind when developing this methodology. The main emphasis is on a methodology suitable for the seasonal or annual evaluation. For example, for an evaluation to be included in the annual report. We believe, however, that the methodology developed can equally be suitable for assessing if some improvement has been achieved by some investment in rehabilitation or some change in the management policy.

With these restrictions, the objective of the study is narrowed to the development of a methodology which can be used to measure the quality of services provided by the irrigation system (as defined above) to the water users. This is to be achieved through the following:

1) Identification of the performance criteria.
2) choice of a measuring scale by which each of these criteria can be quantified.
3) A methodology for evaluating the trade-offs between these criteria in order to combine them into one overall performance index which reflects the overall picture of the system performance.

1.3. Overview of the Thesis:

Following this introduction, Chapter 2 reviews the relevant literature. It consists of two sections. In the first section irrigation performance criteria proposed in the literature are reviewed and their usefulness and limitation are pointed out. In the second section multiobjective and multicriterion evaluation techniques are discussed. Special consideration is given to the application of these techniques in the field of water resources

In Chapter 3 a conceptual framework of a generalized approach for the evaluation of irrigation systems performance is developed. The chapter starts with a discussion of the types and nature of irrigation systems performance criteria in a generalized manner without reference to any particular type of systems. Hierarchical structure of objectives is then used for selecting the performance criteria for the type of systems considered in this study. The chapter ends up by identifying a set of six criteria for this purpose. These are: *adequacy*, *equity*, *water losses*, *water user convenience*, *cost* and *durability*.

For testing the applicability of the methodologies developed in the study, the Gezira scheme, Sudan is used as a case study. Chapter 4 contains a brief description of the irrigation systems in Sudan in general and the Gezira scheme in particular. The chapter also contains a survey of the data which is relevant to performance evaluation and routinely collected in these systems. The quality, completeness and reliability of these data is also discussed.

In Chapter 5 a soil moisture simulation model is developed and validated using field data. Two methods of characterizing the adequacy of water supply from the output of this model are developed. One method consists of constructing a graph which summarizes the intensity-duration characteristics of the stress experienced during the season. The other method consists of formulating a procedure through which all the characteristics of the stress are combined into a single number called "*Irrigation Adequacy Index (IAI)*". The chapter then uses data from the Gezira scheme with the soil moisture simulation model to calculate each of the *IAI*, *water losses* and *equity* at three levels in the irrigation system. The results are presented and discussed.

In Chapter 6, using the concept of the fuzzy set theory, a method is developed for characterizing the *water user convenience*. This is a measure of the suitability of the water supply schedule to the irrigator. Three factors are taken to determine this convenience. These are: *predictability*, *timing of the water supply* and *supply flow rate*. The fuzzy set theory is used to estimate the overall convenience from judgements given by the water user to each of the three factors and their importance. The method is applied with a sample of six farmers from the Gezira scheme to demonstrate the applicability of the approach.

In Chapter 7 we set out to evaluate the trade-offs between the six performance criteria selected in Chapter 4. The Multi-Attribute Utility Theory (MAUT) is employed for this purpose. Using the MAUT approach, eight Sudanese officials involved the decision-making in irrigation were interviewed in order to let them explicitly state their opinions on what evaluation criteria are to be used in evaluating the Sudanese irrigation systems and the trade-offs between these criteria. The result is presented in this chapter with some discussion and conclusions.

Finally, in Chapter 8, a summary of the main conclusions of the study together with outline recommendations for future work related to the study are presented.

CHAPTER 2

LITERATURE REVIEW

2.1. Criteria for Irrigation Systems Performance Evaluation:

In order to be able to judge whether a particular irrigation system is performing satisfactorily or not, it is first necessary to define the performance criteria against which the judgement can be based and then determine how far the system was able to go in satisfying these criteria. In this section some of the irrigation performance criteria proposed in the literature are reviewed.

2.1.1. Historical Background:

With the development of modern irrigation methods and the expansion of the irrigated area, demands for water from the available resources increased. With the surge of increasing competition over the available water and the need for its allocation to new users, some problems within the existing irrigation systems were identified as deserving attention and their consideration carries some potential for increasing the benefits from these water resources. Some of the early problems identified were: (a) Large quantity of water is wasted without being effectively used. (b) Some areas are receiving more water than others. In trying to deal with these problems, irrigation engineers developed the concept of *irrigation efficiency*, which is a measure of the extent to which water is effectively used, and the concept of *irrigation uniformity*, which is a measure of the extent to which water is evenly distributed. With irrigation efficiency and uniformity the sole criteria for judging irrigation systems performance, the traditional wisdom was that the problems are principally at farm level and exclusively of engineering nature.

It was only in the late 1970's and early 1980's when the multi-disciplinary nature of irrigation started to be recognized and social scientists began to be involved in researching irrigation management, particularly that of the large-scale small-holder schemes. Those social scientists brought with them some changes in the way of thinking. New issues in irrigation management started to attract increasing attention and to be looked upon as carrying large potential for improving the performance of existing systems. These include the study of the management of the main supply and distribution system, (Wade and Chambers, 1980; and Bottrall, 1981), and the management of the people and institutions which manage the systems (Chambers, 1980; and Chambers, 1981).

Concurrently with this, dissatisfaction with the performance of existing systems was widely expressed. Improving the performance of existing systems through rehabilitation has been widely advocated as more cost-effective than investing in new systems. This has helped the change in the way of thinking to extend and include the methods of evaluating the performance of existing systems. Instead of concentrating on the engineering problems at the farm level, a wider view emerged and a more comprehensive evaluation approach started to be attempted.

Building on the traditional evaluation criteria originally devised for the farm level system (i.e. efficiency and uniformity) which were then adapted for use in the evaluation of the main system, large body of literature now exists on other criteria for evaluating the irrigation system as a whole, including the main and farm level systems. The following sub-sections review some of the numerous performance criteria which have been put forwards in the literature. Their appropriateness, relevance and methods of measurement are also discussed.

2.1.2. Irrigation Efficiency:

One of the earliest formal definitions of the concept of irrigation efficiency was introduced in 1932 by Israelsen. This definition is given by equation (2.1) (Israelsen, 1950, pp.18–19).

$$E_i = 100 \times \frac{W_c}{W_r} \qquad (2.1)$$

Where E_i = Irrigation efficiency (percentage).

W_c = Water consumed by the crop during its growth period.

W_r = Water diverted from the river or other natural source.

Clearly this definition was designed to measure how much of the irrigation supplies were used to meet the crop evaporative demand and, therefore, how much were lost. Since this definition was introduced several workers have developed, modified or redefined the concept of irrigation efficiency. Most noteworthy of these are the works of Jensen (1967) and Hall (1960). Jensen pointed out the importance of the consideration of: (i) the contribution of the rain, (ii) the change in the soil moisture storage, and (iii) the volume of water required for leaching the salts from the soil. Accordingly, he proposed the definition given by equation (2.2).

$$E_i = 100 \times \frac{W_{et} + W_l - R_e + \Delta W}{W_i} \qquad (2.2)$$

Where E_i = Irrigation efficiency (percentage).

W_{et} = Volume of water consumed by the crop evapotranspiration.

W_l = Volume of water required for leaching the salts.

R_e = Volume of effective rainfall.

ΔW = Change in soil water storage.

W_i = Volume diverted or pumped for the purpose of irrigation.

Hall (1960) pointed out the limitation of the concept of irrigation efficiency in that it fails to tell whether enough water has been supplied for a decent crop growth or not. He stated:

> " *... an efficiency of 100 percent can be obtained in a 40-acre field if one gallon of water is sprinkled lightly over a portion of the surface. Though the "efficiency" is perfect, the purpose of irrigation has been ignored.*"

To deal with this limitation of the definition, he introduced the concept of *system application efficiency* which he defined as the efficiency of the irrigation system when at least 95% of the land has been adequately irrigated.

Many other definitions of the term "*irrigation efficiency*" has been suggested in the literature. Karmeli, *et.al.* (1985, chapter 13) reviewed some of them. Although the irrigation efficiency is the criteria most widely quoted by irrigation managers in describing the performance of their systems, people differ in their precise conception of its meaning and the factors to be considered in calculating it, probably each affected by the particular circumstances in his system. The lack of a standard definition and the confusion which may arise from using different formulae for calculating the efficiency of different systems led the American Society of Civil Engineers (ASCE) and the International Commission on Irrigation and Drainage (ICID), separately, to try and standardize the definition of irrigation efficiency at different levels of the irrigation system.

The ASCE definition of irrigation efficiency is similar to those designed to measure how much of the water delivered was effectively used. This definition is given by equation (2.3) (ASCE, 1978).

$$EI - \frac{\textit{Average depth of water beneficially used}}{\textit{average depth of water supplied}} \qquad (2.3)$$

Although the definition was originally meant to describe the efficiency of a single field, it can be applied for the scheme as whole. "*Beneficially used*" in this definition includes: salt leaching, crop cooling and pesticides and fertilizers applications.

The ICID (Bos, 1979), for the part of the main distribution system, defined the conveyance efficiency as:

$$e_c - 100 \times \frac{V_d + V_2}{V_c + V_1} \qquad (2.4)$$

Where e_c = Conveyance efficiency (percentage).

V_d = Volume of water delivered to the users.

V_2 = Non-irrigation deliveries from the main system.

V_c = Volume of water diverted or pumped from the river or ground water.

V_1 = Inflow from other sources.

Because the definition of equation (2.4) was designed to evaluate the performance of the main system alone, the concept of irrigation efficiency here is different. The distribution network is treated in a similar manner to that of the thermodynamic engine. The efficiency of an engine is measured by the ratio of the work output to the energy input. Equation (2.4) also measures the efficiency of the distribution system by the ratio of the water input to the water output. It, therefore, has always a value of less than or equal to 100%. The value of efficiency calculated in this way tells us how well the distribution system was able to transport the volume of water imposed on it, safely, to its destination at the users' outlets. It does not, however, distinguish between whether this water was delivered to satisfy some demands at these outlets or was delivered when it was not needed and therefore found its way to drains.

It must be noted here that neither of the ASCE and the ICID definitions (equations (2.3) and (2.4)) tells how much of the irrigation requirements were met. A basic limitation of the concept of irrigation efficiency pointed out by Hall (1960) as mentioned previously. Both definitions are basically measures of the water losses. The ICID definition measures transmission losses (i.e. canal seepage and direct evaporation from the canals network water surface) and the ASCE definition measures water losses in all the scheme.

A different conception of the term irrigation efficiency was taken by Bhuiyan (1982). He defined irrigation efficiency (IE) as the ratio of the net irrigation requirements to the supply (equation (2.5)).

$$IE - 100 \times \frac{ET + SP - RF_e}{IR} \tag{2.5}$$

Where ET = Evapotranspiration requirements.

SP = Seepage and Percolation requirements.

RF_e = Effective rainfall.

IR = Irrigation water supply.

With this definition, irrigation efficiency is a measure of how much of the irrigation requirements were met. The target value of IE is 100%. A value greater than 100 means that the supplies were less than the net requirements and, therefore, the crop must have suffered some water stresses. A value of IE less than 100, on the other hand, indicates the water supplies were more than the net requirements and, therefore, some water must have been lost. The reciprocal of the ratio in equation (2.5) is exactly a measure of the adequacy with which the irrigation requirements were met. The difference between the definition of irrigation efficiency in equation (2.5) and the ASCE definition (equation (2.3)) is that the definition of equation (2.5) compares between the *net requirements* and the supplies, whereas the ASCE's definition compares between what was *actually used* and the supplies. The definition of equation (2.5) assumes that the irrigation requirements are satisfied first before any water can be lost anywhere. As such it was clearly designed with rice systems in mind. This is because rice fields are usually flooded and the bulk of the water losses takes place as an unnecessary deep percolation in the field.

The forgoing review indicates that there are numerous different definitions of irrigation efficiency put forward in the literature. All of them take efficiency as a measure of output to input, but differ in what exactly are these inputs and outputs. Some times there are differences in the meaning of the concept of irrigation efficiency itself. Moreover, all the definitions offered in the literature are concerned with over-a-season total water supply. They do not, in any way, comment on how these supplies were distributed with respect to time or space.

A serious mistake associated with the concept of irrigation efficiency is that it is some times taken as if it is a comprehensive criterion adequate for complete evaluation of the performance of the irrigation system. Chambers (1976) discussed why such an exaggerated importance is sometimes given to efficiency. For a proper characterization of the performance, together with efficiency, other criteria are needed. Some of these are discussed in the following sub-sections.

2.1.3. Equity:

Equity is a measure of the spatial distribution of the irrigation water over the command area. The problem of inequity between users is known to exist in many large-scale small-holders irrigation systems around the world. It is commonly known as the top-tail ends problem and has been well documented in many field studies (e.g. Tabbal and Wickham, 1979; and Abernethy, 1985). At the main system level, inequity between users can result from various engineering, management and social factors. Engineering factors include inadequate system capacity caused by, for example, siltation and/or weed growth in the canals or can result from excessive seepage losses. Management factors include corruption of the operation staff and lack of proper sanctions for misuse of water. Social factors include differences in the social status between users. Inequity problems at the main system level are always associated with water shortage, because as the water supplies are reduced, competition on the water increases.

Like irrigation efficiency, numerous ways of measuring uniformity, or equity, of water distribution have been offered in the literature. Karmeli, et.al. (1985, chapter 13) reviewed some of them. Almost all of these measures were originally proposed for quantifying the uniformity of water application at the field level. Several of them have also been adapted for measuring the equity of the water supply to different users. In this sub-section some of these measures are discussed.

One of the oldest and most widely quoted measures of equity is the one proposed by Christiansen originally for measuring non-uniformity of water application by sprinklers (Christiansen, 1942). The method can equally be applied for characterizing inequity between different users. Christiansen uniformity coefficient (Cu) is defined by equation (2.6).

$$Cu = 1 - \frac{\sum_{i=1}^{N} |x_i - X|}{NX} \qquad (2.6)$$

Where x_i = Application depth at the i-th point.

X = Mean application depth.

N = Number of observations.

The target value of Cu is unity. A value less than that tells us how much of the excess water was supplied to the part of the system receiving more than the mean depth and how much water was in deficit in the other part. For example, a value of Cu = 0.8, can mean that the part of the area receiving more than the mean depth has taken 10% of the total applied water in excess of its share. Similar water deficit in the other part follows. Therefore, the Cu value can give an indication of how much additional water should be supplied in order to substitute the effect of inequity.

Because Cu as defined in equation (2.6) takes only the first moment of the water depth around the mean, it does not show how the excess or deficit water was distributed over the area receiving that excess (or deficit). i.e. The Cu value is the same whether the excess (or deficit) was distributed over 50% or only 10% of the area receiving more than the mean depth (less than the mean depth in case of deficit).

Because the universal statistic for the sample scatter is the variance σ, or the coefficient of variation $Cv = \sigma/X$, Wilcox and Swailes (1974) suggested that the coefficient of variation can be a more effective measure of the scatter of the quantities of water supplied to different areas. Their definition of the uniformity coefficient is given by equation (2.7). The terms in this equation are as defined for equation (2.6).

$$C_{wc} = 1 - \frac{\sqrt{\frac{\Sigma(x_i - X)^2}{(N-1)}}}{NX} \tag{2.7}$$

Varlev (1974), assuming a quadratic crop-water production function, showed analytically that the reduction in yield in the whole area due to non-uniformity is directly proportional to σ/X^2. He, therefore, proposed the use of the coefficient $F_{non} = \sigma/X^2$ as a measure of non-uniformity because, he argued, instead of using a purely statistical measure, a more logical evaluation could be obtained if the characterization is made in terms of the loss in yield.

In our view, both the C_{wc} and F_{non} provide some measure of the standard deviation of the variable under consideration. High values indicate the excess (and/or deficit) water was spread over a large area but both coefficients do not have the desired clear physical meaning which Christiansen coefficient (Cu) have.

The ASCE (1978), in seeking to standardize the efficiency and uniformity definitions, recommended the use of a measure originally devised by Criddle, *et.al.* (1954) who called it *pattern efficiency* (E_p) and is defined by equation (2.8).

$$E_p = \frac{\textit{average low quarter depth of water infilterated}}{\textit{average depth of water infilterated}} \tag{2.8}$$

Abernethy (1986) in similar lines, when dealing with the equity at the main system level in canal irrigation, suggested the use of the modified *inter-quartile ratio*, I_2, defined by equation (2.9).

$$I_2 = \frac{\textit{average depth of the best quarter of the area}}{\textit{average depth of the poorest quarter of the area}} \tag{2.9}$$

In our view, any of Christiansen coefficient (equation (2.6)), Criddle pattern efficiency (equation (2.8)) or Abernethy modified inter-quartile ratio (equation (2.9)) is easy to measure and has a clear physical meaning. They tell us how much, on average, the luckiest part of the system (the poorest in case of Criddle) is getting in relation to the other parts.

A departure in the conception of equity from the above mentioned definitions was taken recently by Sampath (1988) and Levine and Coward (1989). Sampath, discussing the characterization of equity in his (1988) publication, argued that equity should not be looked upon as uniformity of water allocation in the statistical sense. It must be considered together with its likely social impact. He differentiated between *equity* and *equality*. According to him, equality refers to the difference in the volume of water received by different users. If some inequality exists then, if it is in favour of the poor small farmers or in favour of some desperate social group the problem of inequality is more severe than the inequity. Otherwise the inequality of water allocation between users may have different social consequences. He went on and proposed a framework for evaluating equity. His framework involves the consideration of the differences between rich and poor, tail and head users and crop and water resource characteristics.

Levine and Coward (1989), expressed a similar view on the difference between equity and equality. They argued that sharing the water resource in proportion to the command area served is not always the pattern which the water users perceive as equitable. A "*fair*" or "*unfair*" sharing of the water resource is always based on some social principles accepted by the society. They gave the example of "*first in use first right*" as practised in western United States and some systems in Taiwan and the example of sharing the water in proportion to the labour contribution in the common canal construction as practised in some systems in Sri Lanka.

2.1.4. Consideration of Other Criteria:

With the focus of attention of research in irrigation management moved from the conventional diagnosis which concentrates on the farm level system towards adopting a "whole system" approach since the late 1970's, several workers have developed or advocated various types of evaluation criteria. However, in choosing their criteria, different approaches have been adopted.

Chambers (1976) set out to identify first the objectives of the irrigation system and then select criteria which reflect the degree of achievements in these objectives. Addressing the performance of gravity-fed bureaucratically managed systems, he pointed out their multi-objective nature and, therefore, the need for a multi-criterion approach in their evaluation. But he also cautioned against trying to include too many criteria in the evaluation, as this may generate the need for large quantities of data and, therefore, makes it difficult for the irrigation department alone to carry out the evaluation. In identifying his criteria, Chambers looked at the objectives of the irrigation system which can be achieved through some water control measures lying in the hands of the irrigation manager. He identified five criteria (see also Chambers, 1981)): (1) *Productivity*, which he defines as the ratio of the crop produced in the scheme to some scarce resource consumed. The scarce resource can be water, land or labour. (2) *Equity*, which refers to the "fair" distribution of the resources or services, specially water, between users. (3) *Utility to the cultivator*, referring to the convenience or appropriateness and predictability of the water supply schedule to those users. (4) *Stability* of the system or its ability to sustain long term operation without serious deterioration or loss of productivity. (5) *Cost-effectiveness*, i.e. the benefit achieved in terms of the above criteria must exceed the financial and organizational resources used.

In similar lines, Abernethy (1984, 1986, 1987, and 1989) derived his criteria from the objectives of the distribution network. He also looked at the objectives which the irrigation manager should strive to achieve. In these publications, Abernethy proposed the use of: *productivity*, *adequacy*, *equity*, *cost* and *durability*. He defines productivity as the ratio of the yield obtained under the given water supply pattern to that which could be achieved under an ideal supply. He proposed an outline for a possible way of characterizing productivity from the time history of the water supply, the ideal crop water requirement and some water production function (Abernethy, 1986 and 1987).

Several other workers took a different approach in selecting their performance criteria. Lenton (1983), addressing the performance of large-scale small-holders irrigation systems, which may be serving several thousands of users, argued that in such type of systems, criteria which reflect the level of achievement in the objectives such as the ones discussed previously require unmanageable volumes of data. He preferred instead to focus on a small number of key performance *indices* which describe the important characteristics of the system performance and which are measurable at a reasonable cost and with the existing staff. He selected: (a) a *cropped area measure* given by the ratio of the actually irrigated area to the potentially possible, (b) a *water delivery measure* given by the time average of the ratio of the water delivered to the target required, (c) a *crop yield measure* given by the ratio of the actual to the potentially attainable yield, and (d) an *equity measure* representing the variability of the three above measures across the irrigation system. In order to reduce the data requirements to a manageable size, he suggested the use of some sampling technique. A limited number of farms are to be sampled for data collection and the sample average for each index is to be taken as an estimate of the system performance.

Similar indices were suggested by Bhuiyan (1982) when he was discussing methodologies for evaluation field research for improving irrigation system performance. Bhuiyan also stressed the point that a better picture of the conditions in the field could be obtained by employing multiple criteria rather than a single one. He discussed the usefulness and limitations of: (a) *Crop yield.* (b) *Cropped area* (this is because improved system performance is expected to result in some water saving which could be used for expanding the irrigated area). (c) *Water use efficiency*, which refers to the water use relative to the water supply. (d) *Irrigation efficiency*, referring to the net water requirements to the water supply. (e) *Water adequacy*, measured, for example, in terms of the number of days in which the crop suffered certain level of stress. (f) *Equity*, measured in terms of the water supplied or net return to different farmers.

Similar indices, but a more comprehensive approach, has been taken by Garces (1983) in his study of the performance of the rice irrigation systems in Philippines and by Mao Zhi (1989) when evaluating the effect of a rehabilitation program undertaken in one of the Chinese irrigation systems. Both Garces and Mao Zhi subdivided the irrigation system into a number of sub-systems. The performance in each sub-system was gauged by a number of indices which they considered as critical indicators of healthy performance. The sub-systems include: (a) An engineering sub-system, gauged by indices related to the water and land utilization. (b) An economic sub-system, judged by indices related yield and income per unit area or per unit volume of water. (c) A human or social sub-system evaluated by indices reflecting the distribution of the benefits to and the satisfaction of the cultivators.

Several other workers adopted a less comprehensive approach by concentrating on a single key phenomenon and using it as an index which they took to reflect the overall health of the irrigation system performance. The idea is that such an index could easily be measured. Such an approach was adopted by, for example, Malhotra, Raheja and Seckler (1984) and Seckler, Sampath and Raheja (1988). Those workers argued that the difficulty of measuring water flows at farm level and the insistence on precision are part of the reason why performance of irrigation systems is rarely monitored. They also argued that while measurement of water flows at individual farmer's outlet may be possible for few number of fields or plots, for research purposes for example, it may prove impossible if the performance monitoring is to be taken as a continuous part of a management information system. They concluded that for continuous monitoring of large irrigation systems, a single approximate *indicator* of the performance should be adopted. Working with the warabandi system of management in northwest India, in which the objective of the irrigation system is to supply water to irrigate only a pre-specified part of each farmer's cultivatable command area, they set out to measure the achievement of this objective by, simply, visual observations of how much of each farmer's land was wetted. Their index is a ratio of the "*net wetted area*" or the "*total wetted area*" to the farmer's cultivable command area. They defined the net wetted area as the area of each farmer wetted at least once during the irrigation season and defined the total wetted area as the net wetted area times the number of irrigations during the season.

The literature on irrigation systems performance criteria reviewed above indicates the multi-objective nature of the irrigation systems, particularly those which are bureaucratically managed and serving large number of users. These are the most common in developing countries, the subject of this study. For proper characterization of the performance of these systems, a set of criteria, rather than a single one (such as efficiency) needs to be employed. In doing that, it is, however, important to avoid the over inclusiveness "*trap*" mentioned by Chambers (1976). For the evaluation to be part of a seasonal or annual monitoring process, its data requirement must be manageable and, preferably, use the type of data routinely available. In this respect, Biswas (1984 and 1990) discussed the trade-offs between the coverage and accuracy, on one side, and the cost and utility, on the other side, of the information to be collected for the purpose of monitoring the performance of irrigation systems.

As for the criteria proposed in the literature, although, in our view, they offer enough range of choice for characterizing all aspects of the performance, the definitions offered for some of the newly introduced criteria are very general. While some were offered without detailed methods of how to measure them, some work has been done on the characterization of *productivity* and *adequacy*. This is briefly reviewed in the next two sub-sections.

2.1.5. Productivity:

Productivity was defined by Chambers (1976 and 1981)) as the ratio of crop production to some scarce resource used. The scarce resource can be water, land or labour, depending on which of them is the limiting factor for the production. Although productivity is commonly quoted as ton per hectare (i.e. productivity of land) for water management purposes, the productivity of water is more appropriate. However, because the crop production is influenced by many factors, water being only one of them, if productivity is to be used as a measure of the quality of services provided by the irrigation system, the influence of all factors other than water have to be isolated. This is the approach adopted by Davey and Rydzewski (1981) and by Abernethy (1987). From a record of the actual pattern of water supply, Davey and Rydzewski, (1981) using some crop-production functions derived by other workers, calculated the theoretical yield which could be achieved under the actual water supply pattern. The ratio of this yield to the yield obtainable under an ideal water supply pattern is taken as the measure of productivity in the scheme.

Abernethy (1987) differentiates between land productivity and water productivity. He followed an approach similar to that of Davey and Rydzewski mentioned above to calculate what he considered as *potential productivity of land.* Because the procedure does not recognize cases of excess water supply, in situations where wasted water could have been used elsewhere for crop production, he introduced the concept of *potential productivity of water.* He defined potential water productivity as the ratio of crop produced under the given water supply pattern to the yield which could be obtained if the same quantity of water was delivered under a supply pattern which exactly matched the crop demands.

Clearly these productivity measures can be good parameters for describing how adequate was the water supplied for satisfying the crop needs and how effectively was the water used. The concepts are, however, relevant only for mono-crop systems where a single crop-water production function is applicable everywhere in the system.

2.1.6. Adequacy:

This refers to the ability of the irrigation system to supply enough water for satisfactory crop growth. Although this may be the most important criterion for evaluating irrigation performance, relatively little work has been done on methodologies for measuring it when compared with irrigation efficiency and uniformity. A crude measure of adequacy is the *relative water supply* (Bhuiyan, 1982) which is defined as the ratio of the overall seasonal supply to the demand. Such a measure, however, neglects the fact that although the total supply during the whole season may be satisfactory, some periods of water stress may be experienced. Characterization of adequacy must, therefore, reflect what is referred to as *regularity* (Abernathy, 1986) or *timeliness* (Abernethy, 1987) of the water supply. i.e. How did the water supply pattern match the time variation of the water needs of the crops.

Wickham (1971) (as referred to by Bhuiyan (1982)) developed a simple low-cost methodology for measuring the farm level adequacy in rice systems. In a rice field the water supply is adequate as long as the soil moisture is above saturation. A count of the number of stress days during the season, by visual observations, were taken by Wickham as the measure of adequacy. The stress days were taken by him as the number of consecutive days during the season without standing water in the field (excluding the first three days in each event of a stress period).

The International Irrigation Management Institute (Ng, 1988) also developed a simple but a more detailed technique for characterizing the farm level adequacy in rice irrigation systems. The technique consists of recording the water levels inside a perforated tube installed inside the field. The water levels are recorded daily, from transplantation to 20 days before harvest. The data is then used to calculate indices measuring the *frequency*, *duration* and *intensity* of the water shortage events during the season.

For non-rice irrigation systems, Lenton (1983) introduced a measure of adequacy which takes into consideration the timing of the water supply in relation to the crop development stages and, therefore, its sensitivity to water stress. He defined the Water Delivery Performance (WDP) as:

$$WDP = \sum_{t=1}^{T} k(t)\frac{v(t)}{V(t)} \tag{2.10}$$

Where

v(t) = Volume of water delivered to the area under consideration in a time period of t-days during the season. The time period t can be a week, 10 days or of any other convenient length.

$V(t)$ = Target volume of water to be delivered to the area during the time period t for the crop(s) grown and the existing condition of the soils and rainfall or any other source of water.

$k(t)$ = Weighting factor reflecting the relative sensitivity of the crop in the time period t. The values of $k(t)$'s are normalized so that, over the season, they sum up to unity.

T = Number of time periods in the season.

With the definition given by equation (2.10), the WDP equals unity if the water delivered to the area during the time period was exactly equal to the target volume, equals zero if no water was delivered during any time period and takes a value between zero and unity if the supply during some or all time periods was less than the requirements. To deal with over supply, which according to equation (2.10) produces a WDP value greater than unity, Lenton suggested that either we set $v(t) = V(t)$ as an upper limit, or the definition of equation (2.10) is to be modified for the over supply periods by taking the reciprocal of the term $(v(t)/V(t))$.

All adequacy measures reviewed above are expected to have a strong correlation with the yield. In fact both adequacy and productivity (i.e. *land productivity* in the terminology of Abernethy (1987)) are essentially measures of the same thing. Both criteria reflect the level of success of the irrigation system in delivering water for a decent crop growth.

As was mentioned previously, proper evaluation of the irrigation systems performance requires the use of a set of criteria, rather than a single one.

It will be argued in this study that for many purposes it may be necessary to combine the achievements of all these criteria into a single overall performance measure. In the reminder of this chapter methods which are used in water resources planning for comparing different water resources projects and development plans are discussed.

2.2. Multicriteria Evaluation Techniques:

The selection of a water resource development plan for implementation involves the consideration, evaluation and ranking different possible alternative projects and development plans. These projects and plans are always expected to serve a number of objectives. The consideration of all these objectives in the evaluation necessitates the use of evaluation techniques which can deal with more than one objective. The development of such techniques has received considerable attention in the last three decades. A large number of techniques have been developed. They are generally known as *multiobjective* and *multicriteria evaluation techniques*. Although these techniques were originally developed for evaluating proposed projects, they are relevant to the evaluation of existing irrigation systems. Their relevance comes from the fact that they are basically methods of combining the achievement in all individual objectives into one overall measure of effectiveness. In this section the main characteristics of these techniques are reviewed.

2.2.1. Historical Background:

Traditionally, ranking alternative water resources development plans employs benefit-cost analysis[1] for this purpose. For each alternative plan or project, the benefits and costs are estimated and then, based on some benefit-cost criterion, alternative investment plans are ranked. The benefits are estimated based on the increase in the national income expected from the investment and the costs are defined as the financing required plus the benefits forgone by the use of the resources involved. Such criterion for ranking alternatives based on their impact on the national economy is generally known in the literature as the *economic efficiency* objective or criterion. Other social, regional and environmental impacts of the proposed investment may be mentioned in the planning documents as *secondary effects* (Maass, 1966) but the selection criterion was always economic efficiency alone.

During the 1960's concern was expressed about the deficiency of using economic efficiency as a single criterion for ranking water resources development alternative plans. The main criticisms of the approach, at that time, were: (1) its failure to consider the distribution of the impact of the proposed development plans among different people and regions (Maass, 1966) and (2) lack of incorporating public opinion in the selection process (Ortolano, 1976).

The formulation of procedures which can take into consideration objectives other than economic efficiency and the development of models for the political

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[1] The principles of benefit-cost analysis is contained in many text books. Complete overview of the technique is given by Rydzewski (1987). With the benefit-cost technique projects and plans are ranked using one of the following criteria:

1) *Benefit-cost ratio*. i.e. The ratio of the discounted benefits to the discounted costs
2) *Net present value*. i.e. Excess of the net discounted benefits over the net discounted costs.
3) *Internal rate of return*. i.e. The discount rate required to given zero net present value.

decision process for incorporating public opinion in analysis was initiated by the work of Harvard University Water Program published by Maass, *et.al.* (1962). This work basically contains adaptation of the benefit-cost analysis to incorporate economic efficiency and benefit distribution. Based on that work formal procedures for the generalization of the benefit-cost analysis to consider all relevant objectives was developed and is generally known as *multiobjective benefit-cost analysis*. It differs from traditional benefit-cost analysis in that while the latter focuses on economic efficiency alone, the former considers all relevant objectives. For an irrigation project, for example, in addition to the economic efficiency, the multiobjective benefit-cost analysis can incorporate objectives such as self-sufficiency in food production and creation of jobs.

Multiobjective benefit-cost analysis for selecting the optimum water resource project or plan is explained by Major (1977). The procedure consists of employing some social consensus or some political process for choosing the relevant objectives to be used in the analysis and then translating these objectives into design criteria. Having done that, then for each alternative all objectives are expressed in monetary terms and the net discounted benefit (discounted benefits minus discounted costs) is estimated. If the preferences of the society can be obtained then alternatives can be compared based on their attractiveness to the society.

To explain the procedure, fig.(2.1) was adopted from Major (1977). To enable graphical representation only two objectives are considered in this example: (a) increasing national income and (b) increasing the income of a certain region. The net discounted benefits of the two objectives, B_n and B_r respectively, are used as coordinates in fig.(2.1).

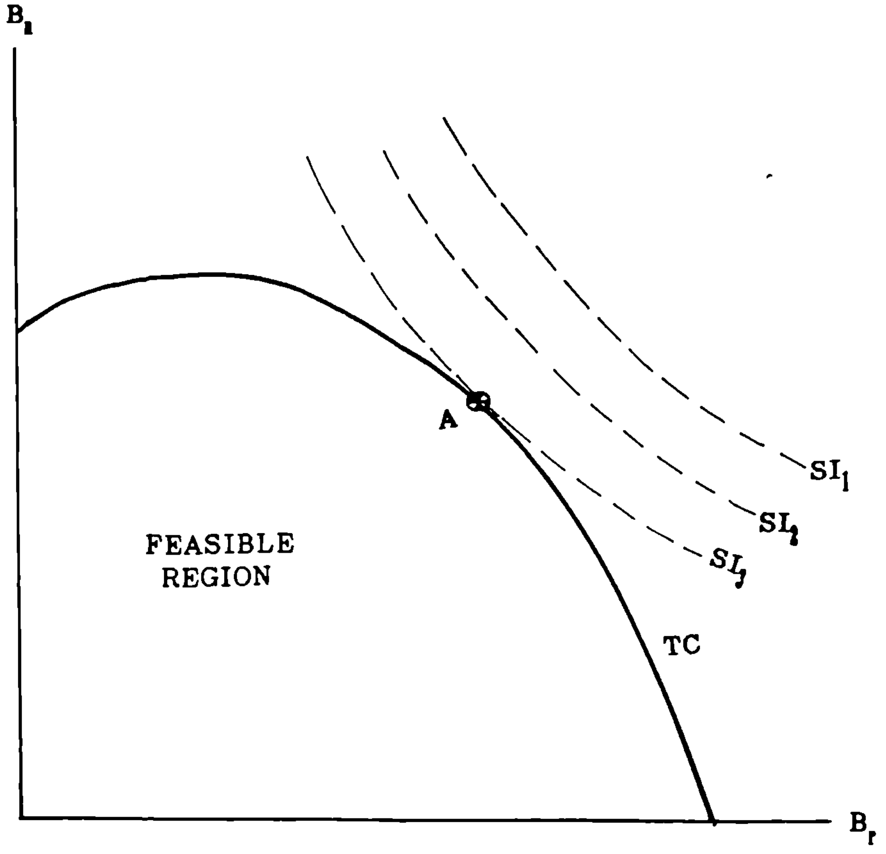

Fig.(2.1): Graphical solution of a multiobjective problem with two objectives.

If for each alternative project or plan, the net discounted national income (B_I) and the net discounted regional income (B_r) are estimated, alternatives can be represented by points in the graph of fig.(2.1). One project, say an irrigation system, can be represented by different points each representing, for example, different size of the command area, different geographical location or different investment level. The set of all points in the figure represents the *feasible alternatives* or *feasible region* from which the optimum choice is to be selected. The boundaries of this set, curve TC, is known as the *transformation curve* and represents the *noninferior set* of alternatives. The set of noninferior alternatives is defined as the set of alternatives for which an improvement in one objective cannot be achieved without some loss in another objective. The optimum choice must necessarily be represented by a point in this noninferior set.

If the social preferences between the two objectives can be ordered, then all points of equal social preference can be plotted and connected together to form lines of equal *social indifference* such as SI_1, SI_2 and SI_3 in fig.(2.1). These are lines of decreasing social utility. From this figure, clearly point A, which is the point where one of the social indifference curves and the transformation curve are tangent, is the alternative of the highest utility to the society among the possible alternatives. Other alternatives can be ranked according to the utility curve passing through them. The slope of the tangent to the transformation curve at point A indicates the relative weights which the society assigns to the two objectives under consideration at the particular levels of their achievements. These relative weights are of great importance when the analysis is to be carried out analytically. For the example of fig.(2.1), if the slope of the tangent at point A is $(-1/\alpha)$, it means that the weights which the society assign to the national income objective and the regional income objective are respectively 1 and α. The problem can, therefore, be expressed mathematically as:

$$\max. (B_n + \alpha B_r) \qquad (2.11)$$

Subject to (B_n, B_r) is within the feasible region.

Such representation of the problem into a weighted objective function was introduced by Marglin (1962, pp.78-81) in the work by Maass, *et.al.* (1962). Discussing methods of combining the two objectives of economic efficiency and distribution of benefits, Marglin suggested that the relative weights of these two objectives may be taken as the willingness of the society to sacrifice efficiency for distribution. In real life, however, these relative weights are not necessarily constant. The trade-offs between any two objectives may depend on the level of achievement in the objectives. This point is discussed in more detail later in this section.

The example presented above is for the case of two objectives only. Obviously for a large number of objectives such graphical representation is not possible and a more general analytical approach must be adopted. There are a number of techniques for doing that. These techniques are generally known as *multiobjective programming techniques*. A review and classification of these techniques are given by Cohon and Marks (1975) and Starr and Zeleny (1977). References to the applications of these techniques in the field of water resources are given by Goodman (1984, chapter 13).

As can be seen from the example of fig.(2.1), identification of the most attractive project or plan to the society (point A) requires the construction of the transformation curves TC and the derivation of the family of the social indifference curves SI_i (which represents the preference of the society) from the decision-maker[1] or from some form of social consensus. Analytical procedures for doing that can be broadly classified into two categories: (a) techniques which do not ask for an explicit statement of the social preference and (b) techniques which require explicit information about the social preference. The two categories are briefly reviewed in the following two subsections.

2.2.2. Techniques Not Asking for Explicit Statement of Preferences:

The approaches under this category assume that the preferences of the

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[1] By decision-maker in this thesis it is referred to the decision-making body which, in public sector, may be a group of experts, a government department or a selected committee.

decision-maker are difficult to quantify. The difficulty comes from the fact that the decision-maker himself may not be able to express his preferences before he get some idea of what are the possible alternatives. These approaches also assume that multiobjective planning is largely a political decision in which the role of the analyst is confined to the identification of the range of possible alternatives and the impact of each of them. It is up to the decision-maker then to choose the optimum from these alternatives. These approaches, therefore, require the analyst to identify the set of all the noninferior alternatives. i.e. He must first construct the transformation curve TC of fig.(2.1). These noninferior alternatives are then presented to the decision-maker (for example in a form of a graph as shown in fig.(2.1)). The decision-maker then uses his own judgement to select the optimum alternative. Several techniques can be followed for generating the noninferior set of alternatives. The most common are the *weighting method* and the *constraint method* (Cohon and Marks, 1973).

With the *weighting method* the relative weights of all objectives (i.e the value of α in equation (2.11)) are assigned some arbitrary set of values. The problem becomes normal maximization of the weighted sum of the objectives for which any linear optimization technique such as the simplex method[3] can be used to generate the optimum solution. This solution gives one point in the set of the noninferior alternative. The set of weights of the objectives is then changed to generate other noninferior points. The process is repeated till all the noninferior set of alternatives is obtained.

The *constraint method* is similar to the weighting method. The only difference

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[3] Techniques for solving linear programming optimization problems are contained in many text books. See, for example, Taha (1976).

is that instead of varying the weights, with the constraint method the level of achievements in all objectives, except one, are fixed at a given level. A linear programming technique is then employed to generate one point in the noninferior set. The fixed level of the objective is then changed to generate other noninferior points. The process is repeated for all objectives till all the noninferior set of alternatives is generated.

Clearly, both the weighting method and the constraint method put a heavy computational burden on the analyst as all possible noninferior alternatives have to be generated. Many of the generated noninferior points will turn out to be far from being satisfactory to the decision-maker. To reduce this computational burden some methods have been developed (Cohon and Marks, 1975). They include an *adaptive search* procedure in which initial points in the noninferior set are generated and then used to indicate the direction of search for other points. Another approach is to let the decision-maker provide some limited information about his requirements. For example by asking him to specify the minimum acceptable level of achievement in each objective as is done, for example, in *goal programming* (Lee, 1972). In this way the computational burden can be considerably reduced by restricting the analysis to the domain within which the minimum level of achievement in each criteria is satisfied.

The techniques mentioned in the previous subsection may be the most suitable for multiobjective decision making in public sector planning. This is because in the public sector it may be difficult to extract the preferences of the decision-maker in an explicit form. Unfortunately these techniques have their limitations: (1) As was mentioned previously their major weakness is their computational inefficiency particularly when several objectives are involved

(Cohen and Marks, 1975). This is because the set of the noninferior alternatives has to be generated completely (or at best partially when the preferences of the decision maker are partially known). (2) For up to three objectives the results of the analysis can be presented graphically to the decision-maker for the selection of the optimum alternative. For more than three objectives the presentation of the noninferior set is a problem. (3) in addition to these there are the traditional problems associated with the benefit-cost analysis itself: a) estimating the benefits and costs of each alternative has to be based on a non-existing market, as the proposed project may considerably change the equilibrium of the existing market, b) because of the subjectivity involved in estimating the benefits and costs of any proposed project, Biswas (1984) argued that the benefit-cost methods of analysis are sometimes deliberately misused by the tendency of government officials to inflate the benefits and reduce the costs in order to get a proposed project accepted for funding. In this context Tiffen (1987) discussed the drawbacks of the over-dependence on the benefit-cost analysis in practice for selecting proposed projects for funding. She cautioned against its failure to incorporate all aspects of benefits and costs involved, particularly operation and maintenance cost.

2.2.3. Techniques Requiring Explicit Statement of Preferences:

To overcome the difficulties of the techniques discussed in the previous section a set of alternative techniques have been developed in which instead of transforming all the objectives into monetary units, they are measured in different units and a weighting system is employed to reflect their relative importance. To do that, however, means the preferences of the decision-maker have to be explicitly stated. These techniques are some times known as *multicriteria evaluation techniques* and are most useful when it is difficult to transform the benefits and costs into market prices. There is a large variety of them including vector optimization techniques such as *compromise programming* and *weighted goal programming method*, simple aggregation models and techniques which use a utility function.

Compromise programming, which has been applied in the field of water resources planning by, for example, Duckstein and Opricovic (1980), seeks to identify the noninferior alternative with the least distance from the optimum alternative. For each objective the decision-maker specifies the ideal level of achievement and the relative weight. The general formulation of the optimization problem is then:

$$\min. \left(\sum_{i=1}^{N} \omega_i^{\alpha} \, [Z_i - z_i]^{\alpha}\right)^{\frac{1}{\alpha}} \tag{2.12}$$

In this expression; Z_i, and ω_i are respectively the ideal level and the relative weight specified by the decision-maker to the i-th objective and z_i is the level of its actual achievement. Sometimes the term inside the square bracket is normalized by dividing it by the difference between the ideal and the minimum level of the objective. The value of α is varied between 1 and ∞ to obtain a range of solutions. For example, when $\alpha = 1$, the expression of equation (2.12) becomes the weighted sum of the deviation from the ideal solution which is the expression used in *weighted goal programming technique* (Lee, 1972). When $\alpha = 2$, the solution becomes the minimization of the geometric distance between the i-th alternative and the ideal alternative.

Techniques using vector optimization such as compromise programming and goal programming are particularly suitable when a large number of possible alternatives is involved and where the objectives Z_i (i=1, 2 ... N) are functionally related to some other decision variables x_j (j=1, 2 ... M). i.e When each Z_i can be expressed as $Z_i = Z_i(x_j)$. In many practical situations the problem may be choosing from a limited number of alternatives in which the level of achievement in each objective is determined directly rather than being a function of other decision variables. For this latter type of problem it may be more suitable to employ simple aggregation models such as the ones reviewed by Huber (1974) or a technique such as ELECTRE (David and Duckstein, 1976). Cohon and Marks (1975), however, argued that these latter techniques may not be suitable for water resources planning problems because water resources planning is usually characterized by a large number of possible alternatives associated with different decision variables.

Huber (1974) reviewed what he called *multi-attribute utility models* and defined them as models designed to obtain an overall measure or utility for items which are characterized by more than one property and therefore require a multi-criterion evaluation. Selecting a job from a number of offers depending on the salary, location and nature of the work, or the decision on which house to buy depending on its location, size and cost are typical problems in which such models are useful. Huber examined various studies in management science in which additive (equation (2.13)) or multiplicative (equation (2.14)) aggregation models were employed for calculating the utility of a multi-criterion item. In both models b_i and x_i are respectively the relative weight assigned by the decision-maker and the level of performance with respect to the i-th criteria and N is number of performance criteria. In the studies reviewed by Huber no proper justification was given for selecting one model or the other. The choice was based on the ability of the model to predict the evaluation of the decision-maker.

$$U = \sum_{i=1}^{N} b_i x_i \tag{2.13}$$

$$U = \prod_{i=1}^{N} x_i^{b_i} \tag{2.14}$$

With the *ELECTRE* method, which has been applied in the field of water resources planning by David and Duckstein (1976), the decision-maker specifies the weights of the objectives or criteria together with the maximum expected and minimum acceptable levels of performance in each of them. Alternatives are compared using the *concord index* c(i,j) and the *discord index* d(i,j). The concord index c(i,j) is defined as the normalized sum of the weights of all criteria for which alternative j performs better than alternative i, and the discord index d(i,j) is defined as the maximum range (i.e. the difference between the maximum and minimum performance levels) of all criteria for which alternative j performs better than alternative i, divided by the maximum range of performance of these criteria. The c(i,j) and d(i,j) are presented in a matrix form. The matrix elements are limited to those for which c(i,j)>p and d(i,j)<q for some selected values of p and q. Other elements of the matrix are replaced by zeros. The matrix elements are then used to construct graphs or sketches to facilitate comparison. A separate graph is drawn for each pair of values for p and q.

The main problems with the techniques which require explicit statement of preferences and which are reviewed so far are that: (1) They assume constant trade-offs between the criteria irrespective of their performance level. In real life this is hardly the case. The trade-offs are always expected to change with the performance level of the criteria. (2) The decision-maker has to state his preferences by assigning the weights to the criteria in an ad hoc manner. This is made even more difficult by the fact that these weights have to be given in the absence of any idea of what are the likely levels of performance in each criterion. To cater for these problems some techniques have been developed in which *trade-off functions*, rather than weights, are generated. i.e. The trade-offs are generated from the decision-maker as a function of the level of performance in each criteria. Such techniques include the *surrogate worth trade-off method* and the *multi-attribute utility theory.*

The *surrogate worth trade-off method* as described by Haimes and Hall (1974) consists of generating the noninferior set which is then used with the decision-maker to generate the surrogate worth trade-off function. The optimum solution is the point at which all the surrogate worth trade-off functions are equal to zero.

Objectives are considered only two at a time, say objectives Z_i and Z_j, all other objectives are kept at their minimum levels. Objective Z_j is then used as a constraint and objective Z_i is optimized for various levels of Z_j. A functional relation T_{ij} between the optimum levels of Z_i and their corresponding values of Z_j is derived. Haimes and Hall (1974) call this T_{ij} the *trade-off function* between objectives i and j. For each combination of two objectives there is a trade-off function. For a problem of N-objectives, therefore, there are N(N-1)/2 such trade-off functions (Cohon and Marks, 1975). Each of the T_{ij} function is then used with the decision-maker to generate the *surrogate worth trade-off function* W_{ij} between objectives i and j. The function W_{ij} is defined as a relationship between the desirability (in a scale of -10 to +10) of the decision-maker to exchange T_{ij} units of the i-th objective with one unit of the j-th objective. Having generated all the W_{ij} function the optimum choice is the point at which all the W_{ij} functions are simultaneously equal to or near zero.

In this way the surrogate worth trade-off method realizes the variation of the trade-offs with the level of achievements in the objectives but only in a limited way since these trade-offs are generated for two objectives at a time assuming fixed levels for all other objectives. On the other hand the method, like the constraint method discussed in the previous sub-section, is computationally inefficient when several objectives are involved. One of its advantage is, however, that the decision-maker is lead in his decision through a systematic comparison, only two objectives at a time. In this way the confusion which may arise from having to give his judgement considering all objectives simultaneously may be considerably reduced.

The multi-attribute utility theory approach, which will be discussed in detail in Chapter 7, is different from all approaches discussed above. Instead of formulating the problem in a vector optimization form, the multi-attribute utility theory approach aims to derive the choice principles from the choice behaviour of the decision-maker in the form of a utility function. This utility function reflects the decision-maker's preferences over various levels of achievement in each objective and his trade-offs between different objectives. Once this utility function is obtained then it can replace the decision-maker and be used for ranking alternative projects and plans with respect to their attractiveness or strength of desirability to that decision-maker without him necessarily being present. The main assumption made with the theory is that, provided certain conditions are satisfied, the utility function of the decision-maker can be explicitly derived from his choice behaviour. The theory is a self-contained method containing a step-by-step procedure for deriving the utility function from the decision-maker. The application of the theory is, however, not free from difficulties. These are discussed in Chapter 7.

To sum up this section, some of the multiobjective and multicriteria evaluation techniques are reviewed. The review is far from covering all techniques available in the literature and the purpose here is to point out the availability of a large variety of them, each has its advantage and limitations. The choice of a particular technique largely depends on the problem under consideration.

CHAPTER 3

CONCEPTUAL FRAMEWORK

3.1. General Approach for Evaluation

The literature on organization effectiveness contains two approaches for evaluating that effectiveness: the "*goal model*" and the "*system model*" (Price, 1970; and Strasser, *et.al.*, 1981). The difference between the two approaches lies in the type of the performance criteria to be used in the evaluation.

The traditional and most widely used is the goal model approach which views organizations as a goal-achieving machines for attaining specific set of goals or objectives. The effectiveness of the organization is, therefore, directly measured by the degree to which these objectives are achieved. All effectiveness or performance criteria are designed to reflect the degree of achievement of the organization objectives.

Critics of the goal model approach have pointed out some problems with its use. The main difficulties are: (a) Organization objectives are usually difficult to identify (Katz and Kahn, 1978, pp. 19). (b) Difficulties in comparing the performance of different organizations. The difficulties stem from the fact that such comparison requires the use of performance criteria which are common between the organizations to be compared. Because the objectives of different organizations differ widely, if only goal criteria are used for the evaluation, it may not be possible to find these common criteria (Price, 1970).

The system model approach, which is a more recent development, views the organization as a social organism composed of a complex collection of units, subunits and individuals sharing some facilities. These units are also interconnected together with some rules with which they interact internally and with the surrounding environment (Pasmore and Sherwood, 1978). The effectiveness of the organization is measured in terms of its ability to maintain itself internally and interact with the surrounding environment (Strasser, *et.al.*, 1981). There is no general rule for the choice of the effectiveness evaluation criteria. They depend on the conception of the evaluator to the processes involved in the organization and the way it should work. Criteria commonly used are "*indicators*" or "*signs*" which reflect the behaviour or status of the processes in the organization or its interaction with its surroundings but not necessarily the achievement of its goals. They may include some goal criteria but if they are included their weights in the overall performance are suppressed by the dominance of process criteria. The advantage of using the approach which is claimed by its users is the possibility of finding criteria of universal relevance to all similar organizations and, therefore, intercomparison of these organizations may be possible.

To help clarify the difference between the performance criteria used in the two approaches, let us consider them in the context of irrigation systems. The evaluation of the irrigation system performance can proceed in two ways: The user of the goal model approach should first define the objective of his systems and then design his evaluation criteria to reflect the degree of achievement of these objectives. In this way he should end up confining himself to goal criteria such as *adequacy*, *efficiency* and *profitability*. The user of the system model, on the other hand, may look at, for example, the "*Numbers of farmers' complaints*", "*Collection of water fees*" or "*frequency of violation of the rotation by the farmers*". The latter type of criteria signal some indicators about the processes taking place in the system. They may not reflect the degree of achievement of the objectives of the irrigation system but their values may be correlated to the overall health of the system performance and they may be common to different types of irrigation systems.

The system model approach is criticised because: (a) The criteria do not allow for the identification of the reasons for the observed level of performance (Strasser, *et.al.*, 1981). (b) The model does not offer any specific way of choosing the criteria (Mohr, 1973). This resulted in a lack of agreement in the way in which criteria are chosen when the model is used by different people.

In our view, the question of which of the two approaches is to be followed depends on the organization to be evaluated, the purpose of the evaluation and the availability of the data. For the purpose of the study at hand, a goal model is adopted for the following reasons:

1) The main emphasis of this study is on methodology suitable for the regular seasonal or annual evaluation, or may be for measuring if an improvement in the system performance was brought about by a rehabilitation investment, rather than comparing the performance of systems which are operating under different settings.

2) Although we recognise the difficulties involved in the identification of the objectives of the irrigation system (these are discussed later in this chapter), nevertheless, we believe it is still possible to overcome these difficulties.

However, the system model approach may provide a more appropriate and cheap method for the irrigation managers to use in their day to day monitoring of their systems. The manager can pick up some of the key variables of the ongoing processes and monitor the variation of some indicators which reflect their status. Such indicators can signal how "*things are going*" within the system and help the manager make frequent adjustments in his management policy. For example, the manager may like to know the effect of "*organizing some regular meetings between the water users and the operation staff*" or the effect of "*tightening the regulations concerning unofficial water withdrawal from the canals on the supply to the tail farmers*". An indicator of the effect of these could be "*the variation of the water level at the tail of the canal*" or "*the number of farmers complaints*".

3.2. Nature of Irrigation Systems Objectives

Adopting the goal model approach, an irrigation system is said to be performing satisfactory if it is able to achieve its intended goals. The first step in the evaluation is, therefore, to acquire a clear idea of what are the objectives which these systems are aiming to *achieve and then see if we can* set measurable standards against which our judgement of the performance can be based. Such standards are called "*performance criteria*". In setting these standards, we do not seek to specify definite thresholds above which or below which the performance is either accepted or rejected altogether. In irrigation systems performance there is always a range of degrees of acceptability corresponding to a similar range of levels of achievements in what ever objective we are seeking to achieve. This means that for us to measure the degree of acceptability of the performance we need to have a scale by which different levels of achievements of the objectives can be segregated. i.e. A scale by which we can measure different degrees of satisfaction in each criteria. The scale with which the level of achievement in any objective is measured is called the *attribute* of that objective.

3.2.1. Multiplicity and Conflicting Nature of the Objectives:

In the previous chapter it was established that irrigation investments, like most other public investments, always serve multiple objectives. Satisfactory characterization of their performance, therefore, requires the use of a set of criteria rather than a single one. Obviously not all these objectives are equally important to achieve. Some may be essential for good system performance, some may be less critical and others may just "make things better" if they can be achieved. Moreover, irrigation systems objectives are not only multiple, but can also be conflicting in that the achievement of one objective may not be possible without some sacrifices in other objectives. For example, an increase in the water use efficiency can be achieved through introducing some structural or managerial control measures. But this should necessarily result in some loss in the flexibility with which the water users receive their supplies. Improvement of the water use efficiency can also be achieved by lining the canals to reduce seepage losses. But again this is associated with the high cost of this lining. Therefore, the problem of evaluation must necessarily involve trade-offs between different objectives: i.e. Judgements on how much sacrifice are we prepared to give up in the achievement of one objective in return for an improvement in the level of achievement of another objective by some fixed amount.

The multiplicity and conflicting nature of the objectives of different systems mean that comparison of the performance of these systems cannot be achieved without combining the level of achievement in all individual criteria into a single overall index. Such an index should also reflect the trade-offs between the objectives, i.e. their relative importance. If such an overall performance index can be obtained, it would only then be possible to rank the performance of different irrigation systems. It would also be possible to monitor the performance of the same system over time in order to judge how much improvement in the overall performance is gained from an investment in a rehabilitation program or from adopting one design approach and/or management policy or another. A single index which summarizes the overall performance of the irrigation system can also be useful to report this performance to the public and to the non-specialized government administrators and decision-makers.

However, in reporting the performance with respect to all the criteria considered in the evaluation in the form of a single index, some important information must necessarily be masked. In many cases together with the overall performance index, the performance with respect to individual criterion is also needed. For example, if further investigations are to be conducted for understanding the reasons behind the observed level of performance or to decide on what specific remedial measures can be taken in order to improve the situation. In other situations it may be necessary to report some of the details on which the judgement was based, such as what criteria were used? and which of them were considered most important?.

3.2.2. Variability of Objectives and Trade-offs:

The fact to be recognized in evaluating irrigation systems is that individual systems differ widely in two important aspects: (1) The objectives which each systems is expected to achieve and, therefore, the set of criteria to be used in its evaluation. (2) The trade-offs between these objectives and, therefore, their relative importance. The set of objectives and the trade-offs between them in every individual system are dictated by the physical, economic, social, political, legal and environmental settings in which the system is operating. They some times differ even across systems in the same country or region. For example, while the adequacy of water supply may be the most important single criterion in most irrigation systems, it may be irrelevant in evaluating the performance of the *Warabandi* systems of the Punjab in India and Pakistan. The objective of the warabandi irrigation systems is to distribute the available water between the users according to pre-agreed shares. It is up to those users to decide what crop to grow and how much area to irrigate in order to make the best use of their water allocations (Seckler, *et.al.*, 1988). It is, therefore, not appropriate to measure the performance of the warabandi irrigation systems by how adequately were the crops irrigated. Similar differences between irrigation systems exist also in the importance attached to different criteria. For example, water use efficiency which assumes high priority in places of water scarcity is less important in places where the water availability is not a constraint for the expansion of the irrigated agriculture.

Even for the same irrigation system, the set of objectives and the trade-offs between them may be different for different participants in the system. For example, the farmers primary concern may be a flexible access to water and the agricultural manager would like to see the optimal irrigation requirements satisfied every where in his area. The local system manager have to live with these together with the pressure from the irrigation department to save water and cut down in the operation and maintenance cost. This means that the objectives and the trade-offs between them are, to a large extent, determined by the personal values and preferences of individual participants. For this reason proper identification of the objectives and the evaluation of the trade-offs between them must necessarily involve some input from those participants.

The above discussion suggests that the set of objectives and the trade-offs between them are system-specific. For each individual irrigation system(s) the objectives and the trade-offs have to be considered in the light of the particular setting under which the system(s) is operating and can only be determined by those who are involved in running the system(s). This means that it would not be possible to identify a set of objectives which are sufficient and all relevant for any person in any system. For this reason, the approach which we will follow in this study is first to prepare a list of all objectives which some people somewhere may expect their system(s) to achieve and develop an appropriate scale for measuring the level of achievement in each objective in this list. The idea is that the performance of any system can be adequately measured by a sub-set from this list. Having prepared this list then for evaluating any particular system(s) we present this list to the participants in that system(s) and let them select the criteria which they consider as relevant and important for evaluating their system(s). They will then be asked to specify their trade-offs between the criteria which they selected.

At this stage a number of important questions arise: Firstly, in any irrigation system(s) several groups of people with, may be, conflicting objectives and preferences are involved and concerned about the performance of their system(s). The question here is against whose objectives and preferences should the evaluation be based? i.e. Who is the client of the evaluation job? Secondly, to what extent are the objectives and preferences of this client representative of that of the other actors involved? Or how to combine those of different people or groups of people into some form of a group decision? And thirdly, having identified the client(s), how to proceed with the evaluation?

These questions are different in nature. While the first two are policy questions, the third one is a methodological or analytical one. In this study concern is mainly confined to the third question. The reason for that is, in our view, for the first two questions to be answered, the third question have to be answered first and that proper treatment of the first two questions may require separate study. In this study we will assume that in irrigation management a client who represents all beneficiaries is identifiable. Although the issue of the identification of the client in irrigation will be discussed briefly in Chapter 7, the main concern of the study will be how to derive this client objectives and preferences.

Another dimension of variability of the objective and the trade-offs between them comes with time. Here two types of variation can be identified: *long-term* and *short-term* variations. Usually the life time span of an irrigation system is long, may be many decades. This may be long enough for considerable changes in the values of the society to take place due to changes in the economic conditions and/or social structure. We refer to this as the *long-term* variation. Clearly to cater for this the objectives and the trade-offs used in the evaluation may need to be updated, or at least carefully examined, from time to time. But even from one year to the other the preferences of the society may vary. For example, a single drought year may considerably affect the trade-offs between the objectives. This is what we refer to as the *short-term* variation and is discussed later in Chapter 7.

3.3. Identification of the Performance Criteria

3.3.1. Desired Features of a Set of Attributes:

For any multi-criterion situation (irrigation system performance is not an exception) the set of attributes which describe the level of achievement of a given set of objectives is not unique (Keeney and Raiffa, 1976, pp.53). It is always possible to define different sets of attributes which can be nearly equally appropriate and sufficient for measuring the levels of achievements in the same set of objectives. The choice of a particular set of attributes depends on the availability of the data, the ease with which the attributes can be quantified and the meanings of their values to the people involved.

Keeney and Raiffa (1976, pp.50-53) discussed the desired properties of the set of attributes to be used for measuring the levels of achievements in any given set of objectives. According to them, the desirable set of attributes possesses the following characteristics:

Complete: The set contains sufficient number of attributes to describe, to an acceptable level of accuracy, all the important features of the performance.

Operational: The practical meaning of different values of each attribute are easily understandable to the people involved. If possible it is always preferable to use the type of attributes with which the decision-maker is familiar.

Non-redundant: Avoid double count, i.e avoid duplicating the consideration of the same criterion in more than one attribute. This is particularly important in the context of irrigation systems performance, because of the large number of criteria put forward in the literature. In many cases several of them, under different names, may be characterizing the same aspect of the system performance.

Minimum: The smaller the number of attributes in the set the easier will be the analysis. One way of reducing the size of the set is by combining several features of the performance into one criterion.

For the particular case of irrigation systems performance, Abernethy (1989) also mentioned the importance of using attributes which are cheap to measure, preferably based on routinely collected data.

3.3.2. Hierarchy of Objectives:

In chemical engineering terminology, the process of manufacturing any product is composed of a number of "*units processes*" and/or "*unit operations*" connected together in series and/or in parallel to give the intended product as a final output. A unit process involves some chemical and/or biological treatment and a unit operation involves some physical treatment. With this terminology, the irrigation system can be viewed as the part of the irrigation scheme responsible for one unit operation, namely the supply of the irrigation water. This unit operation together with other unit operations lead to the production of crops, improvement of the well-being of the people or what ever the final objective of the irrigation scheme may be. The performance of the irrigation system is judged by its ability to accomplish the unit operation for which it was set up. The objectives of the irrigation system should, therefore, be confined to this unit operation.

In order to define the objectives of the irrigation system, all human activities, including managing irrigation systems, can be looked at as directed towards the use of some resources (which in most cases are limited) in order to satisfy some needs. Kepner and Tregoe (1965, pp.182-183) suggested that the objective of any organization can always be derived from the "*resources*" available for use and the "*results*" which could be obtained from the utilization of these resources. The efforts of the manager can always be viewed as being directed towards optimizing the organization activities in order to economize in the use of the limited resources, maximize the chance of achievement of the desired goals and minimize the undesired effects.

The resources available for the irrigation system manager are the system physical facilities, the water source and some budget. The result expected is the supply of the fields with their water needs. The general objectives of the irrigation system can, therefore, be defined along these lines as: (a) The optimum use of the system facilities. (b) The supply of the fields with their water needs. Such definitions of the general objectives are, however, too broad and vague to be used as standards against which one can judge whether the performance is satisfactory or not. To be able to do that we need to have more specific definitions of these objectives. One way of obtaining these is by breaking down the general objectives into their constituent parts and organizing them in a hierarchical form. Hierarchical organization of objectives into sub-objectives and lower level sub-objectives can help us conceptualize the situation and concentrate on one objective (or sub-objective) at a time. Forman and Selly (1989) cited some studies which claim that organizing complex problems into a hierarchical form is the natural way of human thinking.

To construct the hierarchy of objectives of the irrigation system, the general objectives defined in terms of optimum use of the resources and maximization of results, because they are too vague to quantify the degrees of their achievements, they are to be divided into sub-objectives. We then consider these sub-objectives and try to devise measurable attributes by which we may be able to measure the degrees of their achievements. If any of these sub-objectives cannot be easily quantified by a measurable attribute, it can be further sub-divided into lower level objectives ... and so on. We continue to do that till we arrive at a set of objectives and sub-objectives the degree of achievement in each of which can easily be measured, reasonably accurately, by some attribute.

In both the vertical and the horizontal directions of the objectives hierarchy, there is no obvious level at which subdividing of the objectives must be terminated. The extent of the hierarchy in both directions depends on our judgement. In the vertical direction the general rule is to stop dividing any objective or sub-objective when an attribute can be found with which the achievement of the objective (or sub-objective) can be measured with an *acceptable* degree of accuracy. Naturally, this *acceptable* degree of accuracy depends, among other things, on the purpose of the evaluation and on the resources available for it. For example, sometimes a subjective attribute or an attribute which only approximately measures the level of achievement may be accepted if it is felt that a more precise characterization requires data which may be difficult or expensive to obtain.

Similar judgement is used for the extent of the hierarchy in the horizontal direction. Sometimes one upper level objective may involve a large number of lower level objectives. Which of them are to be considered in the analysis depends on our judgement of their significance. Sometimes the inclusion of too many sub-objectives may complicate the analysis without necessarily producing improved results.

In general, there are always several ways of constructing the objective hierarchy. To arrive at the final set of objectives or attributes which satisfies the desirable features mentioned in the previous sub-section, some of the possible techniques which can be adopted are:

(a) **Elimination** of the unimportant objectives.
(b) **Simplification** by using attributes which approximately measure the levels of achievements in the objectives.
(c) **Combination** of several objectives into a single measure.
(d) **Rearrangement** of the objectives' hierarchy.

Having arrived at the final hierarchy structure, then lower level objectives can be integrated into a single attribute which *measures the level of* achievement of the immediate upper level objective. The process is repeated up the structure to arrive at an overall performance measure of the system. The hierarchical structure can also help identify the reason for the level of achievement in the upper level objectives. By working backwards from the lower levels in the hierarchy the observed level of achievement in the higher level objectives can be explained.

Figure (3.1) is the hierarchy of objectives and criteria adopted in this study. In this figure the boxes contain the criteria used to characterize the objectives or sub-objectives. Six higher level criteria has been derived from the two broad objectives (i.e. resource optimization and result maximization). These criteria are considered in detail later. (*water supply adequacy*, *equity*

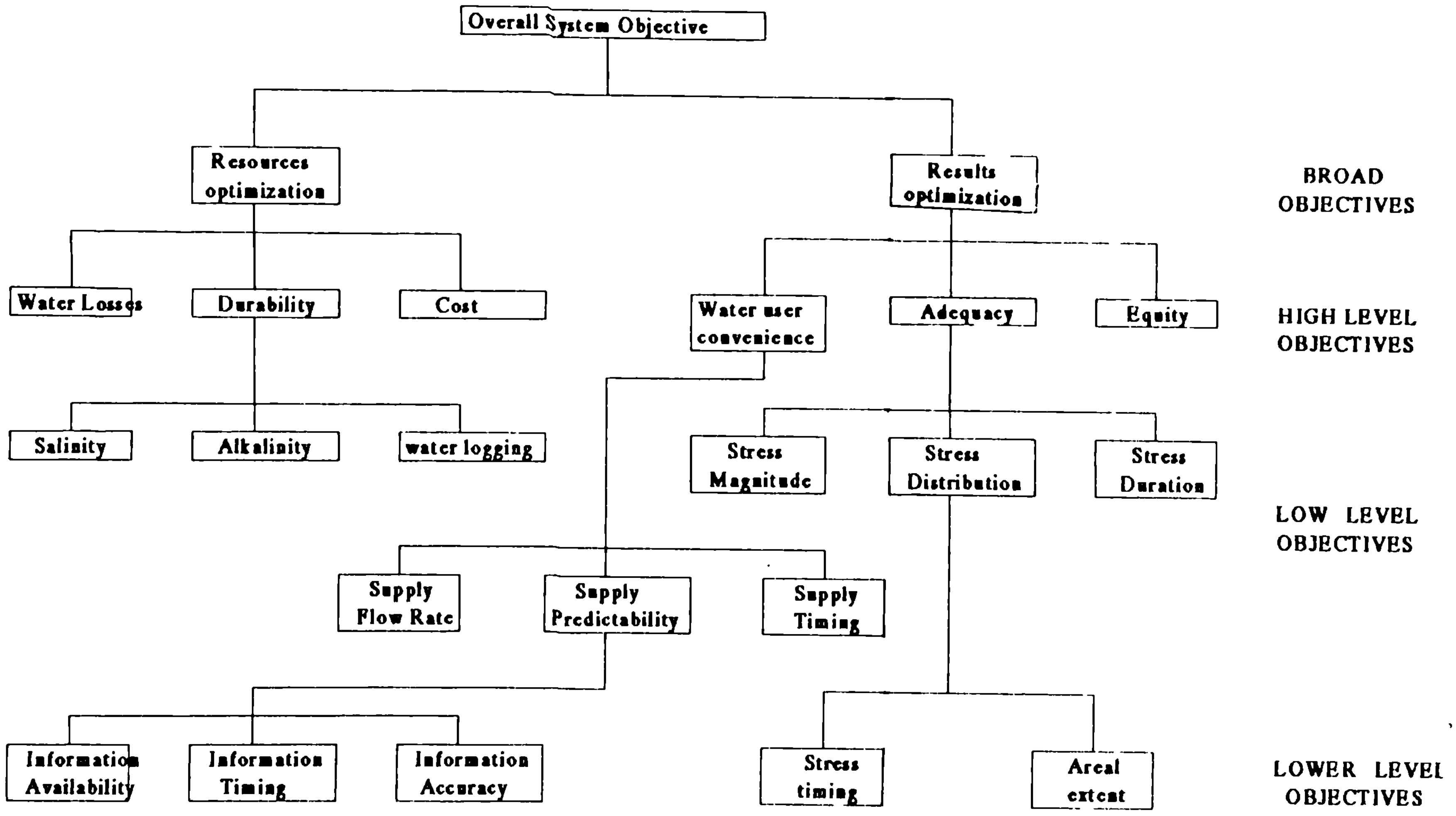

FIG.(3.1): ADOPTED HIERARCHY OF OBJECTIVES AND CRITERIA OF IRRIGATION SYSTEMS and *water losses* in Chapter 5, *water user convenience* in Chapter 6 and *durability* and *cost* later in this chapter). For the purpose of discussing the hierarchy structure, each of these criteria is introduced briefly here:

i) **Water losses** refers to the quantity of water lost without being effectively used.
ii) **Durability** refers to the ability of the system to sustain long-term operation without serious structural or environmental deterioration.
iii) **Cost** refers to the cost of operation and maintenance of the irrigation system.
iv) **Water user convenience** refers to the suitability of the water supply schedule to the water users.
v) **Adequacy** refers to the ability of the irrigation system to supply enough water to satisfy all requirements.
vi) **Equity** refers to the difference in the quality of services provided by the system to different users.

Of these criteria, for each of *water losses* and *cost* a direct measurable attribute can easily be found and, therefore, there is no need for further dividing water losses and cost. The attribute for *water losses* can be the volume of water lost as an absolute measure or can be taken as a percentage from the water supplied or effectively used. The attribute for *cost* can be the cost involved in the operation and maintenance of the system measured per unit area served. For each of *durability*, *water user convenience* and *adequacy*, however, such a direct attribute cannot be found. For characterizing *water user convenience*, for example, it will be seen later in Chapter 6 that no direct measurable attribute can be found. For this reason the water user convenience is divided into three sub-criteria: (i) *supply flow* *rate*, (ii) *predictability* and (iii) *timing of the water supply* . For each of these a separate attribute is developed. It will be shown that out of these three sub-criteria the characterization of predictability may require its further sub-division into lower level sub-criteria (as shown in fig.(3.1)). However, it is also argued the analysis can be simplified if the sub-criteria from predictability (i.e. *information availability*, *timing* and *accuracy*) are combined and a subjective description of *predictability* is used to incorporate its three sub-criteria. The attributes for the *supply flow rate*, *predictability* and *timing* are then combined together to give a measure of their upper level criteria which is the *water user convenience*. Similar sub-division is adopted for *durability* and *adequacy*. As concerning *equity*, in this study *equity* is characterized in terms of *adequacy*. Once *adequacy* is measured then the attribute for *equity* is a measure of the differences in the *adequacy* of the water supply to different parts or different users.

Clearly, there are many other objectives which are relevant in some irrigation systems but were not included in this hierarchy. For example:

- Supplying irrigation requirement other than the crop evaporative demands. For example, pre-season irrigation and soil cooling.
- Minimizing the spread of water-born diseases, such as malaria and schistomiasis.
- Quick removal of excess water to prevent flooding.

In fact one can go on building the set of objectives to a considerable number. We feel that the set of criteria selected here covers the most important aspects of performance in most irrigation systems. If, however, the application of the proposed analysis (to be discussed in Chapter 7) in any particular irrigation system reveals that some important objectives were not included, the framework of the analysis allows the revision of the set as necessary.

In this study detailed methods for measuring each of *adequacy*, *equity*, *water losses* and *water user convenience* are developed and tested. The four criteria and their proposed measurement methodologies are discussed in later chapters. In the remainder of this chapter *durability* and *cost* are briefly discussed.

3.4. Durability:

As was mentioned in the literature review in the previous chapter, it is considered important for the irrigation system to sustain long-term performance without serious structural or environmental deterioration which can affect the future performance of the scheme. Preventing the deterioration of the irrigation system itself and the irrigation scheme as a whole can, therefore, be an objective which the manager should try to achieve. Loss of durability or sustainability can stem from various sources. In this study, and for the purpose of the analysis, a distinction is made between *short-term* and *long-term* durability. By *short-term* loss of durability here it is referred to the deterioration of the system resulting specifically from: (a) siltation and weed infestation of the canal, and (b) deterioration of the physical structures (i.e. canals, water regulators, roads ... etc.). Both of these usually result from neglect of proper maintenance and, therefore, they are directly related to the level of funding made available for the operation and maintenance of the system. For this reason, and to avoid double count of their consideration in the analysis, the evaluation of these factors is incorporated in the cost of running the system which is discussed in the next section.

By long-term durability it is referred to the environmental deterioration of the irrigation scheme which results specifically from some or all of the three factors: (a) salinity, (b) alkalinity and (c) water-logging. There are also other factors which may, in the long run, contribute to the deterioration of the scheme performance. These include, for example: loss of motivation or proper training for the operation staff and relaxation of rules and discipline by the managing staff and the water users. Although these latter problems may exist in many systems and although they directly result from the way in which the system is managed, in our view their impact on the system may be less serious and they may be relatively easy to tackle. Loss of long-term durability can also stem from mismanagement at the farm level in the form of development of problems such as loss of soil fertility, infestation of the fields by weeds and pests and land levelling problems. These are not discussed here because they are considered to be a result of activities at field level which are controlled by the farmer or some organization other than the main system manager.

In this study, no detailed method is put forward for measuring long-term durability. The reason for that is the fact that *long-term* durability is different in nature from all other criteria considered in this study. The difference comes from the fact that the impact of each of its components (i.e. salinity, alkalinity and water-logging) is usually slow to become apparent. When adopting a certain management policy, it may take several years before its effect on these factors can be realized and the policy can be evaluated. If the purpose of the study is the development of an evaluation methodology suitable for the type of evaluation to be conducted on a seasonal or annual basis then it may not be possible to detect the long-term impact of the management policy of one season on the problem of salinity, alkalinity and water logging. Furthermore proper evaluation of long-term durability requires data over an extended period of time to enable prediction of the future.

3.5. Operation and Maintenance Cost:

In the developing countries' public schemes, the usual arrangement is for the irrigation department (or its equivalent) to be provided with an annual budget to cover the cost of Operation, Maintenance and minor repairs (hereafter referred to as O&M) in all the irrigation systems under its control. The level of this budget is, in some way, decided by some financial authority other than the irrigation department. Irrigation managers always argue that if only the level of O&M funding was made adequate, the performance of their systems with respect to all other criteria could be improved. The economists of the financing authority who approve the budget have their own criteria for deciding on the level of the budget to be provided. Clearly there is always trade-off between the O&M level of funding and the performance of the system. Because in the context of this study the irrigation system is taken to include the operation policy, of which the level of the O&M funding is one of many other components, the irrigation system can be evaluated with the budgetary constrains imposed on it. In this way, any level of performance achievement can be looked at together with the cost of achieving that level of performance.

3.5.1. What Costs are to be Included in the Evaluation:

If the objective is to develop a methodology which could be carried out at the end of each season for judging the performance of the irrigation system in that particular season, then the cost to be considered should be the cost for the season under consideration. This is not always obvious to identify for two reasons: (1) The budget and expenditure of the irrigation department are usually quoted for all the schemes under its control. Segregation as per individual scheme may not be an easy task. For example, how to distribute the expenditure of the headquarters or a dam which may be serving several purposes and several schemes. (2) Some items of the budget are concerned with future developments and, therefore, have no impact on the current performance of the scheme. These include, for example: expenditure on new developments, staff training, and planning and research. Such activities consume some of the operation and maintenance staff time and facilities. The question is how much of the O&M cost should be charge from these items.

To work out in detail exactly what and how much of the irrigation department expenditure should be billed to individual scheme may be different for different countries and may depend on individual scheme. In some countries some way of estimating these may exist in practice already. In general, for the purpose of evaluating the annual performance, full funding of the recurrent O&M must be assumed. This means that not only the actual O&M expenditure on the season under consideration, but also any postponed maintenance or repairs must also be included. (i.e. any expenditure which may be required to restore the system to the same physical condition as it was in the previous season).

CHAPTER 4

CHARACTERIZATION OF THE CASE STUDY

The irrigation systems in Sudan in general and the Gezira scheme in particular are used as an example case study area for testing the applicability of the methodologies developed in this study. In this chapter these systems are briefly introduced.

4.1. Irrigation Systems in Sudan:

4.1.1. Historical Background:

Modern irrigation methods are relatively recent in Sudan. Until the turn of this century, the traditional methods used were flood basin irrigation in the flood plains of the Nile and its tributaries and flush irrigation from the seasonal flashy rivers of Gash and Baraka in eastern Sudan. Flood irrigation is basically making use of the high levels of the river in its flood season to divert water in order to flood large natural flat basins. The water is left on these basins for two to three months before it is drained back into the river and then crops are grown to rely on the water remaining in the soil. Flush irrigation is simply relying on the annual spate of the river to flood some area in the river delta. In both methods the area actually irrigated is extremely variable from one year to the other depending on the flood level of the river. Water lifting at that time was confined to the use of simple local devices known as "*sagia*" and "*shaduf*" (Allan and Smith, 1948). Sagia is an oxen-driven water wheel and shaduf is a very simple manually-operated water lifting lever using a bucket. These devices could only irrigate small areas when the water lift required is not too high. Mechanized lifting of water was only introduced in the early years of this century when the first diesel pump was erected in 1904 to supply Ez'zeidab scheme from the Main Nile and large scale gravity irrigation started in the 1920's by the completion of Sennar dam on the Blue Nile and the commission of the Gezira scheme. The area under irrigation then increased steadily to reach its present size of 1.97 million hectares, consuming an annual average of 14.5×10^9 cubic metres of water.

4.1.2. Distribution of Existing Irrigation Developments:

The map of figure (4.1) shows the distribution of the main existing irrigation developments in the Sudan and table (4.1) gives some data on them.

The availability of irrigation water and the suitability of the land topography and soil type led to the concentration of the major irrigation developments in Sudan in a limited area. About 89% of these developments were set up in the fertile flat Central Clay Plains (CCP) of the eastern side of central Sudan immediately south and east of Khartoum (fig.(4.1)). In these CCP the average total annual rainfall increases from 167 mm. at Khartoum in their northern part to 576 mm. at Abu Na'ama in the southern borders of its irrigated part. Almost all of this rain falls in the months of June, July, August and September. As such, supplementary irrigation is necessary for secured crop production. Use is made of the Blue Nile, White Nile and Atbera River, which cross these plains, as the sole source of irrigation water. The main crops grown are cotton, wheat, groundnut, sorghum and sugar cane.

Other than these CCP, smaller size schemes also exist along the banks of the Main Nile north of Khartoum. These constitute about 6% of the irrigated area

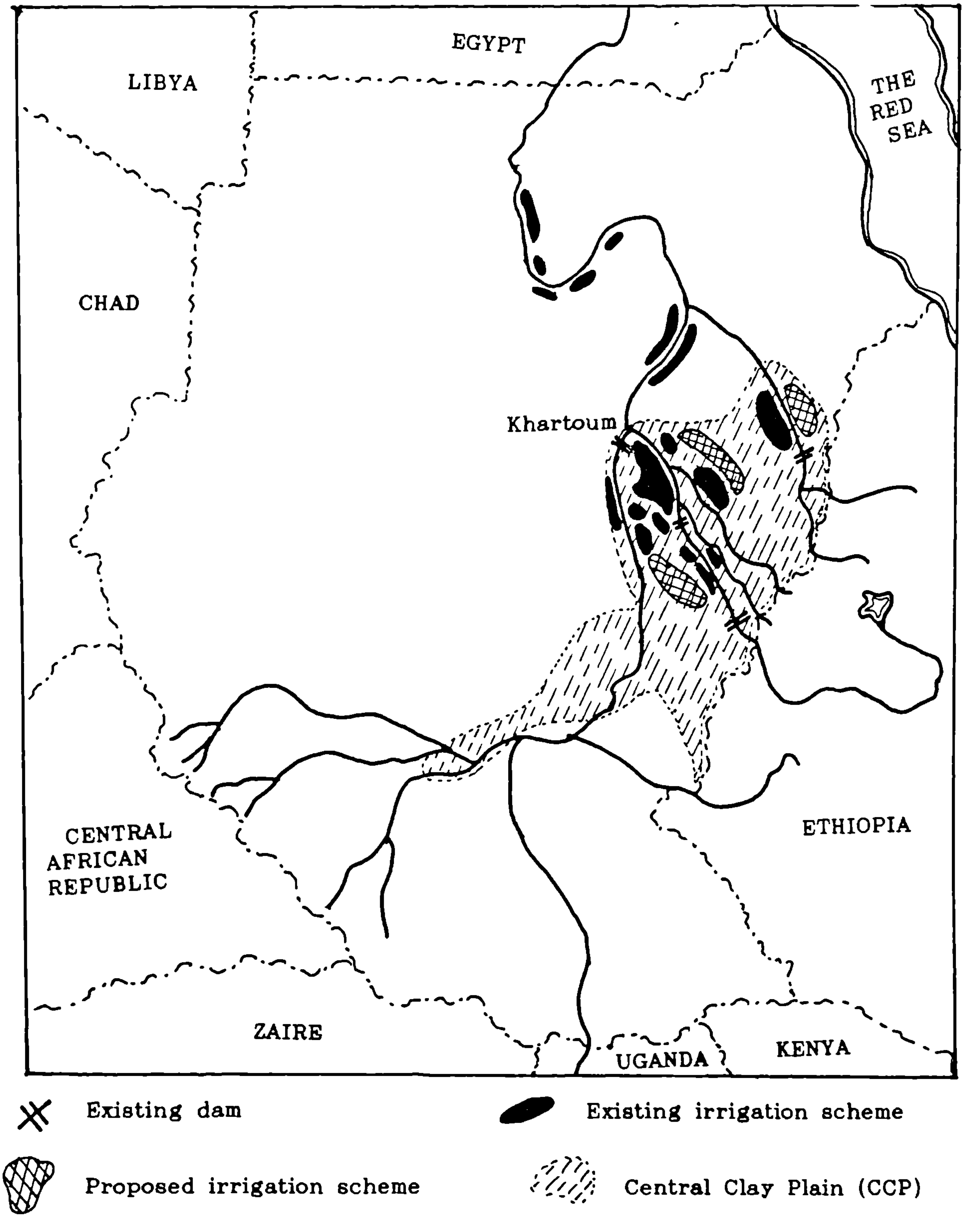

Fig.(4.1): Distribution of the main existing irrigation developments in Sudan.

in the country. Rainfall in this area is extremely low and crops are almost totally dependant on irrigation. More diversified cropping is practised with wheat, beans, date palm and other fruit trees being the main crops.

Table (4.1): General data about the existing irrigation developments in Sudan

WATER SOURCE	TYPE OF OWNERSHIP	SUPPLY METHOD	AREA (1000 ha)	WATER DEMAND (10^9 m^3.)
Blue Nile	public	gravity	924	5.50
	public	pump	353	2.92
	private	pump	38	0.18
White Nile	public	pump	199	1.44
	private	pump	48	1.21
Atbera River	public	gravity	193	1.45
Main Nile	public	pump	38	0.30
	public	basin	34	0.75
	private	pump	87	1.65
Gash & Baraka	public	flush	59	N.A.
Total			1973	15.40

Note: various publications and reports by the MOI may give slightly different figures from the ones quoted in this table. The figures here were based on the best judgement from these sources.

Ground water utilization for irrigation, apart from Sag En'am scheme in north Darfor of western Sudan, is very recent. Up until now it is confined to small scale private enterprises (5-10 hectares) using hand-dug, small tube wells for production of vegetable crops. They exist mainly near the population concentration centres where the cash value of the vegetable crops can justify the high cost of pumping the deep ground water. Flush or spate irrigation is used in about 3% of the irrigated area in the country. The remaining 2% is irrigated by basin flood irrigation which is still practised on a very limited scale along the Main Nile where it is mostly supplemented by small private pumps. Both flood basin and flush irrigation as practised now are somewhat enhanced versions of the traditional methods used for centuries. The enhancement introduced in the beginning of this century was the construction of some dikes or banks for a limited control of the water.

4.1.3. Soil Type and Salinity:

The cultivated area along the rivers is mainly alluvial soil brought up and deposited by the rivers to form a highly fertile agricultural land. This is usually a narrow strip one or two kilometres wide. Away from the river banks, the CCP, where the major irrigation developments took place, are characterized by dark and heavy soils which are high in clay content and Exchangeable Sodium Percentage (ESP). These soils develop deep wide cracks when dry and become remarkably impermeable when wetted. The low permeability of these soils gives them a great economic advantage when considered for irrigation development. This is due to the very low water losses from these soils to deep percolation in the field and seepage from the canals without the need for expensive canal lining. However, as an agricultural land this impermeability may be a disadvantage. It may not allow sufficient downwards movement of water to remove the salt brought in by the irrigation water.

Concern was expressed in the early years of the operation of the Gezira scheme, about the absence of deep drainage from these clay soils and the danger of accumulation of salts in the long run (Greene and Snow, 1939). After more than 60 years of irrigation now, no deterioration of these soils has been detected and field measurement has indicated slow downwards movement of the soluble salts and reduction in the ESP (Fadl and Adam, 1983). The salt washed from the top soil is being accumulated at depths which do not harm the crop growth (Jewitt, 1961). The good quality irrigation water of the Nile and its tributaries and the deep water table (usually more than 15 metres deep) have helped this process.

The conclusion to be drawn from this is that for the bulk of the irrigated area in Sudan, deterioration of the irrigation schemes due to build up of salts in the soil or due to water logging resulting from high water table does not represent a serious concern.

4.1.4. Water Availability:

Detailed accounts of the water resources in Sudan can be found in Democratic Republic of the Sudan (1977) and National Council of Research (1982). Under the terms of the current agreement between Sudan and Egypt on the sharing of the Nile waters signed in 1959, Sudan is entitled to annual abstraction of up to 18.5×10^9 cubic metres of water from the Nile (this is as measured at Aswan in southern Egypt. It is equivalent to 20.35×10^9 m^3. as measured at Sennar in central Sudan). This share can be withdrawn from the river, any where, at any time during the year. Although the present consumption (15.4×10^9 m^3.) amounts to only 76% of this share, it is still water and not land which limits the expansion of irrigated land in Sudan. The reason for this is the lack of the required storage facilities for the exploitation of the remaining part of the water share.

As can be seen from table (4.1), around 65% of the present irrigation requirements (around 76% of the irrigated area) are satisfied from the Blue Nile and Atbera River. Not only this but also all the area potentially suitable for future irrigation developments in the country can only be irrigated from these two rivers (Fig.(4.1)). Both rivers are characterized by a very marked seasonality in their flow patterns. The Blue Nile has an average annual flow (for the years 1912-85) of 49.2×10^9 m^3. (as measured at Ed'deim at the Sudanese-Ethiopian borders) of which 89% occurs in the four months from July to October and only 10.5% occurs in the remaining five months of the irrigation season from November to March. Similar pattern is followed by Atbera River in which the average annual yield (for the years 1912-47) is 11.8×10^9 m^3. of which 97.5% occurs in the four months from July to October and only 2% occurs in the remaining five months of the irrigation season from November to March. The present average abstractions from the two rivers amounts to 10.05×10^9 m^3. per year (8.6×10^9 m^3. from the Blue Nile and 1.45×10^9 m^3. from Atbera River). The available storage (as estimated in 1977) is only 4.0×10^9 m^3. (3.2×10^9 m^3. from both Roseires and Sennar dams on the Blue Nile and 0.8×10^9 m^3. from Khashm El Girba dam on Atbera river).

The foregoing account shows that every year part of the Sudan's share of the Nile waters must be passed to Egypt during the high flood months from July to October and that irrigated agriculture relies heavily on the limited storage available during the low flow months of the season from November onwards. In fact it is this limited storage capacity which determines how much area can be irrigated each season. The conclusion to be drawn here is that water losses from the irrigation schemes may not be of equal significance throughout the irrigation season. It assumes higher importance during the low flow period, when the natural flows of the rivers are less than the irrigation requirements and heavy reliance is put on the water stored in the reservoirs, than during the high flow period when the natural flow exceeds the demands. To put it in more specific terms, at the present time and during the rivers high flow period, water losses from the irrigation schemes may be undesirable because of its health hazard, its effect on the traffic or because of the cost involved in diverting the water from the river into the scheme, but the water itself, as a resource, has very little value. This is unlike the situation during the low flow period when any water loss directly means that some crop, somewhere in the country, is going to suffer.

4.1.5. Management Structure:

In this study distinction is made between public and privately owned schemes. Small scale irrigation schemes (i.e. smaller than 500 hectares) constitute about 9% of the irrigated area in Sudan and are run by private owners. There are several thousands of such schemes. The owner can be a single person, a limited company or a cooperative type of ownership. In these systems several types of management arrangement exist. The most common is the crop sharing system in which the owner, who provides the land and water and may be some of the other inputs, receives some 30 to 50% of the crop produced, depending mainly on the crop grown, the quality of the land and who provides what of the other inputs. Government involvement in the management of irrigation is, for obvious reasons, confined to large and medium size schemes. Within the government managed schemes, sugar cane has its special management version. It is grown in specialized mono-crop estates. There are five such estates (including Kenana scheme which is run by a private company). They occupy around 5% of the irrigated area in the country. Each of the public sugar estates is managed by a separate government corporation which uses direct labour for all activities in the scheme from the farming to the processing of the sugar.

All other non-sugar public irrigation schemes, which are the subject of this study, have similar management structures and cropping patterns. The responsibility of running the scheme is shared between three parties: the Ministry Of Irrigation (MOI), a public agricultural corporation for each individual scheme, and the tenant farmers. As far as the water management is concerned, the MOI operates and maintains the supply and distribution system in the main and major canals, the agricultural corporation controls the delivery of the water from the minor canal to the field and the tenant farmers are responsible for the application of the water in the fields.

The MOI is a centralized body which has control over all surface water resources in the country. Its responsibility includes the design, construction, operation and maintenance of the main irrigation system in almost all public irrigation schemes in the country.

The agricultural corporations are principally in control of the cropping pattern and farming practice. They provide the farmers with most of the important agricultural inputs and services such as seeds, fertilizers, insecticides and ploughing. In return farmers pay for these inputs and services. However, the exact responsibilities of the managing corporations, the services they provide and the degree of their control over the farmer are slightly different from one scheme to the other. Originally these corporations were set up to be financially independent and operate on a commercial basis. In practice, however, the charges for their services and the prices of the inputs they provide are determined by the central Ministry Of Finance and

Economic Planning (MOFEP).

The farmers are to provide the labour input in the farming process, follow the cropping pattern and farming practices dictated by the managing agricultural corporations in their schemes and sell their cotton and wheat crops to the government. The cost of all services provided for all crops are deducted from the individual farmer crop sales. In theory the land is a government property, farmers are only tenants and the agricultural corporation holds the right to terminate the tenancy agreement with any farmer at any time. In practice, however, this right is hardly used in recent years. Tenancy has come to be regarded as a family property and can be sold or inherited by the farmers' children.

4.1.6. Methods of Irrigation:

Three methods of water provision from the river to the scheme are practised in Sudan. Diversion by gravity by means of a dam, *pumping from the river* and run-of-the-river as practised in flood basins and flush irrigation. Diversion from dams, although existing in only two schemes (Gezira and New Halfa) constitutes 57% of the irrigated area in the country, followed by pump-supplied schemes covering 38% and run-of-the-river systems covering only 5%. The irrigation water in all the dam and pump-supplied schemes is distributed by gravity through a network of main, major and minor canals to feed the field canals. At field level, furrow irrigation is the most widely used method of water application. Small basin irrigation is also used for wheat crop (for purposes of mechanized harvesting) and for some vegetable crops. Because of the exceptionally flat ground and low permeability of the soil in the areas where the major irrigation developments exist, no pressurized irrigation is practised in the country. Even for the surface irrigation, the initial cost of land levelling has been almost nil.

4.2. Gezira Irrigation Scheme:

The Gezira scheme covering an area of 880,000 hectares, which is nearly half the irrigated area and 12% of the cultivated area in Sudan, is considered the most important single enterprise in the country. With its 100,000 tenant farmers, 11,000 permanent and 600,000 casual labours, the scheme employs around 7% of the working force in the country (Sudan Gezira Board, 1985) and contributes 7 to 10% of its Gross Domestic Product (GDP) (Elobeid, 1986). Because the scheme is the oldest and by far the largest irrigation scheme in the country, it has been used as a model on which the design, operation system and management structure of almost all other public schemes were based. It is also by far the best documented irrigation scheme in the country. For all these reasons, it is selected for testing the applicability of the methodologies developed in this study.

4.2.1. Climate:

The Gezira (the Arabic word for island) is the name given to the triangular area immediately south of Khartoum, bounded by the Blue Nile from the east, the White Nile from the west and is taken to extend south to the Sennar-Kosti railway line (fig.(4.2)). Within this triangle the command area of the Gezira scheme starts some 40 kilometres south of Khartoum to cover an area about 210 Km. long in the north-west/south-east direction and 60 to 120 Km. wide in the north-east/south-west direction. The area falls in the semi-arid region. At Wad Medani, which fairly represents the central part of the scheme the

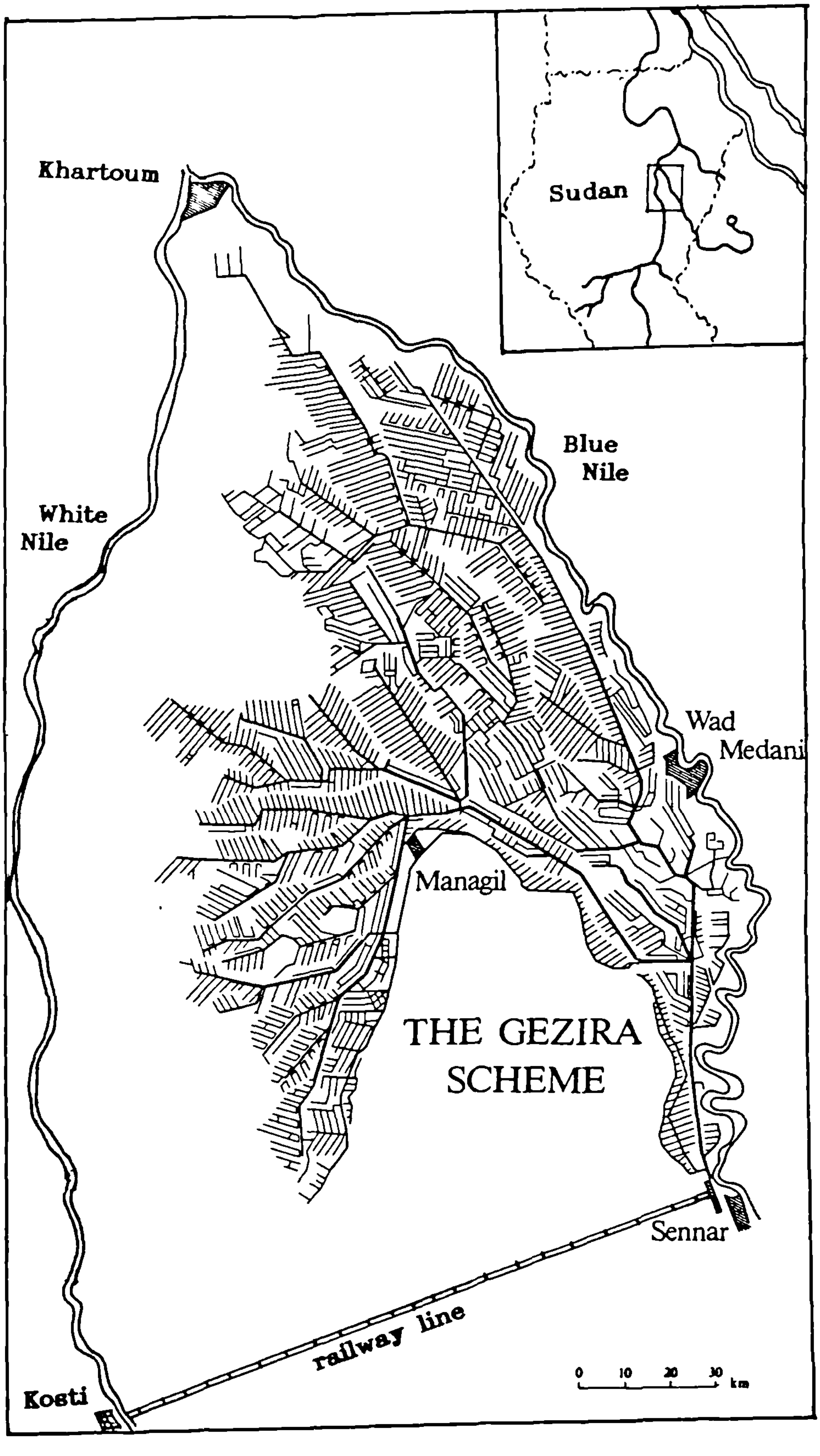

Fig.(4.2): The Gezira irrigation scheme.
(Source: Wallach (1988).

average total annual rainfall (for the years 1941-70) is 362 mm., the average temperature is 28^0 C and the average ETo (Penman) is 7.3 mm/day. Most of the rainfall occur in the months of July and August. With the period from November to May completely dry. There is also considerable variability in the rainfall across the scheme. In the extreme north-west of the scheme, where the rain is lowest, it is 20% lower than at Wad Medani. It then increases steadily to its maximum at the extreme south-east where it is 27% higher than at Wad Medani (Fadl and Adam, 1978). The variations in ETo (Penman) across the scheme is much less than that of the rainfall. Khartoum has an average ETo value which is only 1% higher than that of Wad Medani.

Even for the same location, the variability of the rainfall intensity and total depth from one year to the other is also large. Individual year may be 50% above or 30% below average (Allan and Smith, 1948). During the rainy season, 15 to 20 days without rain and 150 mm. in a single day is not uncommon and a rain depth of 190 mm. in 24 hours has been recorded.

4.2.2. Scheme Lay Out:

Irrigation water for the scheme as a whole is diverted by Sennar dam on the Blue Nile some 300 upstream of Khartoum. No other source of water is used. From the dam water is taken through two main canals having a combined design carrying capacity of 29.8 millions cubic metres per day (345 m^3/sec.). The two main canals run parallel for a distance of 57 kilometres as supply canals before they join together in a common pool. From the pool at km. 57, two main canals emerge, one travels northwards to irrigate the old Gezira area and the other travels westwards to irrigate the Managil south-west extension. From either of the main canals water is supplied to a number of MAJOR

CANALs. Major canals vary in length and supply varying sizes of area. A typical major canal is 16 km. long and commands an area of 8,000 hectares. No direct irrigation from the main or major canals is allowed. From the major canals water is delivered to smaller canals called MINOR CANALs. Like major canals, minor canals command varying sizes of areas and their lengths vary from 4 to more than 20 kilometres. An average minor is 6 km. long and commands an area of 600 hectares. Minor canals are divided into reaches by means of water level controlling regulators. The length of the reach varies from 1 to 4 kilometres depending on the topography of the land. From the minor canal water is fed to field canals called ABU ISHREENs through 35-cm. diameter, 12-metres long pipes which pass under the bank of the minor and are called FIELD OUTLET PIPEs (FOP). Each Abu Ishreen irrigates a standard area of 90 feddans[1] (38 hectares) known as NUMBER. There are around 29,000 such numbers in the scheme. The 90-feddans number is further divided into 18 equal 5-feddans plots, by means of 19 smaller field canals taking off from Abu Ishreen and known as ABU SITTAs.

A notable feature of the scheme is the uniformity and mildness of the land slope of 15 cm. per kilometre. This enabled a fairly uniform geometry of the field system lay out. The minor canals are straight, parallel and at a regular spacing of 1415 metres, the numbers are of a standard rectangular shape of 1400 metres long and 292 metres wide and Abu Sittas are 78 meters apart and at right angle to Abu Ishreen. Figure (4.3) shows a typical lay out of the field irrigation system.

The drainage network in the scheme consists of four escape drains taking-off

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[1] Feddan is the unit for measuring areas of agricultural land used in Sudan and Egypt. It will be used frequently in this thesis.
1 feddan 4200 m^2 = 0.42 hectare = 1.05 acre.

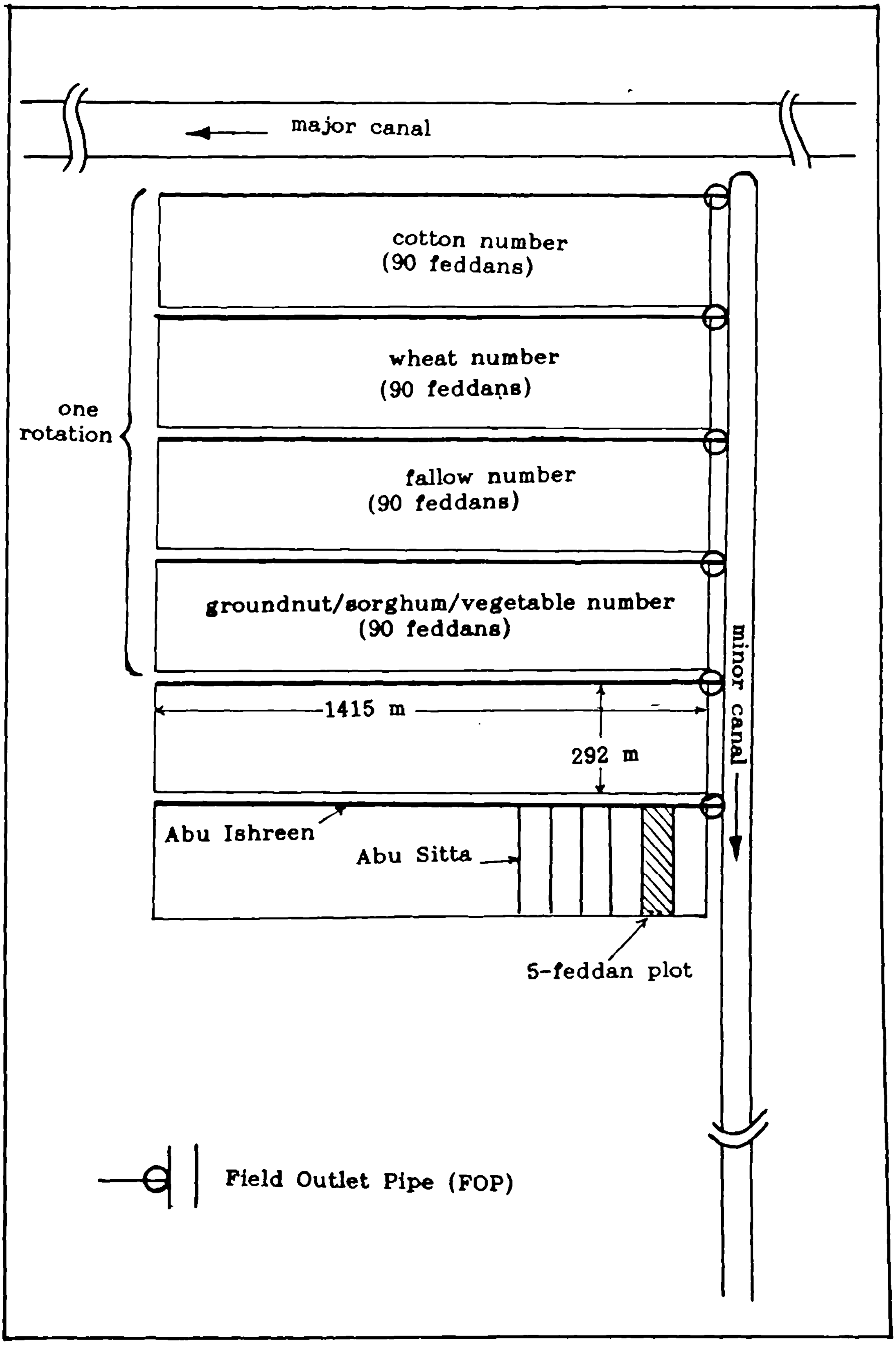


Fig.(4.3): Typical lay out of the field irrigation system in the Gezira scheme from the old Gezira main canal. They were meant to be used during the rainy season to prevent breaches by passing the surplus water back to the Blue Nile when an event of heavy rain necessitates that. These escape drains are almost completely abandoned now. Some other open surface drains are also provided inside the scheme area but only for removing excess rain water. No drainage facilities were provided for excess irrigation water as the assumption made in the design of the drainage system was that once the water has left the main canal it has to be accommodated in the cultivated area (Johnstone, 1928).

For crop rotation purposes, each four neighbouring numbers are grouped together to form what is called a ROTATION (fig.(4.3)). The standard farmer tenancy in the old Gezira area is 40 feddans (16.8 hectares), although many farmers now have only 20-feddans (i.e. half a tenancy). The 40-feddans tenancy of each farmer is such that each 10 feddans are in one of the four numbers of the rotation. Each year one number of the rotation is allocated for cotton, one for wheat and one for a combination of sorghum, groundnut and vegetables. The fourth number is left fallow. In the Managil south-west extension the standard tenancy is only 3x5-feddans (6.3 hectares) and no fallow is allowed for in the rotation. The area of vegetables in the scheme may not exceed 21,000 hectares (i.e. 10% of the cotton area). Usually only the first three upstream farmers are allowed to grow vegetables in part of their sorghum or groundnut area and onions is usually the most dominant vegetable crop grown in the scheme. The crops are rotated in each number as follows: cotton, then wheat, then the combination of sorghum, groundnut and vegetables and then the number is reserved as fallow to be allocated for the cotton in the next season. Each farmer is rotated in the same land in order to encourage good soil management.

4.2.3. Management Organization:

The agricultural corporation responsible for running the scheme, beside the MOI and the farmers is the Sudan Gezira Board (SGB). The MOI operates and maintains the main supply and distribution system from the dam up to and including the off-take structures of the minor canals where the water control responsibility is handed over to the SGB. The SGB operates the intermediate water regulators in the minor canals and the FOP's (the maintenance of the minor canals is carried out by the MOI). Once the water is passed into Abu Ishreen, it is then managed by the farmers sharing that Abu Ishreen with some supervision from the SGB staff.

For water control purposes, the MOI divides the scheme area into six DIVISIONs each under the control of a Division Engineer (DE). The divisions are further divided into SUB-DIVISIONs each under the control of a resident Assistant Division Engineer (ADE). The whole Gezira scheme is divided into 23 such subdivisions. For agricultural adminstration purposes the SGB is organized into 14 GROUPs each divided further into BLOCKs. There are 107 such blocks in the scheme each supervised by a resident Block Inspector (BI) and covers an approximate area of 8,000 hectares. The BI is assisted by two assistant inspectors and, for water management purposes, a number of water watch-men. The SGB employs 1,800 such water watch-men, roughly one for each 500 hectares. Their main function is to operate the intermediate regulators of the minor canal and the FOP's and oversee the progress of irrigation and all related agricultural activities in every individual farmer's field in order to report on that to the BI.

Farmers are responsible for the application of the water in the field, including the construction and maintenance of all water courses (i.e. Abu Sittas and the smaller field canals). The excavation of Abu Ishreen is carried out by the SGB on behalf of the farmer, but each farmer bears the cost of the part passing his land.

4.2.4. Method of Water Management:

The cropping pattern for every individual farmer in the scheme is strictly controlled by the SGB. It decides on how much area is to be allocated to each crop, where and when should it be grown. Every year, and well before the start of the irrigation season, the SGB and the MOI agree on how much area could be sown in each 10-day period with each of the summer crops (cotton, sorghum, groundnut and vegetables). As water availability is not a constraint for the areas of the summer crops, the objective of this pre-season plan is to ensure that water demands will not exceed the main canal carrying capacity during any part of the season. Decision on the area of the winter crop (i.e. the wheat) is suspended till October. At that time the Blue Nile flood will be over and the situation of the water availability for wheat will be clear. The area of wheat will then depend on the expected yield of the Blue Nile in its recession period (November-March), the storage available for the scheme and the water demands of the remaining summer crop (i.e. the cotton).

For the part of the MOI, the method of operation of the main system is described in a manual called The Gezira Regulation Handbook (MOI, 1934). Detailed description of this method is given by Taj Elden, *et.al.*, (1984). For the part of the SGB, a description of the official method of operation of the field system is contained in a manual called Handbook For New Personnel (SGB, 1951). The method of operation of the irrigation system in the Gezira relies heavily on good telephone communication between different control points in the irrigation system on one hand, and between the MOI (the supplier) and the SGB (the user) on the other hand. Water supplies are scheduled from the main system on a demand basis. The SGB each week determines how much water is needed by the crops in each minor and the MOI is to supply these needs as requested by the SGB. In practice, however, the exact method of operation taking place in the scheme now is somewhat different.

In broad terms, on Tuesday every week, the BI of the SGB determines which FOP's are to be opened during the coming week in each minor in his block, multiplies that by a fixed flow rate of 5,000 m^3/day and submits his water demands (called INDENTs) for each of his minors to the ADE of the MOI under control in the area. The ADE in turn sums up the indents for all the minors in each major canal to form the indent at the head of that major, adds that to the accumulated indent of the ADE downstream and passes the total indent to the ADE upstream. This process is repeated up the system to the dam where the headwork gates are to be adjusted to pass the required indent. During the rainy season, changes of indent can be made daily.

On releasing the water from the dam, each ADE adjusts the regulators under his control to ensure that the indent of the downstream ADE is satisfied first before he can pass enough water into his majors (i.e downstream user first, a measure instituted in the operation system to help attain equity) and the off-takes of the minors are adjusted to pass their indents.

The main system operates on continuous basis. The minor canals receive their supplies continuously, day and night. They were designed to store all the night flows and supply the FOP's only during the day time. A system known as NIGHT STORAGE and was introduced in the early years of operation of the scheme in response to dissatisfaction expressed at that time about farmers ability to irrigate at night (Allan, 1939). Every day at 6:00 p.m. all the FOPs and the intermediate regulators of the minor canals are to be closed. In this way, during the night, the first reach of the minor will fill up to the "NIGHT STORAGE LEVEL" and the full discharge entering the minor will then flow over the first intermediate regulator to fill the second reach ... and the process is repeated down the minor. By 6:00 a.m. the next morning all the reaches of the minor should be full and the FOP's can then be opened to draw water at twice the rate at which the minor is supplied.

Each FOP is to be opened every other week to draw water at an approximate rate of 5,000 m^3/12-hours (116 l/sec.). This gives an irrigation depth of about 92 mm. at an interval of two weeks. On the week when the FOP is on, an earth dam is built halfway across Abu Ishreen and the upstream farmers are to share all the flow for the first three to four days of the week. For the remaining part of the week the earth dam is removed and all the flow goes to the downstream farmers. The SGB manual (SGB, 1951) actually goes on to describe in detail how the individual farmer should irrigate his field. A method which is no longer seen in practice now in the scheme.

In recent years and due to various factors, there is clear evidence that the official method of operation as described above is not strictly followed (Francis and Elawad, 1989). For the part of the MOI, on one hand, the supplies to the minors vary in quantity and do not necessarily match the indent. For the SGB, on the other hand, the indent is more a reflection of previous difficulties experienced with the MOI supplies rather than the actual crop demands. The night storage system is no longer followed as the FOP's are frequently opened during the night and the irrigation schedule is not strictly adhered to.

This was also accompanied by a general decline in the scheme performance during the late 1970's and early 1980's. A decline which is reflected mainly in decreasing productivity, deterioration of the physical structures and increase in the cost of operation. Since the mid-1980's, a major rehabilitation program has been started in the scheme. Among other things, attention has been given in this program to the restoration of the irrigation practice to its original methods.

4.2.5. Allowance for Transmission Losses:

A notable feature of the operation system of the Gezira scheme, and probably all other schemes in the CCP of Sudan, is the general assumption concerning seepage losses from the canals. The general belief among the professionals in Sudan is that direct evaporation from the canal network open water surface is the only water loss to be considered in transmitting the water from the dam to the fields (Fadl and Adam, 1983). In both the SGB's 1951 handbook and the MOI's 1934 operation manual, although it is not explicitly mentioned, no allowance is made for any transmission losses.

In recent years the Agricultural Research Corporation (ARC), Wad Medani, Sudan, published a new and more accurate method of water indenting for the Gezira scheme (Farbrother, 1977). The method consists of tables of the crop water requirements for all the crops grown in the scheme depending on their sowing date and growth stage. The method was intended to supplement a proposed "New handbook of irrigation practice in the Gezira".

Although, for their own reasons, the BI's do not use these tables in calculating their indents, for the MOI these tables are the only guide for preparing the pre-season and mid-season plans for the Gezira scheme and for the operation of Sennar dam. In these table the assumption of zero seepage losses is explicitly stated and all the transmission losses accounted for are that due to canal evaporation.

4.3. Data Routinely Collected in Irrigation Systems in Sudan:

To evaluate the performance of an irrigation scheme, several types of data may be required depending on what aspect of the performance are to be evaluated. During the course of this study the author was assigned by the International Irrigation Management Institute (IIMI) to conduct a survey of the data availability in the irrigation schemes in Sudan and the organizations involved in collecting it (Elawad, 1989). In the reminder of this chapter the result of this survey is summarized.

Several organizations are involved in collecting different types of data from the irrigation schemes in Sudan. Beside the organizations which are directly involved in managing these schemes, such as the MOI and the agricultural corporations running the schemes, there are also organizations which provide some services to these schemes and collect data from them. These include, for example, the Meteorological Department, the Soil Survey Administration and the Agricultural Bank of Sudan. Some of these organizations publish periodical reports which contain summaries and sometimes some analysis of their data. The availability and quality of the data, however, differ considerably from one organization to the other and from one scheme to the other.

In general the data availability and quality in the irrigation schemes in Sudan are related to the degree of involvement of the government in the management of the scheme. This is because, usually, if reliable data is available, it will be the data on inputs and services provided by the government and on activities and farming practices controlled by the government. Usually little is known about farmers' controlled activities. For the private schemes, if any data is available it is usually very unreliable estimates of command areas and possibly cropping patterns. These are usually available from organizations such as the local authorities, the Extension Department of the Ministry Of Agriculture or the Agricultural Bank of Sudan. Even such type of estimates is hardly available for items like actual water consumption or crop yields. Within the government controlled schemes, more attention is paid to larger schemes and as such they are better documented than smaller ones.

For the purpose of this study five types of data are required. The availability of the routinely collected items of these data in the government controlled scheme in Sudan is discussed here. As was mentioned previously, the Gezira scheme is by far the best documented scheme in the country and for this reason it is selected for testing methodologies developed in this study. Special consideration will be given here to the data routinely collected in the Gezira scheme.

4.3.1. Meteorological Data:

The meteorological data required for the analysis proposed in this study is ETo (Penman) and rainfall. These data is collected by the Sudan Meteorological Department (SMD). The SMD runs a large number of meteorological stations installed mainly in big towns. In 1957 the agro-meteorological department of the SMD was established and is now running over 10 agro-meteorological stations in which all the parameters required for calculation of ETo using Penman method are collected daily. These stations are distributed in areas representing all the important meteorological zones in the country. The measurements in these stations are taken by qualified staff and the records can be regarded as highly reliable. In addition to the SMD data, almost every scheme runs some local rain gauges which can provide rainfall data for the particular locality of the scheme.

As for the Gezira scheme, data on ETo (Penman) can be available from Wad Medani agro-meteorological station which is situated in the middle of the scheme. For the rainfall data, however, because of the scale of scheme area, large variability across the scheme exists. For this reason, unlike ETo for which readings taken at Wad Medani can be considered to be applicable throughout the scheme, local rainfall data must be used for the locality to be analyzed. There is an intensive network of rain gauges inside the scheme area run by the MOI and the SGB. Probably more than 200 rain gauges. However, we have noticed some inconsistencies in recent years' records of these gauges. Fortunately, for the purpose of this study, some independent rainfall records, taken as part of some research programs, are available for the localities where rainfall data is required.

4.3.2. Agricultural Data:

The agricultural data required is the areas and sowing dates for the crops grown in the scheme (or the part of it under investigation). This is usually available for all government controlled schemes from the agricultural corporation running the scheme. As for the Gezira scheme, the BI's of the SGB at their local offices keep detailed records for every individual farmer in their blocks. This record contains, among other things, data on the areas sown with different crops and their sowing dates. The SGB headquarters at Barakat also publishes annual reports which contain 10-day or weekly summaries of these data for the scheme as whole.

4.3.3. Soil and Crop Characteristics:

The Soil Survey Adminstration and the Agricultural Research Corporation (ARC), both of which have their headquarters at Wad Medani, has accumulated considerable knowledge on the characteristics of the soils and crops grown in Sudan. Much of this can be found in international publications. This is particularly true for the crops and soils of the CCP where most of the irrigation developments exist.

4.3.4. Cost Elements:

The cost considered here is the cost of operation and maintenance of the main irrigation system, all of which, in government controlled schemes, is done by the MOI (with the exception of the Northern Agricultural Production Corporation schemes in which the MOI is not involved and the irrigation systems are run by the managing corporation). The MOI receives annual budget from the central MOFEP to cover all it expenses. In return for the water provision, farmers pay some fees (called Land and Water Charges (LWC)) which are collected by the agricultural corporation in the scheme and paid to the MOFEP.

The LWC are meant to cover the cost of water provision by the MOI and the administrative cost of the agricultural corporation running the scheme (Elobeid, 1986). This is not always so as the actual level of the LWC for each scheme is determined by the MOFEP which in deciding these levels may take other social and political considerations for each individual scheme into account. The LWC are charged based on the area served and the crop type. No measurement of the actual volume of water received by individual farmer is taken and no compensation is paid for failure to supply adequate water.

Like any other government organization, the MOI has to record its expenses using the standard structures of the Sudan Government in which the expenditure is recorded item by item, but each item is quoted for the MOI as a whole. No segregation of the expenditure as per individual schemes is usually available. As such data on cost as per unit area is not usually available.

For the Gezira scheme, however, in 1989 the MOI conducted a detailed study of its cost per unit area for supplying different crops in the scheme. In that study it was assumed that the scheme had already paid back its construction cost and the cost involved is only that of the operation and maintenance. It was further assumed that in any single irrigation water is supplied at a standard depth of 100 mm. and the cost per unit area for each crop was calculated by multiplying the number of irrigations required by each crop and the cost of water supply per irrigation per feddan. Table (4.2) was adopted from this study. The table also shows the LWC (the figures in brackets) which were charged from the farmers for some years.

It may be worth mentioning here that the larger part of the MOI budget goes to the cost of silt and weed clearance from the canals. In the 1987/88 and

1988/89 seasons this was respectively 44% and 37% of the total expenditure of the MOI in the scheme.

Table (4.2): Cost of water supply for the MOI and the LWC (figures in brackets) for different crops in Sudanese pounds/feddan/season.

CROP	COTTON	SORGHUM	GROUNDNUT	WHEAT	VEGETABLES
1981/82	20.64 (28.50)	5.16 (3.50)	7.74 (14.00)	23.70 (18.00)	33.35 (25.00)
82/83	28.32 (38.50)	7.08 (19.00)	10.62 (19.00)	14.16 (23.70)	24.78 (33.25)
83/84	33.92 (38.50)	8.48 (19.00)	12.72 (19.00)	16.96 (23.70)	29.68 (33.25)
84/85	44.16 (50.00)	11.04 (25.00)	16.56 (25.00)	---- ----	38.64
85/86	46.24	11.56	17.37	23.12	40.46
86/87	61.92	15.48	23.22	30.96	50.18
87/88	115.86	28.96	43.44	57.92	101.36
88/89	167.84	41.96	62.94	28.92	146.86

Notes: - In the 1984/85 no wheat was grown in the scheme.
- Figures for LWC were taken from SGB annual reports.
- Up to 1986 one Sudanese pound = 0.4 US dollars. From the 1987/88 season and onwards = 0.22 US dollars.

4.3.5. Water Supply Data:

For the analysis proposed in this study, the most essential data is that of water supply. For any area of the scheme to be analyzed information on the water supply time pattern at the point supplying that area is required. Water supply is also usually the item on which reliable data is most difficult to find. In general, in any irrigation scheme in Sudan the availability and quality of water supply data decreases as we go down the irrigation system levels. It also varies with the size of the scheme. Large schemes are usually better documented than smaller ones (probably because of the large attention paid to them by the government). For example, in all small pump-supplied schemes discharge measurements may not take place at any level of the irrigation system. All the information available may be some records of the daily pumping hours and river levels (i.e. pump lifting head) which can be used together with the pump characteristic curves to estimate the daily water pumped. The pump characteristic curves are usually the ones provided by the manufacturer. In most case they may be 15-20 years old.

The Gezira scheme compared with others in the country has by far the best documentation of water flows at various levels of the irrigation system. However, its data is far from being complete. Again the availability and reliability of the data decreases as we go down the irrigation system. The following is a review of the water supply data availability at various levels of the Gezira irrigation system.

a) At the Dam Headwork:

When the resident engineer at the dam receives the indent for the whole scheme area, he may decide to make some adjustments on this indent before authorizing it. The adjustment to be made depends on the volume of water stored and the two main canals carrying capacities. Data is available for the daily indent, authorized and actual releases from the dam into the two main canals. The actual discharge is measured three times per day by recording the upstream and downstream levels and the gates openings at the headwork. These data is used with the calibration equation of the headwork structure to calculate the discharge passing through. Frequent current-meter measurements on the two main canals are also taken, separately, by both the Sudanese and the Egyptian authorities in order to check the calibration of the off-take structure. These data is published by the MOI and can be considered highly reliable.

b) Main Canals, Major Canals and Minor Canals Off-takes:

The MOI records the upstream and downstream levels and gates openings of all the intermediate regulators on the main and major canals and at all the off-take structures of the major and minor canals. These are well over 2,000 points. In each of these points information is recorded three times a day by the MOI water gate-men. Together with these data, for each of these points, the MOI also keeps daily records of the indent submitted by the SGB, the discharge authorized by the MOI's engineers and the actual discharge. The quality of the data at this level of the system, however, varies considerably depending on the conditions of the structure and the person responsible for recording it. In many cases the records are reflections of the water levels and gate settings (and therefore discharges) authorized by the MOI rather than the actual ones. They always indicate that "*indents are fully satisfied*". In some cases, particularly at the minor canals off-takes, the water level gauges themselves may be shifted or the measuring structure may be drowned to a degree which seriously disturbs its calibration (Francis and Elawad, 1986). Table (4.3) is a sample of the quality of the MOI record at this level of the irrigation system compared with current-meter measurement taken independently by the staff of the Hydraulics Research Station (HRS) of the MOI, Wad Medani, Sudan. Although this is not typical of the quality of data usually available at this level of the system, but it shows the quality of record which can be encountered sometimes.

Table (4.3): SGB indent, MOI recorded discharge and HRS measured discharge (in 1000 m^3) for Eltoman minor, Gezira scheme, for the month of November 1988

DAY	SGB INDENT	MOI RECORDED DISCHARGE	HRS MEASURED DISCHARGE
1	34	34	23.76
2	34	34	19.61
3	34	34	26.06
4	34	34	data missing
5	34	34	9.50
6	34	34	17.11
7	34	34	19.87
8	34	34	13.39
9	34	34	19.44
10	34	34	7.60
11	34	34	data missing
12	34	34	data missing
13	34	34	13.74
14	34	34	10.36
15	34	34	11.32
16	34	34	13.74
17	34	34	15.90
18	34	34	data missing
19	34	34	10.80
20	34	34	18.23
21	34	34	17.54
22	34	34	21.95
23	34	34	21.95
24	34	34	26.09
25	34	34	data missing
26	34	34	data missing
27	34	34	24.62
28	34	34	23.41
29	34	34	22.20
30	34	34	20.91

c) Downstream the Minor Canals Off-takes:

The minor canal off-take is the point at which the water control is handed over from the MOI to the SGB. below this point no water discharge measurements are regularly taken. In fact there are not even any water level gauges or discharge measuring structures. All the information available from the SGB on water supplies at this level of the irrigation system are records of the indents submitted to the MOI for each minor canal. The farmers and the SGB depend totally on their judgements in estimating the flow rate which should be passed to any area. There are, however, some measurements taken at some locations at this level of the system for research purposes. Data from some of these measurements is used in this study.

No use of the water discharge data collected in the Gezira scheme is made for the purpose of performance evaluation. In fact apart from the data collected at the dam headwork which has been some times used by some researchers, water discharge data for all other points downstream is only available in the original notebooks in which it was recorded in the field without any analysis or publications. In our view one of the main reasons for the poor quality of these data is the fact that even those who are recording it know that their records are not likely to be used or checked.

CHAPTER 5

WATER SUPPLY ADEQUACY, EQUITY AND WATER LOSSES

5.1. Adequacy of Irrigation Supply:

At any point in the irrigation system the water supply is said to be adequate if enough quantity of water is delivered when it is required. However, the determination of how much water would be enough and at what time it is required differs widely between systems. Generally there are two main ways in which water deliveries can be scheduled from the main system to the water users' outlets. These are *demand scheduling* and *supply scheduling*. Sometimes they are referred to as *user controlled* and *supplier controlled* scheduling respectively (Wade, 1982; and Manz, 1988) and there are many forms of combination between these two.

In the *demand scheduling* type of systems, the water is delivered to the users in response to their demands. i.e. It is the water user who decides how much water he needs and when. The adequacy of the water supply should, therefore, be judged by how well the water user's demands were satisfied in quantity and in time. In the *supply scheduling* type of systems on the other hand, the main irrigation system manager alone decides on when and how much water should be supplied based on his judgement of the crop water demands. In these latter type of systems the adequacy should be measured by how well the crop demands were met.

The supply scheduling is more suitable for small-holder type of schemes where communication between the irrigation system management and the water users is poor (Moore, 1981). These are the most common in developing countries where the irrigation schemes are characterized by a large number of small users. The methodologies developed in this chapter are basically for this type of systems. However, the basic idea developed for measuring the difference between the water supply and demand can easily be adapted to the demand scheduling type of systems. This point is discussed later in this chapter (section (5.10)).

If we are measuring the degree of success with which the irrigation system was able to satisfy each user's outlet with its crop water demand, we have to assume that the water users are using these deliveries properly. i.e. Any misuse of the water downstream of these outlets lies outside the control of the main system manager and, therefore, he cannot be held responsible for it. For this assumption to be realistic, in supplying the water demands to those users, the theoretical crop water requirement can be increased by a reasonable factor to allow for the unavoidable water losses and the inequity between different users sharing the same outlet.

For a water supply to be adequate, it is not necessary to have an exact match of the time pattern of water supply at the outlet with that of the water demand of the crops supplied from this outlet. What is important is to make sure that these crops have always enough soil moisture stored in their root zone and ready for their uptake. The existence of a water storage facility in the root zone provides the main system manager with a great flexibility in his water delivery schedule. Using this facility he can plan any water delivery schedule and then rely on this storage facility to make sure that water is continuously at the disposal of the plants.

Let us assume that at the end of the season a record of the daily variation of the average soil moisture level in the scheme (or any part of it) is available. Such information can tell us whether the crop suffered any stress during the season or not. It can also tell us how severe and how frequent was that stress. Using this information we can judge the adequacy of the water supply. In this chapter, a soil moisture simulation model is developed to simulate the history of the soil moisture in the area under investigation. By comparing this with the minimum soil moisture level required by the crop, an irrigation adequacy measure is developed.

Before embarking on the development of this analysis, the quality of data usually available from irrigation systems, particularly in developing countries, should be recognized. For this reason it was decided from the start that a simple approximate model would be enough for the purpose of this analysis.

5.2. Soil/Water Reservoir System:

The soil/water/plant system of an irrigation scheme (or any part of it) can be modelled by a reservoir analogy approach. The inflow to the reservoir consists of the irrigation supplies plus any rain falling onto the scheme. The outflow is the actual evapotranspiration of all the crops grown plus any water losses to surface drainage or deep percolation. The storage volume of the reservoir, which is a function of the cropped area and the root depth, varies with time depending on the crops grown, their areas and development stages.

In a typical small holder irrigation scheme, any outlet may be serving a large number of water users, each growing a number of crops. Even for the same crop, the sowing date is not necessarily the same for each user. On any particular day during the season, different crops (or the same crop with different sowing dates) will be extracting water over different depths of the soil depending on the pattern of their root development. Let us consider an irrigation scheme (or any part of it) consisting of, say, six subareas sown with different crops or with the same crop but different sowing dates. In any particular day during the irrigation season, each of the six subareas will be contributing to the total soil moisture storage volume (fig.(5.1)).

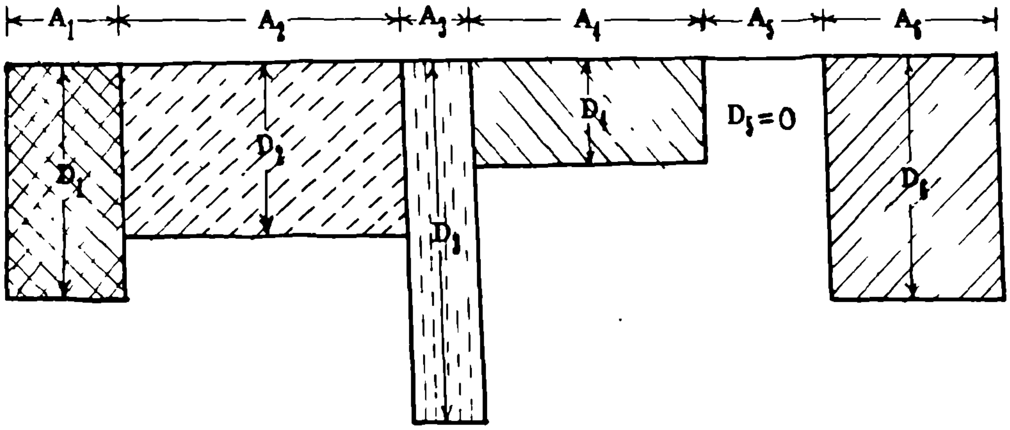


Fig.(5.1): Contributions of different subareas to the total soil moisture reservoir volume

The total soil moisture storage volume available in the scheme on day j is, therefore, equal to the total volume of water which can be stored in the root zone of all subareas. This can be expressed by:

$$V_j = S_a \times \sum_{i=1}^{N} 10 \times A_i \times D_{ij} \qquad (5.1)$$

In this expression, V_j is the storage volume on day j in cubic meters, S_a is the soil moisture storage capacity in mm/m., A_i is the area of crop i in hectares. D_{ij} is the root depth of crop i on day j in mm., N is the number of sub-areas and 10 is a conversion factor (to convert hectares×mm. to cubic meters). If, on any day, no crop is under cultivation in any one or more of the subareas the root depth in that subarea is zero and it contributes nothing to the available soil moisture storage volume on that day.

The value of the soil storage capacity S_a is a measure of the ability of the soil to store water in its voids. It is defined as the depth of water which can be stored in the soil between moisture content at the Field Capacity (FC) and the Permanent Wilting Point (PWP) in mm. per meter depth of soil. As a general guide the value of S_a varies between 200 mm/m. for heavy textured soils to 60 mm/m. for coarse textured soils (Doorenbos and Kassam, 1979).

The processes of inflow and outflow to the reservoir system is continuous over time. However, for the purpose of modelling these processes it can be assumed that precipitation, irrigation and the evapotranspiration for each day take place as instantaneous events at the end of the day. The status of the soil water reservoir at the end of day N can be calculated using the following water balance model:

$$\phi_N = \Phi_{N-1} + I_N + R_N - E_N - Losses \qquad (5.2)$$

Where:

ϕ_N = Soil moisture stored in the root zone at the end of day N (mm.). This is the average depth of soil moisture in the scheme (or the part of the scheme under investigation). It is equal to the total volume of water stored in the root zone divided by the total area under cultivation on that day.

ϕ_{N-1} = Soil moisture storage at the end of the previous day (mm.). The soil is taken to be at its PWP on day zero (the effect of the initial soil moisture is discussed later in section (5.4.2)).

I_N = Irrigation supplies on day N (mm.). This is equal to the volume of water delivered divided by the total area under cultivation on that day.

R_N = Total rainfall on day N (mm.).

E_N = Actual evapotranspiration on day N (mm.). This is equal to the total actual evapotranspiration from all the crops in the scheme divided by the area under cultivation on that day.

Losses = Water lost to deep percolation below the root zone plus surface run-off.

If on any day during the season, the soil moisture ϕ_N in the root zone exceeds the FC then, in our analysis here we assume that the excess water will take one day to run off the surface or percolate to the deep layers of the soil and leave the root zone on the next day at FC. This is in line with the ASCE definition of FC (ASCE, 1978). The assumption is realistic for soils with high permeability or when water ponding above the ground is not allowed for. Sophisticated soil moisture models which account for deep percolation and water ponding in the field have been developed, but it was felt that for our purpose here such a simple model could be enough.

5.3. Actual Evapotranspiration:

Actual evapotranspiration is defined as the total actual amount of water lost from the soil to the atmosphere either by direct evaporation from the soil surface or by transpiration through the crop leaves via the root system. This amount is determined by: i) Climate. ii) Crop characteristics. iii) Soil moisture availability. Each of these factors is discussed below:

5.3.1. Climate:

The effect of climate on the evapotranspiration is normally expressed by the reference crop evapotranspiration (ETo) in mm./day which is a measure of the evaporative demand of the atmosphere. Many methods are available for estimating the value of ETo for a locality. Each method requires certain set of meteorological measurements. These methods are described in many text books. For a good review of some of these reference is made to Burman (1983).

5.3.2. Crop Characteristics:

When the soil contain enough water for unrestricted uptake by the crop the evapotranspiration will be at its maximum rate (ETm). This rate is related to the reference crop evapotranspiration by the relation:

$$ET_m = k_c \times ETo \tag{5.3}$$

Where k_c is known as the crop factor (or crop coefficient) and is determined primarily by the crop type and its development stage. For a given crop the crop factor k_c has a low value when the crop is young, it increases with the crop development to a maximum level when the crop is fully developed and then decreases as the crop approaches maturity. Values of k_c for most crops have been determined experimentally. Doorenbos and Kassam (1979) gave estimates of these values for most important agricultural crops at different development stages.

5.3.3. Soil Moisture Availability:

The level of the soil moisture in the root zone limits the rate at which the plant can absorb water from the soil. The actual evapotranspiration may be expressed as a function of the soil moisture content (Denmead and Shaw, 1962). The relationship between the actual evapotranspiration (ETa) and the maximum evapotranspiration (ETm) can be expressed by:

$$ETa = ETm \times f(\Phi) \qquad (5.4)$$

Where:

f(ϕ) = Soil moisture availability function.

ϕ = Average soil moisture depth in the root zone above PWP.

Several forms of the soil availability function f(ϕ) have been suggested in the literature. Boonyatharokul and Walker (1979) compared some of these forms and recommended the use of a simple linear function. Using this linear form recommended by them, the actual evapotranspiration remains at its maximum rate (i.e. ETa = ETm) for the amount of soil moisture in the root zone ranging from field capacity to a certain limit. For further lower soil moisture f(ϕ) decreases linearly with ϕ. This form of f(ϕ) is shown graphically in fig.(5.2). With this linear form f(ϕ) can be expressed by the relations of equation (5.5) in which D is the root zone depth (m.) and P is the fraction of the total soil moisture which can be depleted before ETa becomes less than ETo.

$$f(\phi) = 1 \qquad for\ FC \geq \phi \geq (1-p) \times Sa \times D$$

$$f(\phi) = \frac{\Phi}{(1-p) \times S_a \times D} \quad for PWP < \Phi < (1-p) \times Sa \times D \qquad (5.5)$$

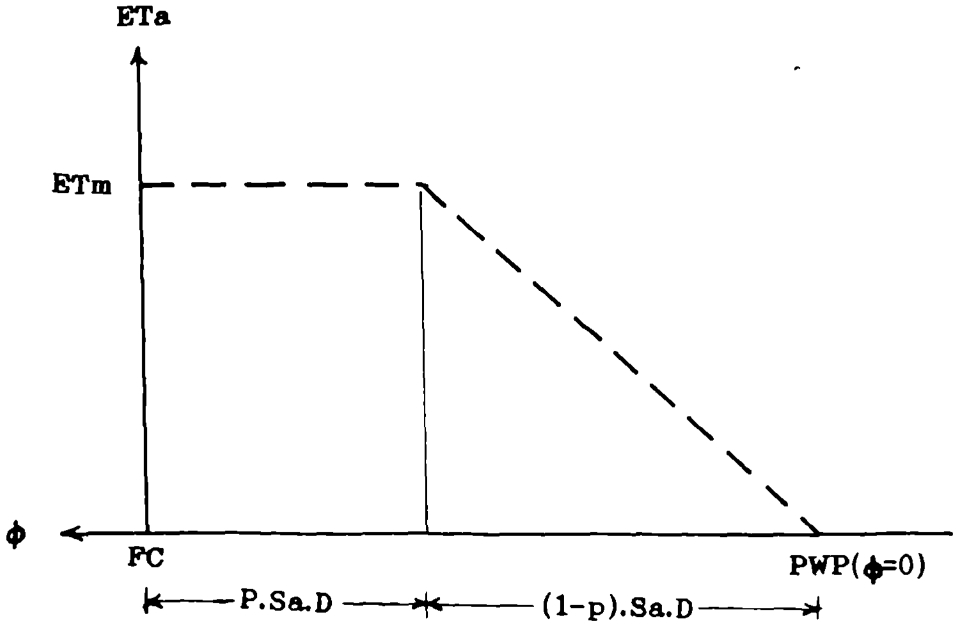


Fig.(5.2): Variation of ETa with the soil moisture level

Equations (5.4) and (5.5) are used in this analysis to calculate the daily actual evapotranspiration with the additional assumption that the evapotranspiration ceases completely when the soil moisture in the root zone reaches the PWP. Although even below the PWP some evaporation may take place, particularly in cracking soils, it seems that the accuracy which may be gained by the consideration of this may not justify such sophistication in such analysis. The soil moisture at PWP was taken as a datum (i.e. $\phi = 0$). Any value of ϕ in this analysis is the soil moisture content above the PWP.

The value of the fraction P depends mainly on the crop type and the level of ETo. Slabbers (1980) using data from other workers gave guidelines for estimating the value of the fraction P for a number of crops. He also indicated that for most crops and in most agro-climatic conditions the value of the fraction P is in the range of 40 to 60%. In this study and because of the approximate nature of the analysis a value of P = 0.55 was adopted for all crops. The selection of this value for P was based on the method given by Slabbers (1988) for the crops grown and for the range of ETo in the Gezira scheme, Sudan.

5.4. Soil Moisture Simulation Model:

To perform the calculations of equations (5.1) to (5.5) a micro-computer based soil moisture simulation model was written in LOTUS-123. The model calculates the daily actual evapotranspiration and the average soil moisture level in the crop root zone of the scheme (or any part of it to be analyzed). The model is micro-computer based to enable its use by the field irrigation officials in their local offices. It is written in LOTUS-123 because, in addition to its good data manipulation capability and quite flexible programming language, LOTUS has good graphical display facilities. This is particularly useful for a quick visual summary of the model output.

The idea is to use the model at the scheme headquarters to evaluate the overall performance of the scheme at the headwork and key distribution points. The same model can be used by the field engineers at their local offices to simulate the performance of individual canals off-takes or individual users off-takes. The model is the same no matter how many crops are grown or how much is the area under investigation.

5.4.1. Description of the Model:

A list of the computer program together with part of the worksheet which shows sample of the input and output data are given in appendix (C.1). The data is for Number 18, hamza minor canal. The input data to the model consists of two parts:

a) Basic Scheme Data: This consists of basic data about the scheme as a whole. It is to be stored in the computer once it is decided to use the model in a particular scheme. It consists of:

(i)- The characteristics of the crops grown in the scheme, namely: the variation of their k_c values (columns AQ - AU, appendix (C.1)) and their root depth (columns AV - AZ, appendix (C.1)) through their life time.

(ii)- Average S_a value for the soil type in the scheme area.

(iii)- Length of the irrigation season.

b) Daily Operational Data: This is the data which should be fed to the model periodically for the particular area to be investigated. It consists of:

(i)- Daily irrigation deliveries (l/s) (column J).

(ii)- Daily average rain depth (mm) (column H).

(iii)- Daily measured ETo value (mm) (column G).

(iv)- Daily areas sown with different crops (feddans) (columns B - F).

When the model is run, the program searches the sowing date data day by day for any piece of land sown with any crop. If found, the program computes its daily contribution to the total crop water requirement and to the total volume of soil moisture storage (equation (5.1)) for the rest of the season. The program then calculates the soil moisture balance day by day (equations (5.2) to (5.5)). In this way the model output consists of:

(i)- Daily total maximum and actual evapotranspiration from all the crops under cultivation in the scheme (or area under investigation) (columns L and M respectively).

(ii)- Variation of the average soil moisture reservoir level (column O).

(iii)- Variation of the area under cultivation (column U).

(iv)- Variation of the minimum and maximum allowable soil moisture reservoir level (columns Z and AA respectively).

(v)- Total seasonal rain falling on the cultivated area (sum of column I for the whole season) and the evaporation losses from the canal network open water surface (Sum of column G for the whole season multiplied by the canal surface area).

The primary objective of the model is condition monitoring for evaluation. At any time during the irrigation season the model can tell the manager how well the crop water demands are being satisfied. This can be achieved by looking at the history of the soil moisture level. In addition to that the model can be used as a planning tool. At the beginning of the season the model can help in decisions concerning how much area of different crops can be grown in different parts of the scheme and when, given the canal network capacity and the volume of water available for irrigation use. The model can also be used for testing any proposed water delivery schedule.

5.4.2. Validation of the Simulation Model:

To calibrate and validate the soil moisture simulation model described previously it is required to have the two sets of data (i.e. the basic scheme data and the operational data) for an area plus some measurements of the average soil moisture level in the same area. For the operational data, irrigation supplies, rain fall, ETo (Penman) and average soil moisture levels were available for two groundnut varieties grown in two separate fields at the experimental farm of the Gezira Agricultural Research Station (GARS), Wad Medani, Sudan, in the 1989/1990 season. Measurements of the soil moisture and irrigation supplies were conducted by the staff of the Hydraulics Research Station (HRS) of the MOI, Wad Medani. Rainfall and ETo data was taken from the records of Wad Medani agro-meteorological station which is situated near the experiment plots. Irrigation supplies were measured at the point supplying the experimental plots using a vane flowmeter. Soil moisture was measured using a neutron probe. Measurements of the soil moisture on any day were taken at several points and the average was calculated.

For the basic scheme data, fig.(5.3) shows the values of k_c for groundnut (together with other crops grown in the Gezira scheme). These values were derived experimentally in the scheme (Farbrother, 1977). Fig.(5.4) shows an assumed development pattern of the root depth for the same crops. In selecting these root development patterns use was made of data given by Doorenbos and Kassam (1979). A value of S_a = 170 mm/m. (Hussain, 1989) was adopted. Some adjustments for the value of S_a and the root development pattern were made before these value were finally adopted. The adjustment made for the root development pattern was that a minimum root depth of 35 cm. for all crops was assumed. As for the value of S_a, other sources give a value of S_a = 240 mm/m. (Fadl and Adam, 1983). The model was found to give much better result if a value of S_a = 170 mm/m. is used.

The above data was used as an input for the model. Fig.(5.5) is a plot of the average soil moisture as measured and as calculated by the model. Although the data is for a single crop sown in a single area, fig.(5.5) indicates that the basic assumptions are reasonable and the model can be used for simulating the soil moisture.

Fig.(5.3): Variation of the crop factor (k_c) for the crops grown in the Gezira scheme (derived from Farbrother (1977))

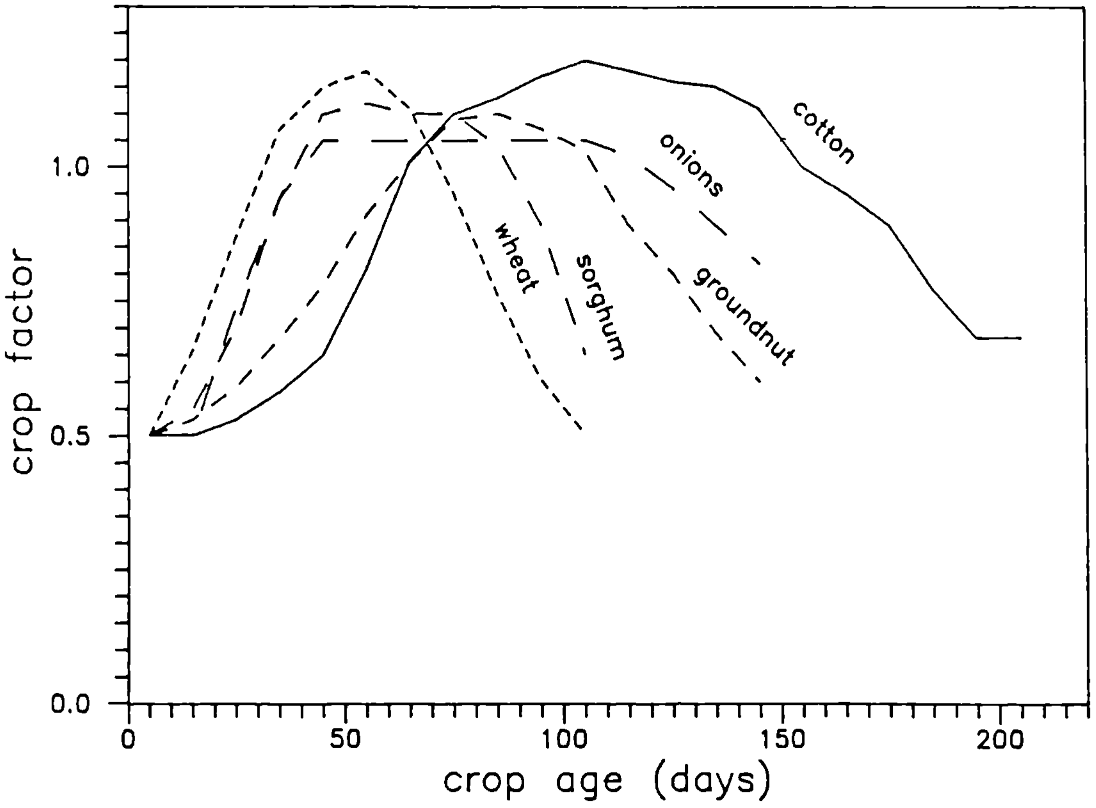
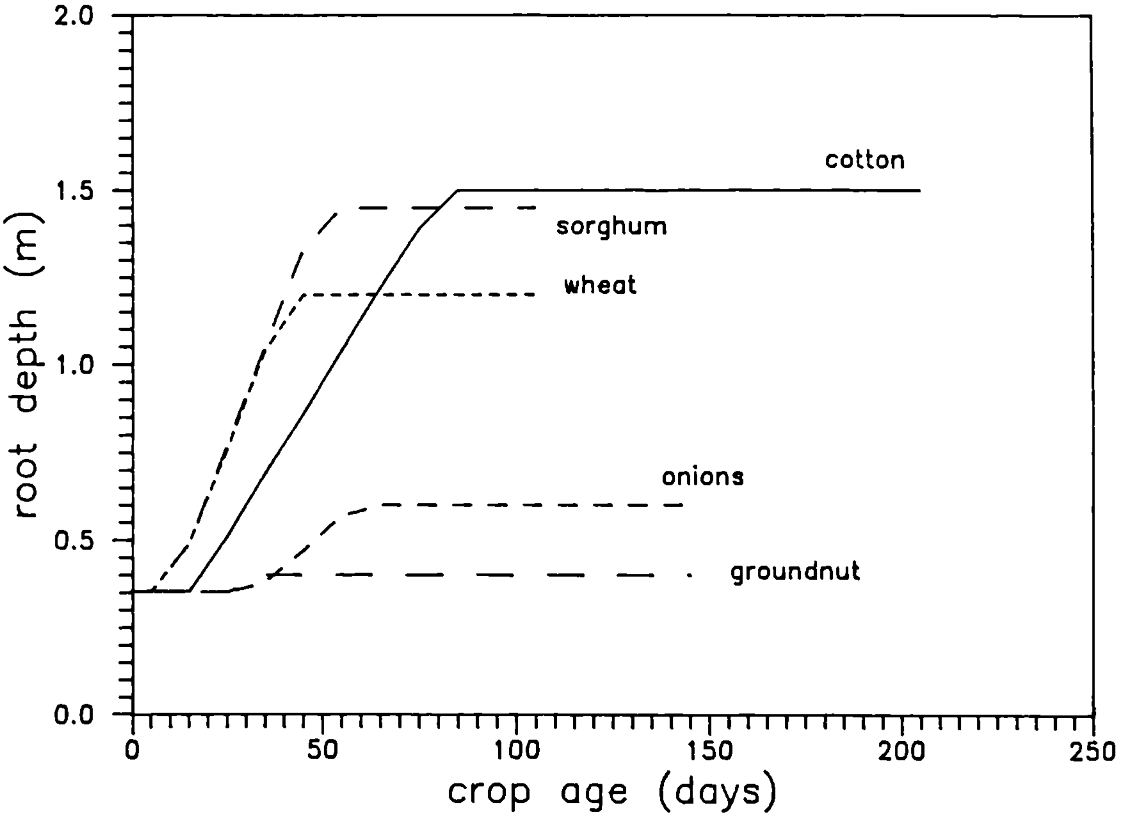
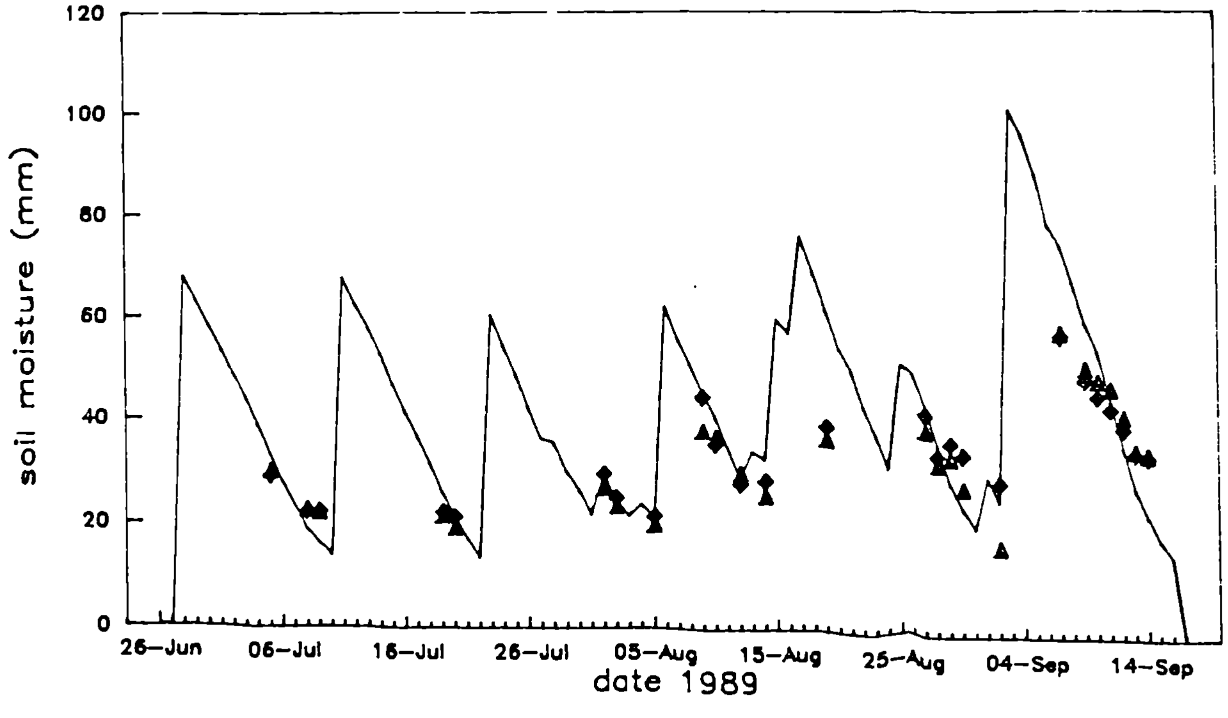


Fig.(5.4): Assumed root development pattern for the crops grown in the Gezira acheme



In order to investigate the effect of the choice of the initial soil moisture (i.e. soil moisture level on day zero in equation (5.2)), several initial soil moisture values were tried. It was established that the result of the model is not sensitive to the choice of the initial soil moisture. The reason for this is the fact that immediately following crop sowing, if there is not enough rain, irrigation is usually applied. What ever the initial soil moisture was, it will be brought to FC by the first irrigation or appreciable rainfall.

Fig.(5.5): Measured and predicted soil moisture variation.
GARS farm, Wad Medani, Sudan.



5.4.3. Model Example Output:

To show the type of output one can get from the simulation model, data from Number 18, Hamza minor canal, Gezira scheme, for the season 1986/87 was

Fig.(5.6): Irrigation, ppt & ETo
No. 18, Hamza minor

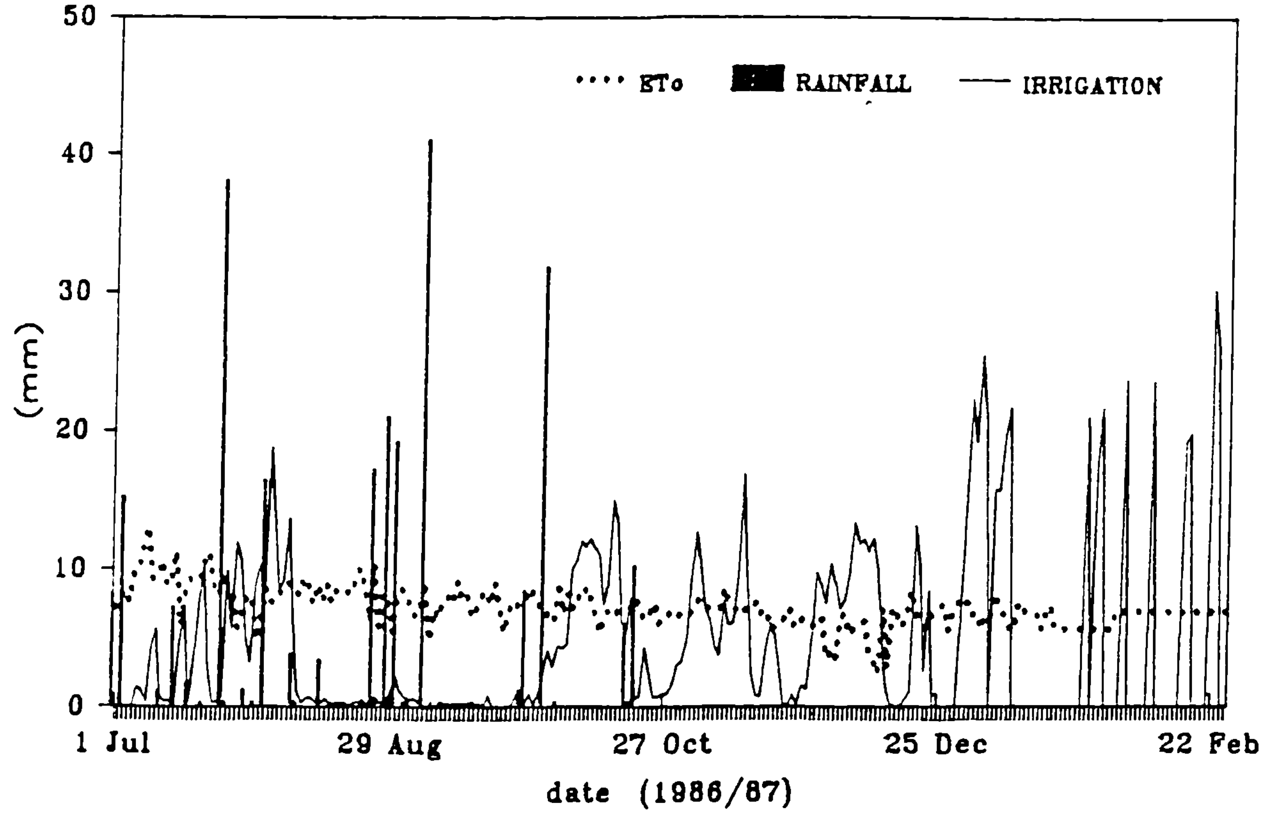
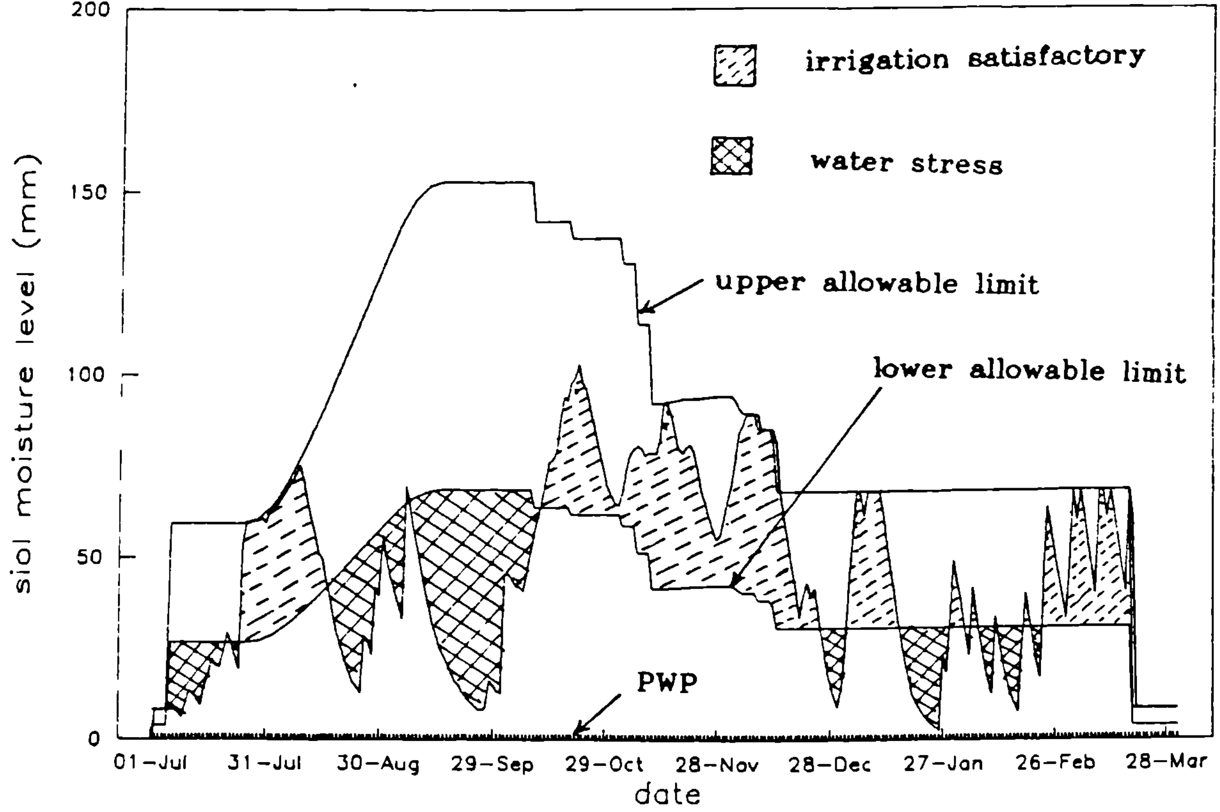


Fig.(5.7): Average soil moisture, Number 18, Hamza minor.
(1986/87 season)



used. This Number is 90 feddans (38 hectares) in area. Three crops were grown in this number in that season: Sorghum, groundnut and vegetables (all vegetables were taken to be onions). Table (5.1) shows the areas and sowing dates for these crops. The data for irrigation supplies, ETo and rainfall used in the analysis is shown in fig.(5.6). The model output is shown in fig.(5.7). This output shows the average soil moisture storage level in the Number together with the upper and lower allowable levels. The upper soil moisture level is the FC and the lower allowable soil moisture level is one below which the actual evapotranspiration is lower than maximum. Clearly a figure like this reflects a complete picture of the periods of water shortage and the periods during which the irrigation was satisfactory.

Table.(5.1): Areas/sowing dates for Number 18, Hamza minor, for the 1986/87 season.

SORGHUM		GROUNDNUT		Vegetables	
Date	Area	Date	Area	Date	Area
16/7/86	5	6/7/86	10	10/10/86	10
20/7	10	7/7	10	20/10	5
24/7	10	8/7	5		
		12/7	10		
		16/7	5		
		17/7	10		

5.5. Characterization of Water Stress Condition:

For the water supply to be adequate optimum soil moisture condition for healthy crop growth must be maintained in the root throughout the cropping season. To be able to judge whether this condition is satisfied or not, it necessary to define the critical soil moisture level below which the crop is considered under stress and, therefore, the irrigation is considered unsatisfactory.

The minimum acceptable soil moisture level varies from one scheme to the other depending on the availability of the irrigation water to the system manager, the characteristics of the crops grown and their economic value in relation to that of the water. In some systems it may be desirable to maintain a very high soil moisture levels. For example, it has been observed that rice farmers start to become concerned when the water level in their fields becomes lower than certain level which may be well above saturation (Ng, 1988). In other systems it may be acceptable to have a much lower soil moisture level. For example, Van Bavel (1953) when studying rain-fed agriculture, considered the day to be a drought day only if the soil moisture on that day reaches the PWP. Any value above that is satisfactory for him. In irrigated agriculture, however, one would expect a much better soil moisture conditions than that of the rain-fed. Water stress must, therefore, be considered to occur at a much earlier stage than in the case of rain-fed agriculture.

It is reasonable to assume that irrigation should be applied whenever the soil moisture starts to limit the plant water (and therefore nutrients) uptake, from the soil (i.e. when ETa starts to become less than ETm). In our analysis here, this is the level of soil moisture below which water stress condition is considered to start. If on any day ETa/ETm < 1 the irrigation supply is taken to be unsatisfactory on that day.

The criteria of having ETa/ETm < 1 (i.e.ETa < ETm) would tell us, for any particular day, whether there is any stress of any magnitude or not. To measure the degree of this stress, if experienced, the form suggested by Hiler and Clark (1971) seems to be suitable. They measured the Stress Level (SL) on any day by:

$$SL = (1 - \frac{ETa}{ETm}) \tag{5.6}$$

The value of SL in equation (5.6) takes its maximum value of unity when ETa is zero. This happens when the soil moisture in the root zone is at the PWP. The minimum value of SL is zero and occurs when the evapotranspiration is at its maximum rate (i.e. when ETa = ETm). The SL as given by equation (5.6) is used in this study as a scale for measuring the level of stress experienced by the crop on any day.

5.6. Characterization of the Water Supply Adequacy:

Having calculated the daily variation of the soil moisture level and defined the minimum acceptable soil moisture level, the next step is to use these for measuring the adequacy of the water supply. Two approaches are suggested here: The first approach provides a graphical summary of the important features of the water shortage experienced during the season. Namely the intensity-duration characteristics of the water shortage. The second approach consists of developing an Irrigation Adequacy Index (IAI) which combines all the features of the water supply adequacy into a single number. In calculating the IAI we do not only consider the intensity-duration characteristics of the water shortage but also its time distribution with respect to the crop sensitivity to water stress. The two approaches are introduced in the following two subsections.

5.6.1. The Stress Intensity-Duration Curve:

When a water shortage is experienced, it is not only important to know how much water was in shortage, but the time distribution of this shortage is also important. A severe continuous water shortage concentrated in, say, only ten days of the season have different consequences from the same amount of shortage spread over longer time span. The difference of consequence can be in the equity between different users or can be to individual user. If the point under consideration is supplying a number of users then, with a severe water shortage concentrated in a short time period, larger number of those users will be affected. If, however, the same shortage is spread over a longer time span, one would expect that only smaller number of users may have to suffer all the shortage. They will always be those who are situated at unfavourable locations. Similarly, if the point under consideration is supplying a single farmer then, with a partial water shortage spread throughout the season this farmer have the chance to optimize on the water supplied to him. He may react to the shortage by sacrificing part of his land and concentrate all the shortage in this part. In this way he may grow less stress-sensitive crops or may reduce other inputs to this stressed part. Whereas, if the same amount of water shortage is concentrated in a shorter time, all his crops have to be stressed.

To summarize the intensity-duration characteristics of the water shortage experienced during the season the following procedure is suggested. The same data for Number 18, hamza minor canal, which was used for plotting fig.(5.7) is used here again to explain the procedure.

From a simulation of the daily soil moisture level like the one shown in fig.(5.7), for example, we can identify the days in which some stress has been experienced. These are the days in which the soil moisture level is less than or equal to the lower allowable limit. Clearly in these days varying degrees of stress have been experienced. The stressed days can, therefore, be grouped according to the stress level (SL of equation (5.6)) experienced in the day. To do this, we choose different values of SL. Say, SL = 0.25, 0.50, 0.75, and 0.90. In fig.(5.7) the lower allowable level represents the line at which SL = 0.0. We can construct similar lines for different values of SL as shown in fig.(5.8) in which the line for SL = 0.25, for example, represents soil moisture levels which are 25% lower than the allowable level. Similar interpretations apply for other lines with other values of SL. From fig.(5.8), for each SL we can count the number of days during the season in which the stress was equal to or less than SL. We can then plot a graph of the percentage of these days against the corresponding value of (1-SL). This is shown in fig (5.9) which we refer to as the stress *intensity-duration* curve for Number 18, Hamza minor for the 1986/87 season.

As was mentioned previously (section (5.5)) the acceptable level of stress differs in different irrigation schemes. In many schemes it may be acceptable to live with some degree of stress. In such case, and for any acceptable level of stress SL, the intensity-duration curve (fig.(5.9)) gives the percentage of time during the season in which the irrigation was not satisfactory. For example, let us assume that we are prepared to accept 25% drop in the soil moisture from the lower level (i.e. ETa can be allowed to be 25% lower than ETm). In this case fig.(5.9) tells us that for Number 18 the irrigation was unsatisfactory for 30% of the season.

Let us assume that the area under consideration can be divided according to priority of water allocation into a number of equal parts and that we always ensure that higher priority parts get enough water before lower priority parts get any. Under these conditions it can be shown that for any stress level SL = δ the number of days N in which the stress level SL $\leq \delta$ is equivalent to the number of days in which δ of the land is under stress and, therefore, $(1-\delta)$ of the land is irrigated satisfactory. Under these conditions the stress intensity-duration curve can tell us how much of the land is suffering and for how long. For example, fig.(5.9) tells us that the luckiest 10% of the land in Number 18 suffered no stress at all during the entire season, while the best irrigated half of the Number suffered stress for 17% of the time. The lower priority area of the Number suffered stress for 38% of the season and, therefore, irrigated satisfactory for only 62% of the season.

The shape of the intensity-duration curve also have some significance. The following type of information can be extracted from its shape:

i) The area (A_r) under the stress intensity-duration curve is given by:

$$A_r = \frac{100}{N}\times\sum_{i=1}^{N} SL_i \tag{5.7}$$

Where SL_i is the stress level on day i and N is the number of days in the season.

The value of A_r is a measure of the total stress experienced during the season. It takes its maximum value of 100% if no water was supplied during the season and takes its minimum value of zero if the crop was irrigated satisfactory during the entire season.

Fig.(5.8):Soil moisture variation and different stress levels.
Number 18, Hamza minor, 1986/87 season

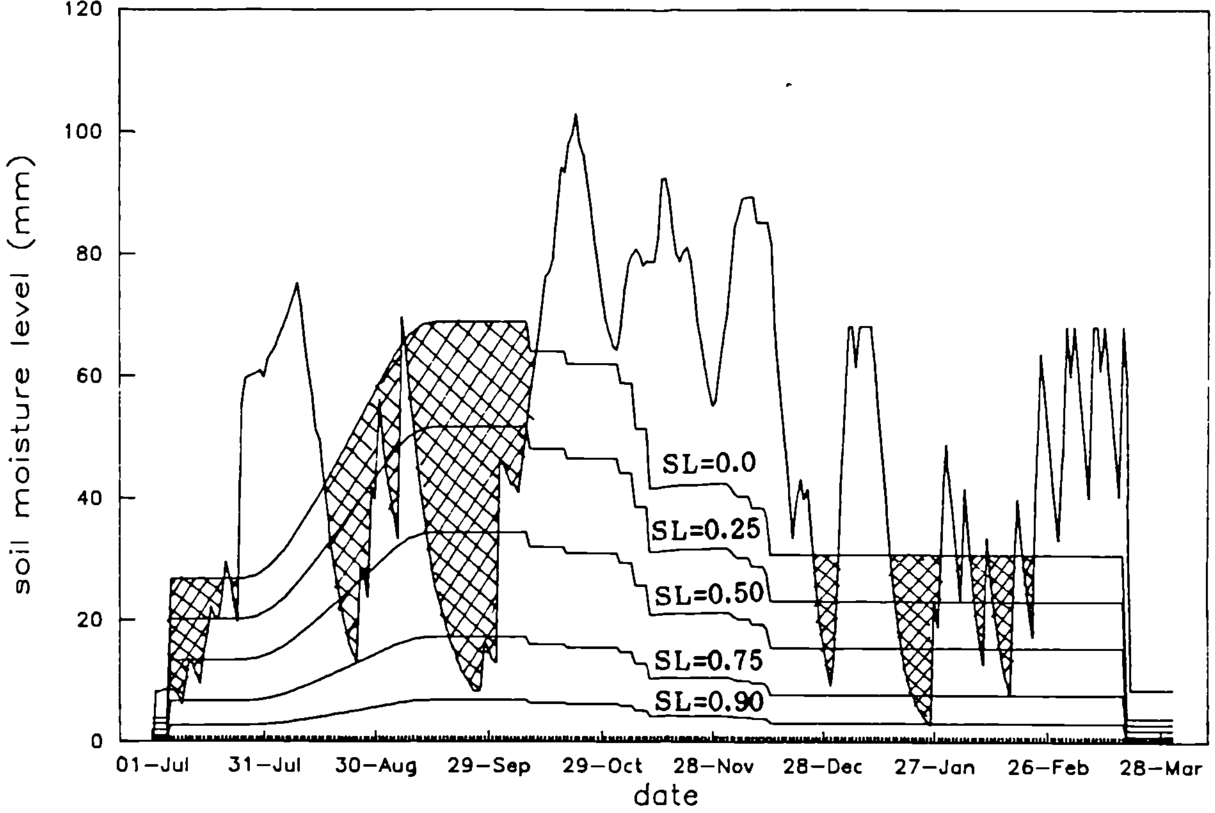
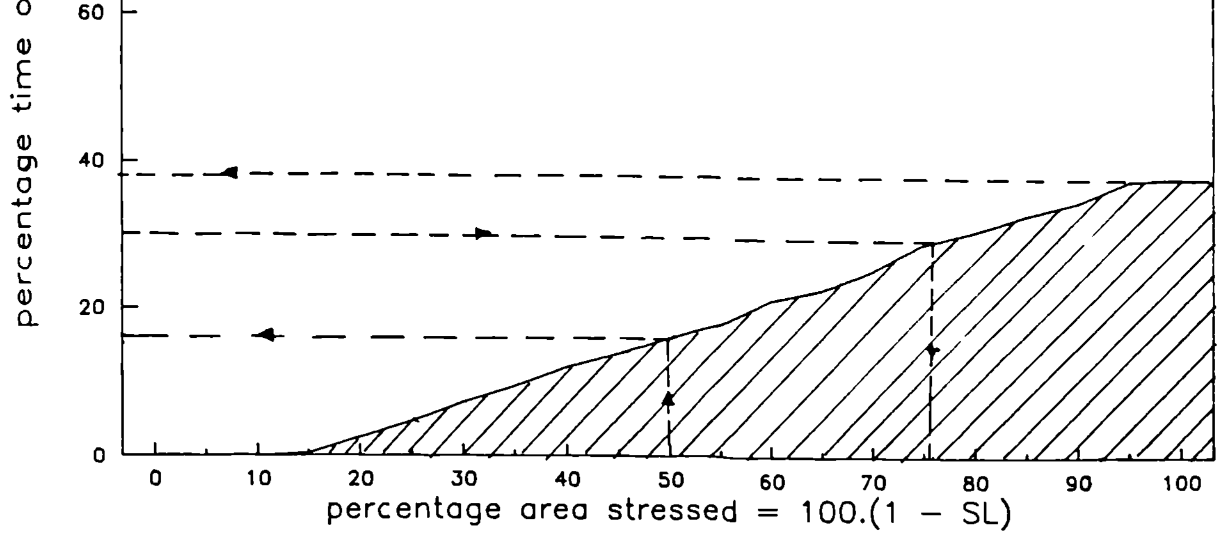


Fig.(5.9): Sress intensity-duration curve, Number 18, Hamza minor
(derived from fig.(5.8))



ii) The slope of the curve is a measure of the spread of the stress. Flat curves indicate that the area under investigation suffered shorter periods of severe stresses, while steep curves means that the stresses were spread over longer time span.

iii) The stress intensity-duration curve can enable comparison of the adequacies of different water supply schedules. This can be done by plotting their individual intensity-duration curves in the same graph and then compare their slopes and A_r's with each other.

5.6.2. The Irrigation Adequacy Index (IAI):

Although a summary of the stress intensity-duration characteristics like the one described previously (fig.(5.9)) provides useful information on the adequacy of the supply, it may not always be sophisticated enough for that purpose. This is because it treats all periods of the season as being equally important. Different periods of the season may have different importance for several reasons. Firstly, crop response to water stress varies with its development stage. Secondly, the point under consideration may be supplying water to a number of crops each has a different life span and, therefore, requiring water for only part of the season. This means that the area under cultivation may be different in different periods of the season. A stress of, say, 50% in a period when 100% of the area is under cultivation is more undesirable than the same level of stress when only 10% of the area is under cultivation. Thirdly, the system manager may have some preferences among the crops grown in the area. Preferences which may be dictated by the government policy or the market prices of the crops. A stress experienced during a period when most of the crops under cultivation are of high importance is different from the same level of stress experienced when most of the crops are of low importance.

To account for these factors it is necessary to assign some weights for different periods of the season depending on the crops under cultivation in each period, their growth stages, how much area of each crop and their relative importance to the system manager. A procedure is developed here to formulate an Irrigation Adequacy Index (IAI) which combines all these factors with the intensity-duration characteristics of the stress experienced during the season into a single number between zero and hundred.

The procedure consists of four steps: 1) Estimation of the relative weights of the crops. 2) Calculation of the adequacy for individual periods. 3) Calculation of the relative weights of the periods. 4) Calculation of the overall season IAI.

Step (1): Crop relative weights:

In the Gezira scheme five crops are grown: cotton, wheat, groundnut, sorghum and onions. To get the relative weights of these crops, five Sudanese officials involved in the management of irrigation, were interviewed. Three of those officials are MOI engineers, one is an agricultural manager and one is a researcher from the HRS of the MOI. They were requested to answer the following question:

"How many feddans of cotton (groundnut, sorghum, onion) are you willing to stress in order to irrigate one feddan of wheat?"

Their answers are given in table (5.2). Clearly from these answers there is no definite policy concerning priorities of water allocation among the crops grown in the scheme. There are considerable differences in the relative importance assigned to different crops by different officials. With the exception of Respondent 5 who believes that all crop should be treated equally, the other four respondents considered wheat as the most important crop. This was probably because the government started a campaign in that season for the country to become self-sufficient in wheat. Imports were reduced and people were expecting some shortage in wheat. Respondent 3 was relatively generous with sorghum and groundnut because, he argued, of their profitability to the farmer. Respondents 1, 2 and 4, however, took a national point of view and gave the sorghum and groundnut crops lower priorities. The reason they gave was that these crops, unlike cotton and wheat, can be produced in the rain-fed areas of the country.

Table (5.2): <u>Preferences among the crops in the Gezira scheme</u>

RESPONDENT	1	2	3	4	5	
POSITION CROP	MOI ENG.	MOI ENG.	MOI ENG.	AGRIC. MANAGER	HRS ENG.	AVERAGE
WHEAT	1	1	1	1	1	1.0
COTTON	2	1.3	2	4	1	2.1
SORGHUM	5	5	1.5	5	1	3.5
GROUNDNUT	3.5	3.5	1.2	5	1	2.8
VEGETABLES	2	2	2	2	1	1.8

It may be worth mentioning here that before the crop intensification and diversification program which took place in the Gezira scheme in the late

1960's, only cotton, sorghum and lubia were grown. At that time the policy of the SGB was very specific about the priorities of water allocation to these crops. According to the SGB operation manual (SGB, 1951) water is primarily for cotton and other crops can only be watered if there is a surplus. After the intensification, new crops were introduced and more water was made available for the scheme, but no new instructions or advice concerning water allocation priorities was issued. Now almost all those who are involved in the operation of the system believe that the priorities of the 1951 manual are no longer binding but different people have different priorities.

Going back to the derivation of the crop relative weights, the calculation procedure is shown in table (5.3). In this table, column 2 is the average taken from table (5.2). The reciprocal of column 2 is the relative importance of the crops. This is given in column 3. These values are normalized in Column 4 to give relative weights summing up to unity.

Table(5.3): Crops relative weights

CROP	ANSWER TO QUESTION	RELATIVE IMPORTANCE	RELATIVE WEIGHT
WHEAT	1.0	1.00	0.37
COTTON	2.1	0.48	0.18
SORGHUM	3.5	0.29	0.11
GROUNDNUT	2.8	0.36	0.13
VEGETABLE	1.8	0.56	0.21

Step (2) Adequacy of Individual Periods:

The irrigation season can be divided into periods of equal lengths. A week, 10 days or the irrigation interval, for example, are reasonable choices for the period length. Having done that then from the soil moisture simulation model, one can calculate the adequacy R_j of period j as the ratio of the sum of ETa to the sum of ETm during the period This given by equation (5.8) in which M is the length of the period in days. In this study M is taken to be 10 days.

$$R_j = \frac{\sum_{i=1}^{M} ETa}{\sum_{i=1}^{M} ETm_i} \tag{5.8}$$

Step (3) Relative Weights of Individual Periods:

During any period of the season a number of crops (or the same crop with different sowing dates) may be under cultivation. Each of these contributes to the importance of the period. The contribution of each crop is determined by its area, its development stage (i.e. sensitivity to water stress) and its importance to the system manager. The importance of the period is the sum of the contributions of all these crops. It can, therefore, be expressed as:

$$W_j = \sum_{i=1}^{n} \beta_i \times A_{ij} \times K_{ij} \tag{5.9}$$

Where W_j = Relative importance of period j.

β_i = Relative weight of crop i, as calculated in step (1) above.

A_{ij} = Area of crop i, in period j.

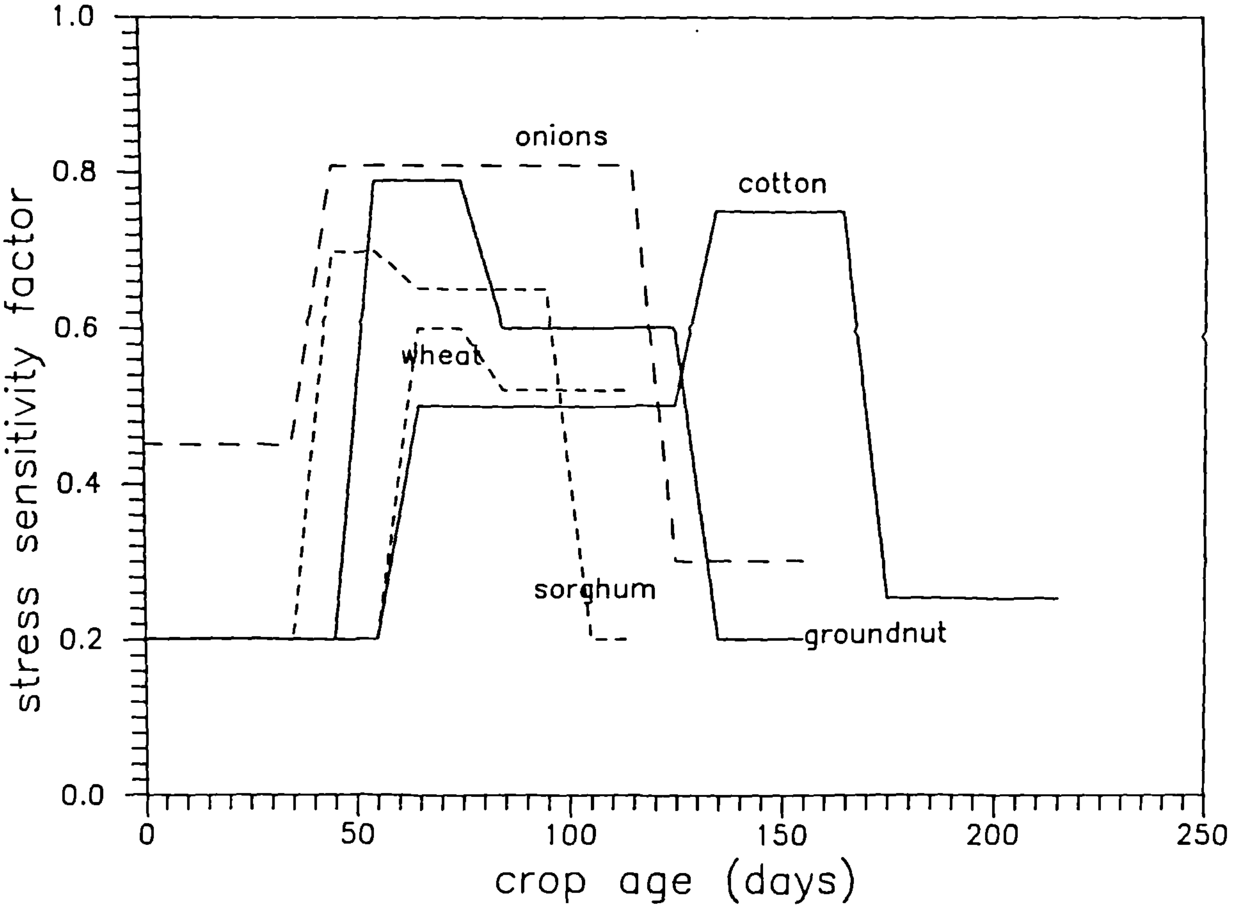
k_{ij} = Sensitivity of crop i, in period j. These values can be derived from the crops yield response factors (Doorenbos and Kassam, 1979). The values of k_{ij} for the crops grown in the Gezira are shown in fig. (5.10)

n = Number of crop sowing dates/area entries during the season.

The relative importance of the individual periods (W_j) can be normalized to give relative weights (w_j). This is done using equation (5.10) in which M is the number of 10-day periods in the season.

$$w_j = \frac{W_j}{\sum_{J=1}^{M} W_j} \tag{5.10}$$

Fig.(5.10): Stress sensitivity factor (K_{ij}) for the crops grown in the Gezira scheme (derived from crop yileld response factor (Doorenbos and Kassam (1979))



Step (4): Overall Season IAI:

The multiplicative function of equation (5.11) which weights the contributions of each individual period is used to calculate the overall seasonal IAI. In this equation R_j, w_j and M are as defined in steps 2 and 3 above.

$$IAI = 100 \times \prod_{J=1}^{M} R_j^{w_j} \tag{5.11}$$

This form of IAI takes a maximum value of 100 when the water demand was fully met throughout the season. It takes a minimum value of zero if during any of the periods the soil moisture level remained at PWP for the full length of period. If some stress was experienced during some of the periods the IAI takes a value between zero and 100. The multiplication form is preferred in equation (5.11) over the additive form adopted by Lenton (1983) (Chapter 2, equation (2.10)) for the following reason:

The multiplicative form is more sensitive to unsatisfactory stress level experienced during only one or two periods of the season. For example, if any of the R_j's became zero the effect is for IAI to go to zero. In the additive form the effect of some of the R_j's becoming zero can be damped by other R_j's in the season having high values. This means that with the multiplication form the penalty (in form of reduced IAI) for stress concentration in a short period is more that if the same stress was spread over the season. With the additive form the time distribution of the stress have no effect on the level of the IAI.

Because the IAI combines all the characteristics of the water supply adequacy into a single number, it provides a good summary of the quality of the water supply. It is also useful for comparing the adequacies of different water supply schedules. However, in doing that some information is necessarily lost. Sometimes some details may be required. The stress intensity-duration curve can be used to provide such details.

Separate computer program was written in LOTUS-123 to calculate the IAI. When run the IAI program reads the daily values of ETa and ETm from the soil moisture simulation model output and then sums their daily values for each 10-day period to get the individual period adequacy R_j. The program then goes through the sowing date/area data period by period to calculate the relative importance of each of them (Equation (5.9)) and then their relative weights (Equation (5.10)). The program then uses equations (5.11) to calculate the IAI value for the whole season. A list of the IAI program together with an example of the input and output data are given in appendix (C.2). The data in this example is for Number 18, Hamza minor canal for the 1986/87 season.

5.7. Characterization of Equity:

In the literature review (Chapter 2, section 2.1.3) it was pointed out that several expressions have been proposed for measuring equity in irrigation schemes. All of them characterize equity by comparing the total seasonal depths of the water (irrigation supplies plus rainfall) received by different users or different parts of the scheme. In our view such an approach for characterizing equity may well misreport its real impact for the following reason:

Firstly, the water deliveries to different parts of the scheme are not only different in depth but may also be different in regularity with respect to time. Tail users are always expected to receive their supplies with more erratic patterns than the head users. In such case, characterizing equity in terms of the water depth received by different users will underestimate the differences of the quality of services provided to those users.

Secondly, in many irrigation schemes, because the water supply to the tail users is more erratic, the rational reaction of those users may be to reduce the risk of crop failure by cultivating less sensitive crops. Even in systems where the cropping pattern is dictated by some government organization, crop zoning may be the deliberate policy of this organization. As a result of this it is usual to find more sensitive and water demanding crops to be grown towards the top of the system. In such cases the differences in the depth of water supplied to different parts of the scheme will overestimate the inequity problem.

Thirdly, the effect of inequity over the whole season is not the same as that over particular periods. As was mentioned previously, different periods of the season may have different importance. Characterization of equity should consider these differences.

Fourthly, some parts of the scheme may be receiving water in excess of their requirements. In such a case the conventional methods of estimating equity will exaggerate the differences in services provided to different users.

For all the above reasons we suggest here that a better picture of the differences in the qualities of services provided to different users can be obtained by comparing the value of the IAI to those users. This can be done by using the IAI instead of the depth of water supplied with any of the equity measures proposed in the literature. If Christiansen coefficient (Christiansen, 1942) which is the most widely used, is adopted then:

$$Equity = 100\times[1 - \frac{\sum_{i=1}^{N}|y_i - Y|}{NY}] \tag{5.12}$$

Where y_i = IAI of the i-th user.

Y = Average IAI for all users.

N = Number of users.

In this way equity is 100% if all users have been receiving water at equal adequacy. An equity of 80%, for example, could mean that the best half of the farmers have been receiving an irrigation adequacy which is 10% better than the average adequacy and that the poorest half of the scheme has been receiving water at 10% more adequacy than average. Similarly, an equity of 60% could mean that the best half of the scheme has 20% better adequacy than the average. The equity is zero when half the scheme received full adequacy and the other half received no water

The basic difference between the measure of adequacy proposed here and the traditional ones is that equity here is a measure of the difference in the *utility* of the water supplied to different users. Traditional approaches measure equity in terms of the difference in the volume of water supplied to different users.

5.8. Characterization of Water Losses:

Minimizing the quantity of water lost without being effectively used by the crop is one of the objectives of all irrigation systems. Water losses can take several forms:

- Seepage and direct evaporation from the canals.
- Deep percolation in the field.
- Surface run-off resulting from excess water supplies and/or rain.
- Canal breaches.

In this study water losses is measured by:

$$W.\ Losses = 100 \times \frac{\Sigma(Supply + Rain - ETa - Canal\ Evap.)}{Supply} \qquad (5.13)$$

The definition of water losses given by equation (5.13) is the same as the definition of irrigation efficiency given by Bhuiyan (1982) (see Chapter 2, equation (2.5)). Other definitions of efficiency can be equally used. It is important to note that if we are measuring how much control has been experienced over the irrigation deliveries, then we have to separate between the part of the water lost due to faulty operation and that which resulted from factors outside the control of the system manager. Rain is unpredictable to the system manager and the only response expected from him to a rain event on the cultivated area is to cut back his supplies on the next day. With the consideration of this the rain term in equation (5.13) should be taken as the effective rain. If on any day the rainfall exceeded the soil moisture deficit (FC minus actual soil moisture) the soil moisture model takes the effective rain to be equal to the soil moisture deficit.

Water losses calculated in this way may take a value of zero if the irrigation supplies plus the effective rainfall every day during the season are equal to the irrigation requirements. It can take any value above zero if there is any excess water supply. Because the soil moisture model calculates the water balance on daily basis, the irrigation system can have an adequacy of less than 100% and still have some water losses. The value of the water losses as defined by equation (5.13) can take a negative value which simply means water deficit.

5.9. Analysis of water Supply to the Gezira Scheme:

The two models described previously (i.e. the soil moisture simulation model and the IAI model) were used to calculate the IAI, *equity* and *water losses* in the Gezira scheme at three different levels of the distribution system: i) The dam headwork. ii) The minor canal off-takes. iii) The field outlets. In analyzing the adequacy at these levels the following assumptions were made:

1- In supplying irrigation water, apart from the evaporation losses from the open water surface of the canals network, no losses were allowed for. (As was mentioned in Chapter 4 (section (4.2.5)) this is the assumption generally made in the operation of the irrigation system in the Gezira scheme. The validity of this assumption is discussed later in this chapter (section (5.9.2)).

2- All vegetables were taken to be onions (usually the most dominant vegetable crop grown in the scheme).

3- All cotton grown in the scheme was assumed to be long staple variety (some parts of the scheme grow short stable varieties which has shorter life time. No data is available about the areas of the two varieties).

5.9.1. Supplies at the Dam Headwork:

Sennar dam is the point from which water supplies to the whole scheme area is diverted. For the availability and the quality of water discharge data at this point reference is made to Chapter 4 (section (4.3.5)). A set of discharge data for eight season (1980/81 - 1987/88) was obtained from the dam site in the form of 10-day average. Out of the releases from the dam, 80,000 cubic meters per day are released for purposes other than irrigating the crops in the normal scheme rotation (e.g. some permanent forests and gardens and drinking purposes) (Abdu, *et.al.* 1984). This quantity was deduced from the daily irrigation supplies from the dam before these supplies were used in the analysis. Also deducted from the supplies from the dam before it was used in the analysis, was the evaporation losses from the canal network open water surface. For estimating these losses the canal surface area was taken to be 50,665 feddans (213 square kilometres) (Abdu, *et.al.* 1984). Multiplying this area by ETo gives the daily evaporation losses.

Data on daily ETo (Penman) and rain fall for the eight seasons was collected from the records of Wad Medani agro-meteorological station. Records of ETo and rainfall at Wad Medani were assumed to apply to the whole scheme area. Area/sowing date data was extracted from the SGB annual reports in 10-day form.

Table (5.4) resulted from the analysis of these data. Figs.(A.1 - A.8, appendix A) are plots of the simulated average soil moisture in the scheme for the eight seasons. In table (5.4) CROP DEMANDS are the sum of the average daily ETm for all the crops under cultivation in the scheme, CANAL EVAP. is the sum of the daily evaporation from the canals open water surface, RAIN CONT. is the sum of the rain falling on the cropped area (i.e. any rain before the sowing data is ignored), IRRIG. SUPPLY is the sum of the daily irrigation supplies diverted to the scheme and WATER LOSS is the water losses as calculated using equation (5.13).

As can be seen from table (5.4), the supply from the dam to the Gezira scheme area as whole is generally highly adequate (for the eight seasons analyzed the average adequacy is 95). The low level of adequacy of the 1984/85 season was because that season was exceptionally dry (second lowest Blue Nile yield this century). In that season additional areas of sorghum were grown to substitute the rain-fed production lead to water demand which exceeded the two main canals carrying capacities throughout the period from October to February (see fig.(A.5), appendix A).

Table (5.4): Adequacy of supply from Sennar dam to the whole Gezira area

SEASON	CROP DEMAND (mm)	CANAL EVAP. (mm)	RAIN CONT (mm)	IRRIG. SUPPLY (mm)	WATER LOSS %	IAI %
80/81	891	68	98	874	1	92
81/82	897	74	155	966	16	98
82/83	933	87	125	1161	23	100
83/84	916	74	115	1066	18	99
84/85	1058	94	103	1081	3	85
85/86	813	69	211	933	28	100
86/87	918	83	139	945	9	93
87/88	835	86	104	1158	29	100

For the eight seasons analyzed, on average around 8% of the supply from the dam was lost to direct evaporation from the open water surface of the canals network. These were the losses which took place only during the seven months of the season (July to March). On the other hand, if all the rain falling on the cropped area can be utilized for crop use, it can contribute, on average, 14% to the crop water demand. This would be possible only if no rain event exceeded the soil moisture deficit (i.e. FC minus actual soil moisture level). By shifting the sowing dates, more use can be made of the rainy season. The large variability of rain falling on the cropped area from one year to the other was largely due to the variability of the area under cultivation during the rainy season (July-September) rather than the variability of the rainfall itself.

5.9.2. Supplies at the Minor Canals Off-takes Level:

As was mentioned in Chapter 4 (section (4.3.5)) the MOI records of water supply at the minor canals off-takes cannot always taken to be reliable. For this reason, to evaluate water supplies at this level of the system an alternative source of data was used. The Hydraulics Research Station (HRS) of the MOI, Wad Medani, Sudan, in collaboration with the Hydraulics Research (HR), Wallingford, England, conducted a joint research program which involves, among other things, the measurement of the discharges at selected points in the Gezira scheme in the 1988/89 and 1989/90 seasons. From their first season data, the daily flows to nine minor canals were obtained. Three of these minors are supplied from Zananda major canal in the upstream (south) and the other six are supplied from Kab Elgidad major canal in the downstream (north) part of the scheme. (see location map fig.(5.11)).

The off-take structures to all the nine minors are a movable weir type of

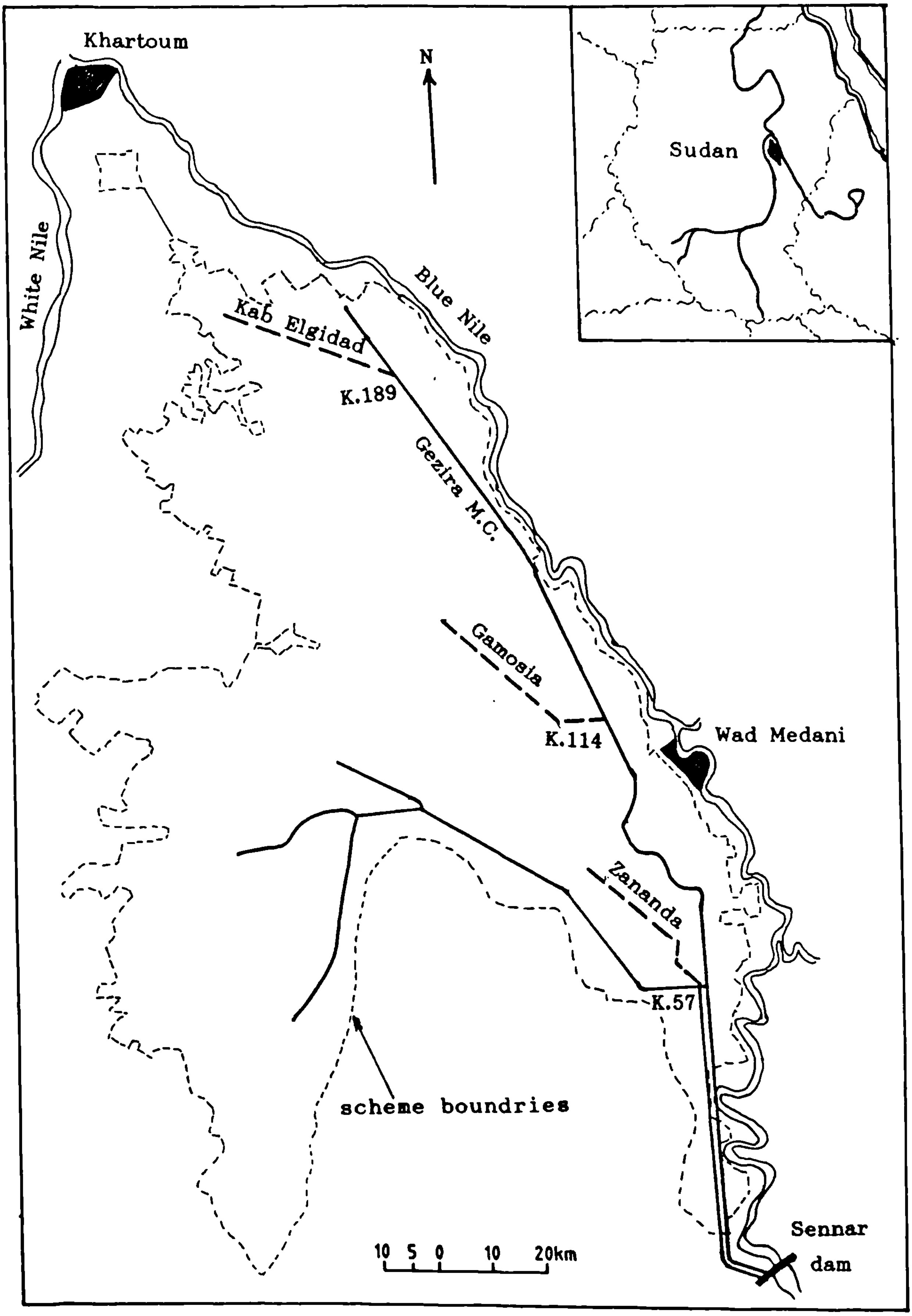


Fig.(5.11): Gezira scheme and location of majors selected for analysis structure, and the discharge entering the canal was measured by recording the head over the crest of the weir. A theoretical calibration equation was then used to estimate these flows. Unfortunately, the HRS/HR discharge data was not complete. The number of days during the season in which the data was missing varies from one minor to the other and ranges from 10% to 30% of the days. For this missing data either linear interpolation or the MOI records were used depending on the length of period in which the data was missing.

As was done with the data from the dam, before using the flows entering each minor in the analysis, evaporation losses from the open water surface of the minor were deducted. These were estimated by taking the minor canal width to be 12 meters (Abdu, *et.al.* 1984). Rainfall data for each minor was taken from a recording rain gauge network installed in the area as part of the HRS/HR program. ETo as measured at Wad Medani agro-meteorological station was assumed to be applicable to all minors and the area/sowing dates data was collected from the local SGB block inspectors' offices in a form of 10-day periods summaries.

Table (5.5) resulted from the analysis of the water supply adequacy to these minors Figs.(A.9 - A.17, appendix A) are plots of the simulated average soil moisture level in the area irrigated by the nine minors analyzed. In table (5.5) CROP DEMAND, CANAL EVAP., RAIN CONT. IRRIG. SUPPLY and WATER LOSS are as defined for table (5.4).

The figures in table (5.5) indicate that the level of adequacy of the supply to the minors sampled was generally high (an average of 95 for the nine minors) but variability between individual minors exists. The generally high level of adequacy of supply to the minors supports the assumption usually made in the Gezira that negligible water is lost by seepage in the main supply system and that transmission losses are basically evaporation from the canal network water surface (see Chapter 4, section (4.2.5)).

Table (5.5): Adequacy of supply to some minors canals in the Gezira scheme 1988/89 season

MAJOR	MINOR	CROP DEMAND (mm)	CANAL EVAP. (mm)	RAIN CONT. (mm)	IRRIG. SUPPLY (mm)	WATER LOSS %	IAI %
Zananda	Gemolia	850	23	213	961	31	98
	Toman	863	31	215	833	18	97
	W.Noman	897	18	219	860	19	90
Kab Elgidad	Furei	892	29	72	1171	28	97
	W.Hizam	902	31	98	1322	37	100
	Tuweir	891	29	75	995	15	93
	Mardi	975	39	128	1100	20	83
	Kabashi	967	57	133	1190	25	96
	Beibash	856	46	120	1332	41	100

Although the minors supplied from Zananda major are situated in the upstream part while those supplied from Kab Elgidad major are situated in the downstream part of the scheme (see location map fig.(5.11)) there is no obvious differences in the adequacy of supply to the two sets of minors (average adequacy of 95.22 for Zananda major and 94.62 for Kab Elgidad major). Similarly, there is no clear trend of decreasing adequacy with distance along Kab Elgidad major. However, this trend is more clear in the minors supplied from Zananda major, (see location map figs.(5.12.a) and (5.12.b)).

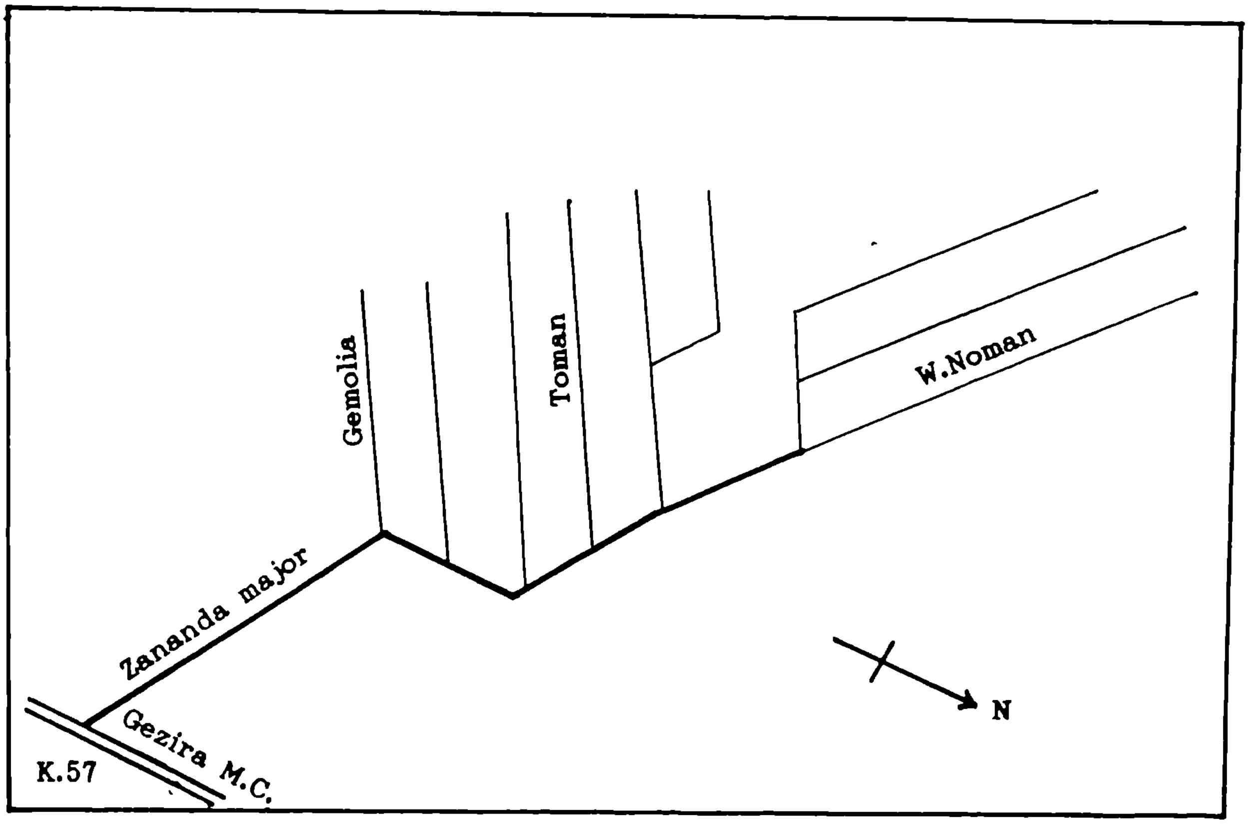


Fig.(5.12.a): Zananda major and locations of minors selected for analysis

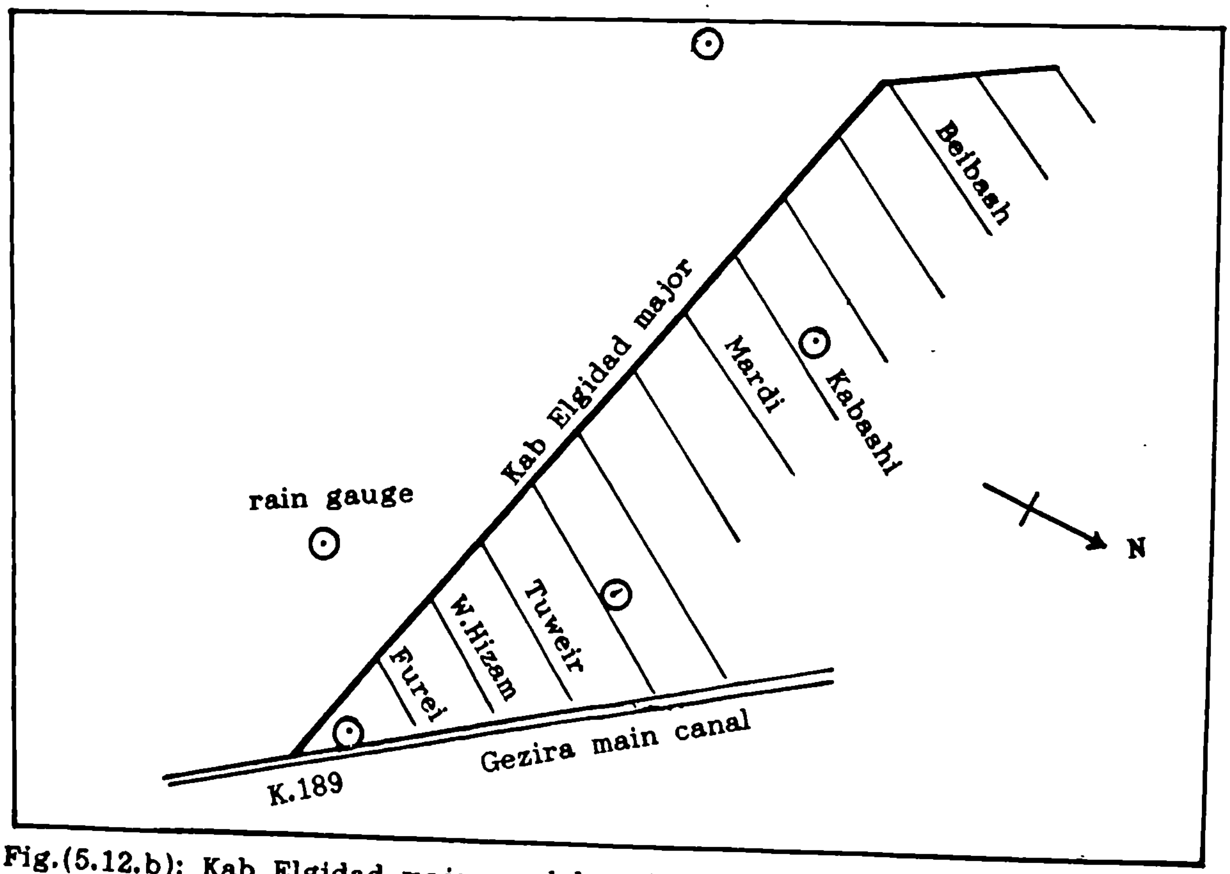


Fig.(5.12.b): Kab Elgidad major and locations of minors selected for analysis

For the minors supplied from Zananda major, irrigation supplies were relatively lower and larger part of the crop demand was provided by rain as compared with those of Kab Elgidad major. This was for two reasons: a) Because in the Gezira scheme in general the rainfall increases from the north to the south. It is, therefore, natural for the southern parts of the scheme to have more rain contribution than for the northern parts. b) The sowing dates in that season in Zananda major were relatively earlier. As such crops were able to catch more rain. In Kab Elgidad major, crops were sown relatively late and, therefore, they missed more part of the rainy season.

The equity between the nine minors as calculated on the basis of adequacy of water supply to each of them (equation (5.12)) was found to be 95.75%. When calculated on the basis of the total depth of the water supplied during the season (or volume per unit area) it was found to be 85.84%.

5.9.3. Supplies at the Field Outlets Level:

As was mentioned in Chapter 4 (section (4.3.5)) no water discharge measurements are regularly taken at this level of the irrigation system. Fortunately. in the 1986/87 season the HRS and HR in a joint research program, in which the author was involved, took discharge measurements in nine Field Outlet Pipes (FOP's) supplied from Hamza minor, Gezira scheme (Francis and Elawad, 1986). The FOP's monitored were the FOP's irrigating three complete rotations in that minor. One rotation from the head, one rotation from the middle and one rotation from the tail of the minor (see location map fig.(5.13)). The measurements were taken hourly, day and night, for the full season, using automatic measuring and recording devices. Frequent manual discharge measurements using vane flow-meter and current-

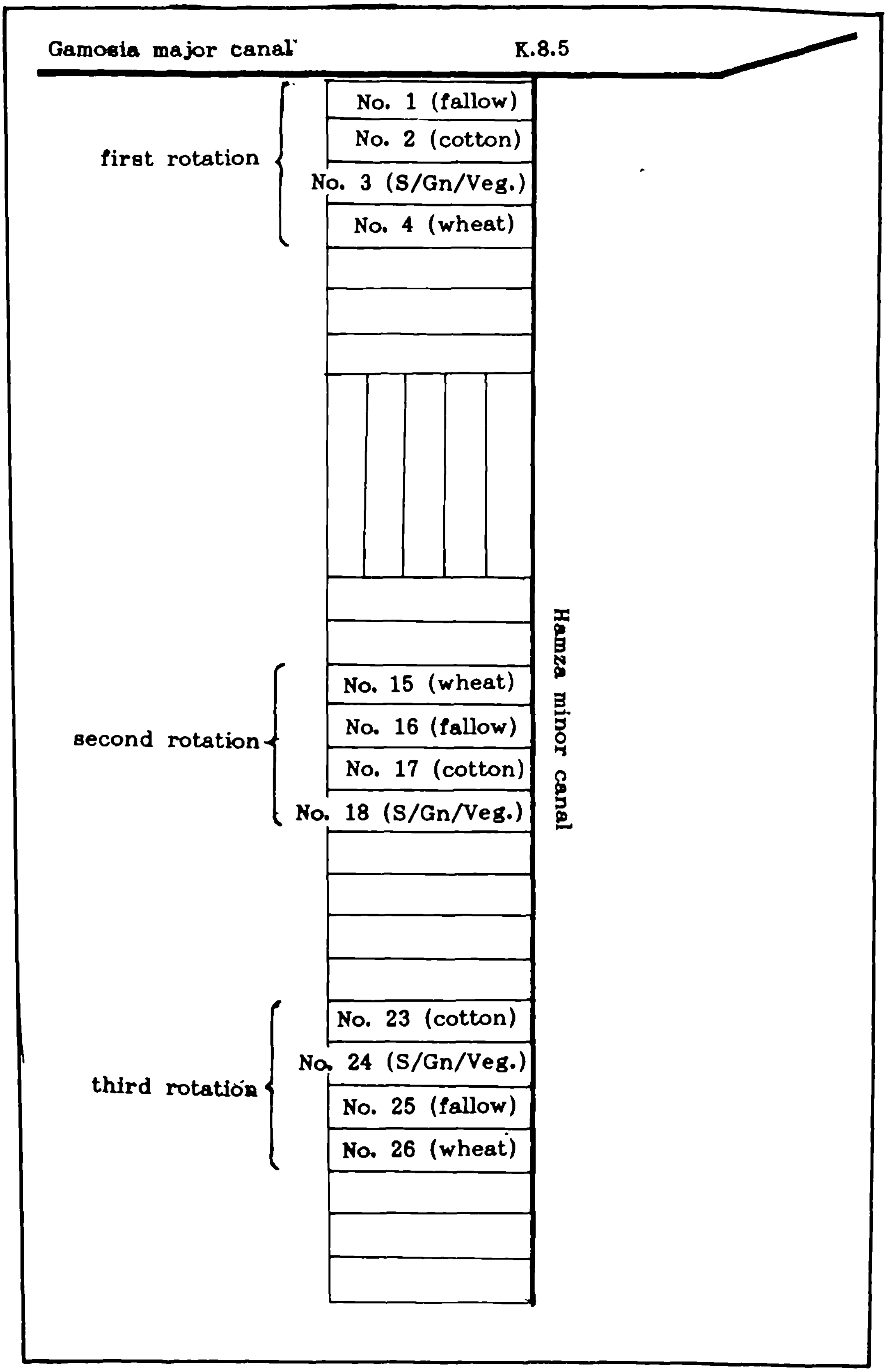


Fig.(5.13): Hamza minor and numbers selected for analysis meters were taken to check the automatic readings. They were found to be of good quality. The hourly readings were summed up for each day to give the daily supplies used in the analysis.

For the rainfall data, daily measurements were taken from a recording gauge installed along the minor. ETo (Penman) as measured at Wad Medani agro-meteorological station was assumed applicable and the daily area/sowing dates data was collected from the local SGB block inspector's office.

Table (5.6) resulted from the analysis of the supply to these FOP's. Figs.(A.18 - A.26, appendix A) are plots of the simulated average soil moisture levels in the nine numbers analyzed. In table (5.6) CROP DEMAND, RAIN CONT., IRRIG. SUPPLY and WATER LOSS are as defined for table (5.4). Negative water losses indicates water deficit.

Table (5.6): Adequacy of supply to some Numbers supplied from Hamza minor, Gezira scheme, 1986/87 season

No.	CROP GROWN	CROP DEMAND (mm)	RAIN CONT. (mm)	IRRIG. SUPPLY (mm)	WATER LOSS %	IAI %
2	cotton	1278	210	1159	8	85
3	S/Gn/Veg.	825	168	732	10	81
4	wheat	600	00	577	-4	77
15	wheat	595	00	770	23	82
17	cotton	1270	159	1802	38	93
18	S/Gn/Veg.	854	190	627	-6	67
23	cotton	1275	140	775	-46	63
24	S/Gn/Veg.	804	183	667	5	82
24	wheat	611	00	365	-67	56

As compared with the level of adequacy to the scheme as a whole (table (5.4)) or to that of individual minor canals (table (5.5)), the level of adequacy to these FOP's was relatively low. Several factors could be cited as having some contribution to this low adequacy:

i) It is natural for the adequacy to decrease as the supply is broken down into smaller subunits. This is because any faulty distribution at the upper level of the system should be reflected in reduced adequacy at the lower levels.

ii) The adequacy of supply from the dam itself in that season (1986/87) was relatively low (see table (5.4)).

iii) Hamza minor in that season suffered from heavy siltation and weed growth which led to high water surface in its upstream reach and therefore difficulties of pushing enough water into the minor.

iv) Two breaches took place in the minor at the beginning of the season. To close these breaches the canal has to be closed. This may have led to some water shortage.

The FOP's and the field channels which were designed to irrigate a 90 feddans number were supplying only 30 feddans in Numbers 15 and 17 in that season. This probably explains the relatively high level of adequacy obtained in these two numbers. Apart from them the trend of decreasing adequacy with distance along the minor is clear. Wheat is a winter crop sown in November-December (i.e. after the rainy season is over). This is why there was no rain contribution in the wheat numbers.

The equity of supply to the nine numbers as calculated on the basis of adequacy (equation (5.12)) was found to be 87.50%. However, because in this case we are looking at areas under different crops, calculating equity on the basis of the total depth of water supplied would be misleading because of the large differences in the water demands of the different crops grown in different numbers. Instead, numbers under similar cropping pattern were compared with each others. In this way, the equity for the cotton, S/Gn/Veg. and wheat numbers were found to be 70.22, 90.41 and 75.97 respectively.

5.10. Discussion of Results:

The methods proposed in the literature for characterizing the water adequacy are reviewed in Chapter 2 (section (2.1.6)). Two of these are suitable for non-rice systems: the *relative water supply* (Bhuiyan, 1982) and the *water delivery performance* (Lenton, 1983). For the data analyzed here (tables (5.4), (5.5) and (5.6)) the *relative water supply* is given by the ratio of (IRRIG. SUPPLY plus RAIN CONT.) to (CROP DEMAND plus CANAL EVAP). It can be shown that this ratio is equal to the reciprocal of (1 minus WATER LOSS). Using the *relative water supply* as a measure of adequacy, any positive WATER LOSS means that the water supply is perfectly adequate. This is the case in all eight seasons of table (5.4), all nine minors of table (5.6) and five out of the nine numbers of table (5.6). The values of the IAI, however, show that in most these cases some stress has been experienced. This shows that some of the water supplied was diverted in times when the soil moisture storage in the root zone cannot take it and, therefore, has found its way either to deep percolation or surface run-off. There is clear evidence in the Gezira scheme which shows that some of the irrigation supplies do find their ways to the drains, particularly towards the end of the season in February and March. This is also clear from the simulated soil moisture shown in figs.(A.1 - A.8, appendix A). The drains in the scheme were originally designed and constructed to remove excess rain water. No drainage facilities were provided in the scheme for excess irrigation supplies (see Chapter 4, section (4.2.2)).

This shows how important is the consideration of the time distribution of the water supply and the consideration of the soil and root characteristics of the crop in measuring the water supply adequacy. The *water delivery performance* measure does take into consideration the time distribution of the water supply but does not consider the soil and root characteristics.

The importance of the consideration of the soil and root characteristics in the supply schedule is well recognized by farmers. Personal experience in the Gezira scheme shows that farmers in their irrigation scheduling practice tend to apply small depths of water at higher frequency for shallow rooted crops such as wheat and vegetables as compared with deeper rooted crops such as cotton and sorghum. Similarly, an irrigation every four or five days is typical in the coarse-textured soils of the small private schemes along the banks of the Blue Nile, as compared with seven or eight days intervals for the same vegetable crops grown by the same farmers one or two kilometres away inside the Gezira scheme heavy-textured soils.

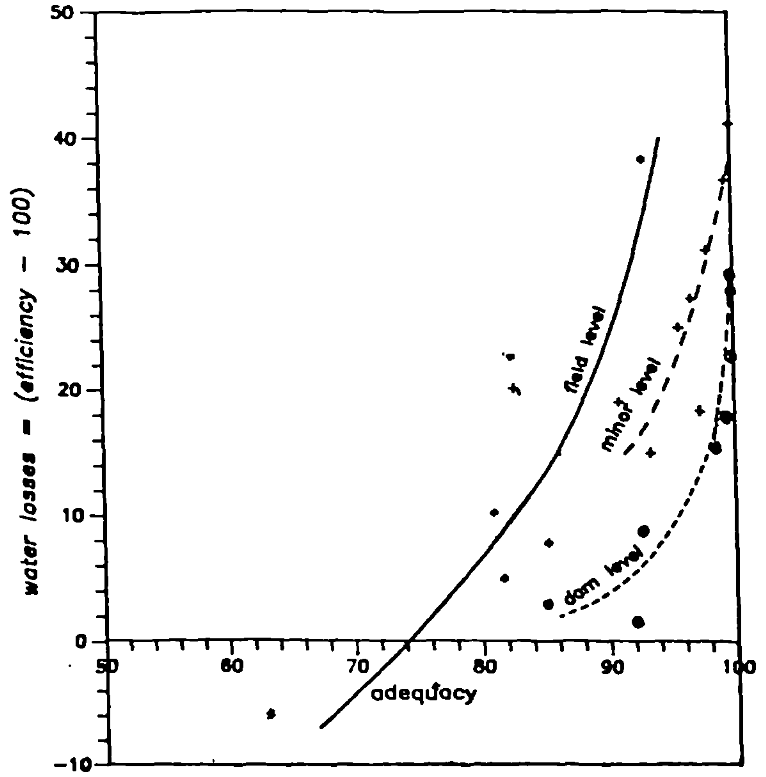
The IAI as derived in this chapter provides a measure of the water supply adequacy in irrigation systems which operate on supply scheduling basis. (i.e. systems in which the system manager alone decide on how much water should be supplied and when). If the IAI is to be adopted for systems operation on demand scheduling basis (i.e. systems in which the system manager supplies water in response to the demands of the users) then R_j in equation (5.11) should be defined as the ratio of the users' demand supplied by the system in period j. In this case the IAI is similar to the water delivery performance (Lenton, 1983) (see Chapter 2, equation (2.10)). One of the major difference between the two measures, however, is that the way in which the *water delivery performance* measure quantifies the importance of the periods makes it suitable only for mono-crop systems.

At both the minor canals and the FOP's levels, the equity based on the level of adequacy achieved reflects a fairer distribution than when we look at it on the basis of the depth of water supplied (or volume per unit area) during the season. This means that although some farmers in the scheme may be receiving more water than others, this additional water is not fully reflected in the level of adequacy they were able to achieve. This result suggests that at least part of the additional water received by some parts of the scheme was not intentionally taken by the farmers at the expense of another stressed part. It is rather water which was supplied at a time when it was not really needed by any crop any where. A possible explanation of this is that some off-take structures cannot be fully closed when required.

At all three levels of the irrigation system evaluated water losses which is equal to (water use efficiency minus 100) is related to the level of adequacy achieved. Fig.(5.14) is a plot of this relation. This result means that for the irrigation system manager to achieve a higher adequacy he must be prepared to accept lower water use efficiency. The figure also indicates that for achieving the same level of adequacy in the three levels the water use efficiency decreases as we go down the system levels.

It is difficult to generalize on the basis of such a limited set of data. However, the sampled locations analyzed here show that the inequity problem in the Gezira scheme is felt much more between FOP's supplied from the same minor than between the minors themselves or between the major canals. The reason for this may be the fact that the main and major canals are relatively free from silt and weeds as compared with the minor canals. Infestation of minors with weed is visually clear in the scheme and the large size of the minor canals banks as compared with that of the main and major canals reflects the proportion of silt removed from each of these set of canals. The existence of silt and weeds in the minor canals greatly reduces their ability to deliver water to their tail-end users. Another factor which may contribute to the increased inequity between the FOP's is the fact that although the water control in all the three levels is under the responsibility of a government organization (MOI controls the supply to the majors and minors and SGB controls the supply to the FOP's) the farmers have much more "informal" access to the FOP's than to the other upper level control points. As such, differences in social power between farmers are expected to have more impact at the FOP level than at the upper levels of the system.

Fig.(5.14): Relationship between adequacy and water losses (irrigation efficiency) at three levels of the Gezira irrigation system.



CHAPTER 6

WATER USER CONVENIENCE

6.1. Introduction:

In analyzing the adequacy of the water supply from the main distribution system to the water user's turnout in the previous chapter, we considered it to be totally the responsibility of the water user, or water users group, to use what was delivered to them at their turnouts in a proper way. In practice, however, and for those users to be able to make the maximum possible use of what was delivered to them, the ideal water delivery schedule is determined not solely by the crop evaporative demand. Other social and economic factors, and other agricultural activities taking place in the field intervene. They should be taken into account in the decision concerning how much, when and at what flow rate should water be supplied. The suitability of the water supply schedule to the individual irrigator circumstances is an important factor in determining how much of this supply will be effectively used and how much will be wasted.

Ignoring the irrigator's view point, constraint and likely reaction to a given water supply schedule can be a major cause for his behaviour to be different from the perception on which the design and operation method of the whole irrigation system was based (Smith, 1987; and Smith, 1988). This may lead to dissatisfaction with the system performance or unnecessary waste of resources.

A widely shared belief among irrigation officials is that the reason for irrigation systems not to perform as expected is that "*farmers are wasting the water*" or that "*farmers are not following the officially recognized schedule for irrigation*". This is said without admitting the fact that the reason for the farmers behaviour may be their discomfort with this officially recognized schedule (Muller, 1976; Barnett, 1979; and Farbrother, 1989). Based on this type of attitude, the plan for the rehabilitation taking place in the Gezira scheme involves imposition of discipline on the farmers and enforcing the official method of scheduling rather than questioning the suitability of this schedule to those farmers (Farbrother, 1989).

A general premise in this study is that part of the reason for irrigation officials not appreciating the farmers opinions, constraints and ability to cope with a given water supply schedule, in order to incorporate that into the design and operation of the system, is the lack of a proper methodology by which the farmers viewpoint can be obtained. This chapter describes a possible approach for measuring the extent to which the irrigation system is successful in delivering a convenient water supply to the water-users. By convenience here is meant the ease with which the irrigator can make full use of the delivered water.

6.2. Features of a Convenient Water Supply Schedule:

Three factor are considered in this study to determine the desirability, appropriateness or convenience of the water supply schedule to the irrigator. These are: (i) *predictability of the supply*, (ii) *timing of the supply*, and (iii) *supply flow rate*. Each is discussed in some detail in the following sub-sections.

6.2.1. Predictability:

By predictability we refer to the question of how much information is available to the farmer about the water supply schedule planned by the main system management and the degree of uncertainty associated with this information. Some researchers have broken predictability down to include *reliability* and *certainty* (Chambers, 1981) or *predictability* and *certainty* (Reidinger, 1974). It is important for the irrigators to have an advance notice of the intended water supply because many of them may be part-time farmers having other jobs elsewhere and, therefore, not always available to accept water at any time. Even for a full-time farmer, he has several agricultural jobs other than irrigation which are needed in the field. Some of these jobs, such as crop sowing and/or transplantation, weeding and fertilizer application, have to be synchronised with the timing of the irrigation. Sometimes the farmer may be willing to accept some water stress in order to match the watering of the crop with the timing of these other activities. A predictable water supply will enable the farmer to program all his activities in the field based on the expected supply schedule. Moreover an unpredictable water supply may encourage top-end users to take more water than they actually need in order to protect themselves against any delay in the next water arrival. This practice means waste of the water resource and increase in inequity between farmers within the same unit command area.

Communication between the main system management and the water users plays an important role in determining the level of predictability. Usually the main system manager has the required management support structure that secures the flow of the necessary information from the field to enable him to decide on when and how much water to supply. The flow of information in the other direction, however, in most systems does not exist and the water users are not usually well informed about the supply schedule intended by the main system management. Accumulation of experience with unpredictable supplies creates problems of mistrust of the main system management by the farmers.

In the Gezira scheme, one of the main reasons cited by the MOI for not being able to supply the full water demands is that, farmers do not stick to the agreed sowing dates for the crops. These sowing dates are usually worked out carefully for different parts of the scheme so that the peak water demand will be spread over a large part of the season, and therefore avoid any water demand which exceeds the canals carrying capacity at any time during the season. The farmers, because of their experience from previous seasons and acting to their own individual benefits, are reluctant to put their seeds in the ground unless they are sure that water is actually available in the canal, fearing that these seeds may be eaten up by birds if left in dry soil for a long time. The system management on the other hand are waiting for the farmers to start sowing before they release the water into the canals.

Predictability may be less important and farmers can manage less predictable supplies if storage facilities are available within the unit command areas or in rice fields where the fields themselves can be used as temporary storage for later releases to other fields.

6.2.2. Timing of the Water Supply:

This refers to the questions of at what time is the water supplied to the users? Is it during the day time or during the night?. A weekend or a working day? ... etc. It is generally more difficult to control water in the field during the night and water loss at night is a widespread phenomenon in many systems around the world (Chambers, 1986). It may also be more expensive for the farmer to hire someone to do the irrigation at night or on certain days which are associated with some social or religious value.

Rijo and Pereira (1987) studying an irrigation system in Portugal found that irrigation efficiencies are higher during working days and normal labour hours and lower during weekends and at night. In other systems farmers may accept, or even prefer, to irrigate at night. Personal experience in the Gezira scheme indicates that farmers make use of the exceptionally flat fields and impermeable soils to let water flow, unattended, to some mature crops, at night to reduce the labour hours needed for irrigation. This night irrigation proved unsatisfactory in the scheme in the early years of its operation (Allan, 1939). After several years of experience in irrigation, the farmers realized that if the flow rate is adjusted carefully, it will be safe to let water flow to the field all night without any need for them to be present.

Chambers (1986) discussed the desirability and non-desirability of night irrigation. According to him, its ease or difficulty depends on: (1) The field condition, i.e. the size and slope of the field and its soil type. (2) The water supply flow rate. (3) The crop type and its growth stage. He argued that irrigation by night is particularly preferred by the farmers when it is very hot during the day time or when the farmer has other off-farm jobs to do during the day. He also argued that tail-end farmers in non-adequate irrigation supply systems may prefer night irrigation because at night the water will not be extracted by the top users to the same extent as it is during the day.

6.2.3. Flow Rate and Duration of Supply:

This refers to the ease with which the irrigator can control the flow rate supplied to him and the time he needs to spend in the field attending the irrigation. It is sometimes referred to as *controllability* (Chambers, 1981; and Reidinger, 1974). Usually a high flow rate in relation to the size of the farm can cause problems of soil erosion and if it exceeds the soil infiltration rate it may lead to flooding, particularly of young crops, and may also cause water losses due to breakage (tail water run-off). Low flow rate, on the other hand, means longer working hours to be spent in the field by the irrigator and may cause nonuniform field application in highly permeable soils.

The acceptability of a given flow rate to any farmer depends on many factors. Some of these are: the size of the farm, its slope and soil type, the type of crop grown and its growth stage and more importantly on the farmer himself, i.e. on his experience in manipulating the water in the field, age, sex and possibly financial status.

We recall here that we are analyzing the performance of the irrigation system in supplying turnouts which in most cases serve a number of users. Certainly co-operation between those users can play an important role in absorbing some of the inconvenience resulting from a too high or a too low supply flow rate at their common turnout. This can be done by dividing the delivered flow in such a way that they can achieve the maximum possible convenience. But still, according to the definition of the irrigation system given in Chapter 1 of this thesis, the existence and effectiveness of such co-operation is part of the irrigation system we are evaluating.

6.3. An Approach for Evaluation:

For the three above factors it is difficult to find an objective numerical scale by which we can rank different water delivery schedules according to their appropriateness or convenience to the irrigator. The degree of appropriateness of a given flow rate or a given timing of water arrival are inherently subjective because of their dependence on the specific physical condition and the socio-economic environment in which the individual farmer is situated. While a given flow rate or timing of water supply may be preferred by one farmer it may be difficult for another farmer to cope with. Therefore the question of the suitability of the supply flow rate and the timing of the water supply is a problem of the subjective judgement of the irrigator. Predictability is probably less subjective. However, for its characterization several components are involved and must be considered:

- How much information, concerning the quantity, time and flow rate or duration of the intended supply is available to the irrigator.
- How long in advance is this information available before the water actually arrives in the field. This is in relation to the time required by the irrigator to prepare himself.
- How accurate is each element of this information.

To measure any of these requires data on flows at farm level. This is usually difficult to find. For all these reasons, if an objective characterization is to be obtained for predictability, it will require considerable amount of resources and time and may end up no more accurate than the irrigators subjective judgements.

Having accepted the use of a subjective scale, in this chapter we illustrate the usefulness of the Fuzzy Set theory in estimating the overall convenience or appropriateness of a given water supply schedule to the irrigators from their own judgements. A set of subjective linguistic statements, rather than numerical judgements, from a sample of farmers, to describe their opinions on each of the three factors, and another set of subjective linguistic statements to describe the importance of each of the three factors in the overall appropriateness of the water delivery schedule to each of them, are required. The fuzzy set theory is then used to aggregate the opinions of all the sampled farmers on each factor and its importance and calculate a statement about the overall appropriateness of the water supply schedule.

In this way the complex question of evaluating the convenience of the water supply schedule is decomposed into a series of simpler questions rather than trying to evaluate the whole question simultaneously. This decomposition of the question into its components reduces its complexity and makes it easier for the farmer to judge. Furthermore, considering the level of education which usually farmers have, they are likely to be more consistent in giving an imprecise verbal description such as "*the water supply is unpredictable*" or "*I am very concerned about the time of water arrival*" than if they are to give this judgement in a rating scale. Experiments in psychology by Sheppard (1954) have shown that in such cases, judging by such qualitative terms may be better than an abstract judgement by a numerical scale.

However, the problem with the use of linguistic terms such as "*unpredictable*" and "*very concerned*" is that although they are the type of description used by people in their every day lives, their meanings are open to wide individual interpretation. For example, to what extent is a "*very* *unpredictable*" water supply predictable? and, therefore, there are difficulties in aggregating different people opinions and in manipulating the description of the individual factors and their importance to arrive at a statement on the overall convenience of the water supply schedule to the irrigator.

The fuzzy set theory (Zadeh, 1965; and Zadeh, 1973) offers a systematic approach for dealing with these problems and has been used in many disciplines to model problems which involve human judgements and vague descriptions. In the field of civil engineering, examples of application of the fuzzy set theory include the assessment of the extent of damage in existing structures using the judgement of experienced engineers (Yao, 1980; and Brown and Yao, 1983) and the assessment of the impact of engineering projects on the quality of wild life habitat using the judgements of experienced ecologists (Ayyub and McCuen, 1987).

6.4. Fuzzy Sets:

In the classical set theory when we talk about, for example, the set A as being the set of farmers, then any person will either be a member of this set or not. If a person is a farmer then he belongs to this set and is said to have a membership of 1 in the set A. Otherwise his degree of membership is zero. Now let B be the set of young farmers. Does a farmer who is 35 years old belong to this set? An answer to this question is not obvious. "*How old is a young farmer?*" What we can say is that a farmer who is 30 years old is more in the set B than a farmer who is 40 years old. The set B is a fuzzy set. Fuzzy sets differ from classical sets in that they do not have clearly defined boundaries which separate the elements which belong to the set from those which do not. The elements of a fuzzy set can take partial membership. The degree of this membership depends on our judgement.

For any member x_i in the fuzzy set B, the degree of membership (written $\mu_B(x_i)$ and called the *support* of x_i in B) is a real number between zero and one which indicates the degree of our belief that the element x_i is a member of the fuzzy set B. A support of $\mu_B(x_i) = 1$ means that x_i is clearly a member of the set B and a support of $\mu_B(x_i) = 0$ means that it is clearly not.

The fuzzy set theory involves assigning fuzzy *linguistic values* (or expressions) to some variable of interest and the representation of these fuzzy linguistic values with a support function. For example, the area of an irrigation scheme (in this case the variable of interest) can be assigned any of the fuzzy linguistic values: *very large*, *large*, *more or less large*, *medium* .... and so on. In the context of evaluating the convenience of the supply schedule, we may talk about, say, the set of "irrigation supplies with *good* predictability" or the set of "supplies with *high* flow rate". If the range of all possible flow rates is represented by the universe $U = \{x_1, x_2, \ldots\ldots x_N\}$, where x_1 represents the least possible and x_N represents the highest possible flow rates, then the fuzzy linguistic value *high* can be expressed as:

$$\textbf{\textit{high}} = \{x_i|\mu(x_i)\} = \{x_1|\mu(x_1),\ x_2|\mu(x_2),\ \ldots\ x_N|\mu(x_N)\} \quad (6.1)$$

Where in this equation $x_i|\mu(x_i)$ means that the degree of our belief that the flow rate x_i can be described as high is given by $\mu(x_i)$. In this way if the universe U of the possible flow rates is taken to be {1, 2, ... 10}, then *high* can be expressed as:

$$\textbf{\textit{high}} = \{1|0,\ 2|0,\ 3|0,\ 4|0,\ 5|0,\ 6|.1,\ 7|.4,\ 8|.7,\ 9|.9,\ 10|1\} \quad (6.2)$$

The expression for *high* in equation (6.22) can be represented graphically as shown in fig.(6.1).

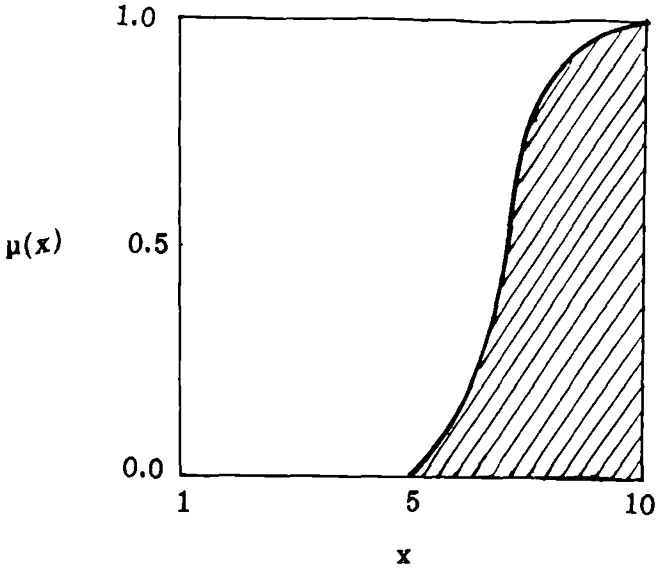


Fig.(6.1): Graphical representation of the linguistic expression *high*

The choice of a particular support function to represent a given fuzzy linguistic expression may depend on the particular problem being modelled (for example, farmers may tend to exaggerate their dissatisfaction and under-stress their satisfaction when they report their opinion on the water supply schedule) but generally the final result of the analysis is not sensitive to small variations in the selection of the support function (Ayyub and Haldar, 1984) as far as the choice is rational and consistent. This point is discussed in more detail later in this chapter (section (6.10)).

In this study the universe U is taken to consist of only five elements. i.e. U = {1,2,3,4,5} (this is due to computer memory limitation as will be discussed later in section (6.9)) and the support functions of table (6.1) are assigned to their respective fuzzy linguistic expressions arbitrarily (the choice of a particular support function to represent a fuzzy linguistic expression is discussed in some detail later in this chapter (section (6.10)). Although the farmer may use any linguistic expression to judge each of the three factors characterizing the convenience of the water supply schedule or each of their importance, in this study, to simplify the analysis, the farmer choice is limited to one of the expressions in table (6.1).

Table (6.1): Assumed definitions of support functions for some fuzzy expressions.

LINGUISTIC EXPRESSION	$\mu(1)$	$\mu(2)$	$\mu(3)$	$\mu(4)$	$\mu(5)$
(very good) or (very high)	0	0	.01	.25	1
good or high	0	0	.1	.5	1
(more or less good) or (more or less high)	0	0	.4	1	.4
medium	0	.4	1	.4	0
(more or less bad) or (more or less low)	.4	1	.4	0	0
Bad or low	1	.5	.1	0	0
(very bad) or (very low)	1	.25	.01	0	0

6.5. Operational Rules of Fuzzy Sets:

In order to use the fuzzy sets approach for modelling any practical problem some operational rules must be employed. The operational rules used in this study are defined in this section. Additional operational rules may be found in Zadeh (1965), Zadeh (1973) and Bellman and Zadeh (1970).

6.5.1. Union and Intersection:

If A and B are two fuzzy sets of the same universe U' then:

The *UNION* operation (or the requirement that A "OR" B) is the fuzzy set C = A∪B, and its support function is given by:

$$\mu_C(x) = \max[\mu_A(x),\ \mu_B(x)] \tag{6.3}$$

The *INTERSECTION* operation (or the requirement that A "AND" B) is the fuzzy set D = A∩B and its support function is given by:

$$\mu_D(x) = \min[\mu_A(x),\ \mu_B(x)] \tag{6.4}$$

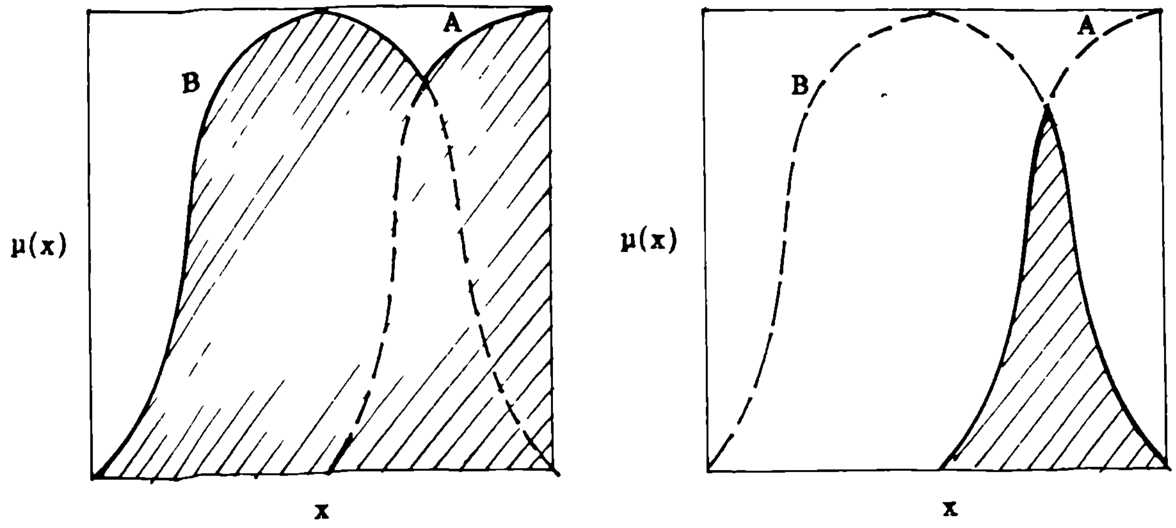
For example, if A is the fuzzy set of water supplies with a *GOOD* predictability and B is the fuzzy set of those with a *MEDIUM* flow rate, then A∪B is the fuzzy set of water supplies which have either *GOOD* predictability OR *MEDIUM* flow rate. A∩B is the fuzzy set of water supplies which have both *GOOD* predictability AND medium flow rate. Using the definitions of table (6.1) for *GOOD* and *MEDIUM*, then:

$$A \cup B = \{1|0.0,\ 2|0.4,\ 3|1.0,\ 4|0.5,\ 5|1.0\}$$

and

$$A \cap B = \{1|0.0,\ 2|0.0,\ 3|0.1\ 4|0.4,\ 5|0.0\}$$

The results of these operations can be represented graphically as shown in figs.(6.2.a) and (6.2.b).



A∪B A∩B

Fig.(6.2): Fuzzy set:Union and Intersection

6.5.2. Hedges:

The support function of a fuzzy set representing a linguistic value or judgement can be modified to account for the significance of this judgement by the use of what Zadeh (1973) called "*HEDGES*". For example, the fuzzy expressions *VERY high*, *ALMOST high* and *EXTREMELY high* are the result of applying the hedges *VERY*, *ALMOST* and *EXTREMELY* to the initially chosen judgement *high*. The effect of these hedges is to modify the support function of the initial judgement in such a way that it is not changed to another judgement i.e. *medium* or *low*. For example, if *high* is expressed by:

$$high = \{1|0.0,\ 2|0.0,\ 3|0.1,\ 4|0.5,\ 5|1.0\} \qquad (6.5)$$

then,

$$VERY\ high = (high)^2 = \{1|0.0,\ 2|0.0,\ 3|.01,\ 4|.25,\ 5|1.0\} \tag{6.6}$$

and

$$FAIRLY\ high = (high)^{\frac{1}{2}} = \{1|0.0,\ 2|0.0,\ 3|.32,\ 4|.71,\ 5|1.0\} \tag{6.7}$$

Fig.(6.3) is a graphical representation of the application of these hedges to the linguistic value *high.* Discussion on the effect of these and other hedges can be found in Schmucker (1984, Chapter 4) and Zadeh (1973).

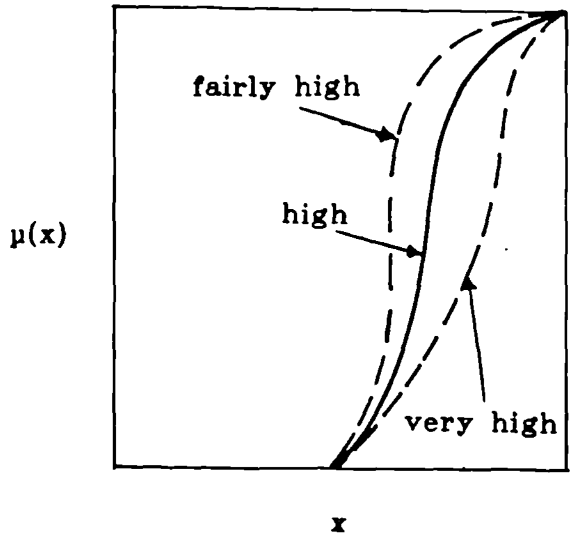


Fig.(6.3): Effect of some hedges.

6.5.3. Convexity:

According to Zadeh (1965) a fuzzy set A is convex if and only if, for any pair of elements (x_i, x_j) and for any value of $0<\delta<1$, the following holds:

$$\mu_A[\delta x_i + (1 - \delta)x_j] \geq \min[\mu_A(x_i),\ \mu_A(x_j)] \tag{6.8}$$

The definition of equation (6.8) is illustrated in fig.(6.4).

In many cases the fuzzy set resulting from the application of some operations on two or more fuzzy sets is not convex. To translate the resulting set to its nearest linguistic expression it may be necessary to modify the supports of some of its members in order to make it convex. For example the fuzzy set A∪B of fig.(6.2.a) can be made convex to become:

$$A \cup B \ (convex) = \{1|0.0,\ 2|0.4,\ 3|1.0,\ 4|1.0,\ 5|1.0\}$$

This is shown in fig.(6.5):

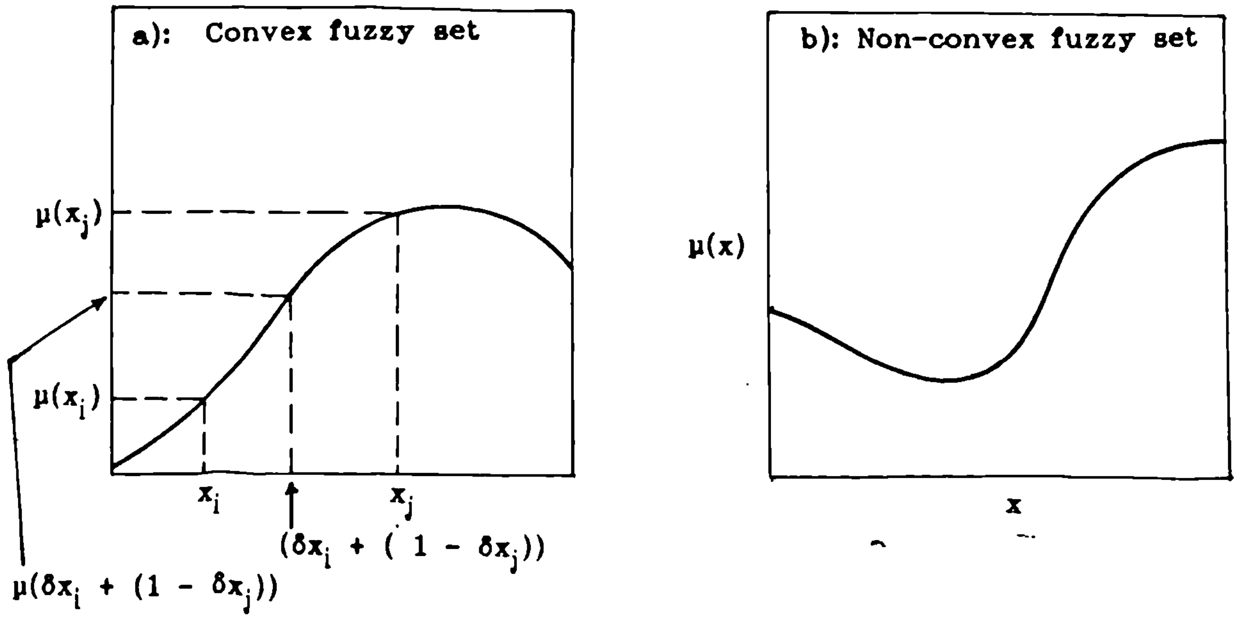


Fig.(6.4): Definition of fuzzy sets convexity.

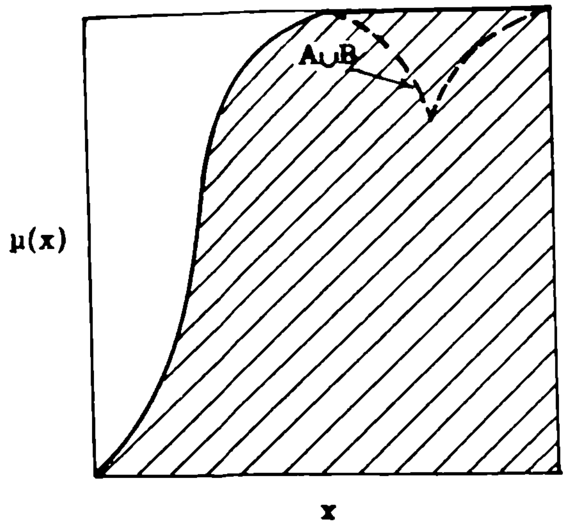


Fig.(6.5): Convex Fuzzy set A∪B of fig.(6.2.a).

Clearly forcing convexity on a fuzzy set may involve considerable distortion of its support function. It has been found that by making a fuzzy set convex the job of converting it to a natural language expression will be easier (Schmucker, 1984, pp.30-31). The convexity condition is forced on the fuzzy set after all the calculation. i.e. Only when the set is to be converted to a natural language expression.

6.5.4. Normalization:

Normalization is the process by which we ensure that at least one element of the fuzzy set has a full membership, i.e. a support of unity. This is done by dividing the support of all elements of the set by the maximum support in the set. If any element in the original set has a full membership, normalization will not change the support function. Otherwise all non-zero supports of the set will be increased such that at least one element will have full membership. For example, the fuzzy set A∩B of fig.(6.2.b) can be normalized to become:

$$A \cap B \ (normalized) = \{1|0.0,\ 2|0.0,\ 3|.25,\ 4|1.0,\ 5|0.0\}$$

This is shown in fig.(6.6).

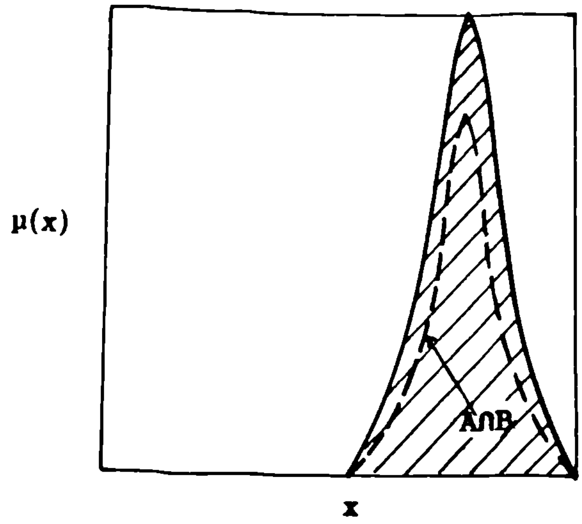


FIG.(6.6): Normalized fuzzy set A∩B of fig.(6.2.b).

The same justification for the distortion of the support function resulting from forcing convexity applies to normalization

6.5.5. Linguistic Approximation:

The application of some operation on two or more fuzzy sets will not, in general, result in a support function which exactly corresponds to one of the natural language expressions. To translate any support function to its nearest natural language expression several methods exist. Schmucker (1984) reviewed some of them. Of these the method of *best fit* is the most suitable when the fuzzy set is to be approximated to an expression to be selected from a limited pre-specified set of natural language expressions. In this study the best fit method is used to translate fuzzy sets to one of the expressions of table (6.1). With the best fit method the difference between the given support function and each of the support functions of the fuzzy expressions of table (6.1) is to be calculated. The expression with the least difference is chosen to represent the set. In this way, if A is the support function resulting from the application of some operation on two or more fuzzy sets and Z_i (i = 1, 2 .....7) are the fuzzy expressions of table (6.1) then, the difference DIF.(A, Z_i) between the fuzzy sets A and Z_i is given by:

$$DIF.(A,Z_i) = \sqrt{\sum_{j=1}^{5}\left[(\mu_A(x_j) - \mu_{Z_i}(x_j)\right]^2} \qquad (6.9)$$

We calculate this difference for i = 1, 2 .....7 and then set Z_i with the least difference, is chosen to approximate the set A. For example, if the set A can be expressed by:

$$A = \{1|.04,\ 2|.32,\ 3|.78,\ 4|1.0\ 5|.36\}$$

Then, using equation (6.9) with each of the expressions in table (6.1):

DIF.(A, *VERY GOOD*) = 1.29
DIF.(A, *GOOD*) = 1.11
DIF.(A, *MORE OR LESS GOOD*) = 0.50
DIF.(A, *MEDIUM*) = 0.74
DIF.(A, *MORE OR LESS BAD*) = 1.37
DIF.(A, *BAD*) = 1.60
DIF.(A, *VERY BAD*) = 1.63

Based on this, the nearest estimate to fuzzy set A is *MORE OR LESS GOOD* (or *MORE OR LESS HIGH*) as this is the expression with the least difference from the set A.

6.6. Aggregation of Opinions:

In a typical large-scale small-holder irrigation system several thousands farmers may be involved, each with his own opinion on the appropriateness of the water supply schedule. Each of those farmers would like his opinion to be considered in the evaluation. In order to incorporate different opinions, a sample of farmers is to be selected. Each farmer sampled is to be asked to give six linguistic descriptions or judgements; one for each of the three factors and another one for the importance of each factor.

Let the data on table (6.2) be the descriptions given by five farmers asked to give their opinions on the predictability of the water supply to their outlets. To facilitate an indication of the diversity of opinions on the predictability, Znotinas and Hipel (1979) suggested the use of the divergent aggregation (DVG) as a measure of the range of opinions expressed. They defined DVG as:

$$DVG = (F1 \cup F2 \cup F3 \cup F4 \cup F5) - (F1 \cap F2 \cap F3 \cap F4 \cap F5) \qquad (6.10)$$

Table (6.2): Hypothetical opinions of five farmers on the predictability of the water supply

FARMER	OPINION	µ(1)	µ(2)	µ(3)	µ(4)	µ(5)
F1	GOOD	0	0	.1	.5	1
F2	AVERAGE	0	.4	1	.4	0
F3	VERY GOOD	0	0	.01	.25	1
F4	MORE OR LESS GOOD	0	0	.4	1	.4
F5	GOOD	0	0	.1	.5	1

For the data of table (6.2), DVG(predictability)

$= \{1|0.1,\ 2|0.4,\ 3|1.0,\ 4|1.0,\ 5|1.0\} - \{1|0.0,\ 2|0.0,\ 3|.01,\ 4|.25,\ 5|0.0\}$

$= \{1|0.1,\ 2|0.6,\ 3|.99,\ 4|.75,\ 5|1.0\}$.

To convert this measure of diversity of opinions into a numerical index, we introduce here the *Diversity Index* (DI) which we define as the average of the supports of the DVG. Clearly, from the definition of DVG the larger the difference of opinions between the farmers the higher the support of the DVG and, therefore, their average. For the example here this index is found to be:

DIVERSITY INDEX (predictability) = 0.69

In general, a high diversity index indicates differences in opinions of the farmers on the factor under consideration (or its importance). A low diversity index, on the other hand, indicates their agreement, but is not necessarily a sign of satisfactory water supply schedule. The index takes its minimum value of zero when all farmers has identical opinions and its maximum value of unity with the maximum possible disagreement.

The aggregation of different viewpoints expressed in the form of fuzzy statements can be obtained by several methods. Nguyen (1985) reviewed some of them. According to him the best method for aggregating the opinions of the five farmers of table (6.2) is to calculate the average support given by the farmers to each element in the set, add it to the maximum support and divide by two. i.e. The average of each column in table (6.2) plus the maximum of the column and then divided by two. The resulting support function can then be normalized and/or made convex if required. It can then be approximated to the nearest linguistic expression by applying equation (6.9) with each of the linguistic expressions of table (6.1).

For the data in table (6.2), using this method, the average opinion on predictability is:

$$= \{1|0.0,\ 2|.24,\ 3|.66,\ 4|.77,\ 5|.84\}$$

Normalizing

$$= \{1|0.0,\ 2|.29,\ 3|.79,\ 4|.92,\ 5|1.0\}$$

This is a convex function. By applying equation (6.9) with each of the fuzzy expressions of table (6.1), the nearest description of the predictability here is *GOOD*.

6.7. Evaluation of the Irrigator Convenience:

Having calculated the average fuzzy measure for each of our three factors and their importance, the calculation of the overall convenience to the irrigators follows a procedure described by Schmucker (1984) for the calculation of the fuzzy weighted mean.

If N_i is the set of M integers and W_i is the set of their weights, then the arithmetic weighted mean **N** of these integers is given by:

$$N = \frac{\sum_{1}^{M} N_i \times W_i}{\sum_{1}^{M} W_i} \qquad (6.11)$$

If, however, both the elements of N_i and W_i are fuzzy sets, then we need to define fuzzy operations similar to the arithmetic operations used in the calculation of the weighted arithmetic mean. Namely; fuzzy addition, fuzzy multiplication and fuzzy division. The definition of these fuzzy operations as given by Schmucker (1984) are as follows:

Let **A** and **B** be two fuzzy sets such that:

$$A = \{i|\mu_A(i)\}, \quad \text{for} \quad 1 \le i \le M.$$

and

$$B = \{j|\mu_B(j)\}, \quad \text{for} \quad 1 \le j \le N.$$

then:

1) The fuzzy set **S** of the sum of the two fuzzy sets **A** and **B** is given by:

$$S = A + B = \{k \backslash \mu_S(k)\} \tag{6.12}$$

Where: $\mu_S(k) = \max.[\min.(\mu_A(i),\ \mu_B(j))]$

such that $k = i + j$

$1 \le i \le M$

$1 \le j \le N$

2) The fuzzy set P of the product of the two fuzzy sets A and B is given by:

$$P = A \times B = \{h \backslash \mu_P(h)\} \tag{6.13}$$

Where: $\mu_P(h) = \max.[\min.(\mu_A(i),\ \mu_B(j))]$

such that $h = i \times j$

$1 \le i \le M$

$1 \le j \le N$

3) The fuzzy set D of the division of the two fuzzy sets A and B is given by:

$$D = \frac{A}{B} = \{t \backslash \mu_D(t)\} \tag{6.14}$$

Where: $\mu_D(t) = \max.[\min.(\mu_A(i),\ \mu_B(j))]$

such that $t = i/j$ is an integer

$1 \le i \le M$

$1 \le j \le N$

To perform any of the three above fuzzy operations on two fuzzy sets, say, A and B with numbers of elements M and N respectively, the approach followed here is to construct an M×N matrix with its element $(i,j) = \min.[\mu_A(i),\ \mu_B(j)]$. The support of any element k of the fuzzy set of the sum $S = A+B$ is equal to the maximum of all the matrix elements (i,j) such that $i+j = k$. For example, the support of the element 4 in the fuzzy set $S = \mu_S(4)$ is the maximum of the matrix elements: (1,3), (2,2) and (3,1). Similarly, the support of the element 8 in the fuzzy set $S = \mu_S(8)$ is the maximum of the matrix elements: (1,7), (2,6), (3,5), (4.4), (5,3), (6,2) and (7,2).

For the product fuzzy subset $P = A \times B$, the support of any element h is equal to the maximum of all the matrix elements (i,j) for which $i \times j = h$. For example, the support of the element 4 in the fuzzy set $P = \mu_P(4)$ is the maximum of the matrix elements: (1,4), (2,2) and (4,1). Similarly, the support of the element 8 in the fuzzy set $P = \mu_P(8)$ is the maximum of the matrix elements: (1,8), (2,4), (4,2) and (8,1).

Clearly with these definitions and with number of elements in the two fuzzy sets A and B being N and M respectively, the number of elements in the resulting fuzzy set of the sum S is $M+N$ and the number of elements in the product fuzzy set P is $M \times N$.

For the division fuzzy set D, the support of any element t is taken as the maximum of all the matrix elements (i,j) for which $i/j = t$ and t is an integer. This means that the support of the element 4 in the fuzzy set $D = \mu_D(4)$ is the maximum of the matrix elements: (4,1), (8,2), (12,3) ... etc. Similarly the support of the element 5 in the fuzzy set $D = \mu_D(5)$ is the maximum of the matrix elements: (5,1), (10,2) (15,3) ..... etc. The number of elements in the division is taken to be 5 (i.e. equal to the number of elements in the judgements fuzzy sets) any other element is ignored.

EXAMPLE:

Let us assume that only one farmer was interviewed and that this farmer gave the judgements shown in table (6.3).

Table (6.3): Hypothetical example of a farmer opinion on the convenience of a water supply schedule

FACTOR	JUDGEMENT	IMPORTANCE
PREDICTABILITY	bad	very high
FLOW RATE	medium	low
TIMING	good	very low

The overall convenience to this farmer is given by:

$$\frac{(\textit{bad} \times \textit{very high}) + (\textit{medum} \times \textit{low}) + (\textit{good} \times \textit{very low})}{(\textit{very high} + \textit{low} + \textit{very low})} \qquad (6.15)$$

To perform the calculations in equation (6.15) using the support functions of table (6.1), we first add the fuzzy sets *very high* and *low* to yield a fuzzy set with 10 elements. This set is then added to *very low* to give the denominator of equation (6.15) as a fuzzy set of 15 elements. We then calculate each of the fuzzy sets (*bad* x *very high*), (*medium* x *low*) and (*good* x *very low*) separately to give three fuzzy sets each with 25 elements. Each of the three sets may need to be normalized and/or made convex if necessary. The three 25-elements fuzzy should then be added together to yield a fuzzy set of 75 elements, which is the numerator of equation (6.15). The division is then performed to calculate the final fuzzy set.

Applying these operations to equation (6.15) and normalizing and forcing convexity as necessary yielded the fuzzy set:

$$\textit{convenience} = \{1|.46,\ 2|1.0,\ 3|.65,\ 4|.37,\ 5|.31\} \qquad (6.16)$$

Approximating this to the fuzzy linguistic expressions of table (6.1) by using equation (6.9), the nearest linguistic expression is *MORE OR LESS BAD.* To this farmer, therefore, the water supply schedule can be described to be MORE OR LESS BAD.

6.8. Utility Measure:

The linguistic statement resulting from the fuzzy set analysis given previously can be a useful measure for the convenience of the water supply schedule to the irrigator and may be enough for many purposes. In order to use this measure as part of a multi-criteria evaluation of the irrigation system performance, however, it is necessary to convert these linguistic expressions (or their support functions) into a numerical scale. Let us call this numerical scale the *FARMER UTILITY.* In this section we suggest a method for deriving such a utility measure.

Equation (6.16) is the fuzzy measure of the convenience of the water supply schedule to the irrigator of the example of table (6.3). This fuzzy set can be represented graphically as shown in fig.(6.7).

In this type of graph (fig. (6.7)) the higher the supports on the right side and lower on the left side of the graph, the more convenient is the water supply schedule to the farmer interviewed. This means that the larger the distance of the centre of area under the graph from the $\mu(x)$-axis the better is the schedule to the farmer. In this way a numerical measure (or the *farmer utility*) can be taken as the distance of the centre of the area under the graph from the $\mu(x)$-axis. It can then be normalized to give a utility value between zero and one. For the example under consideration:

$$utility = \frac{1}{4}\times\frac{0\times.46 + 1\times1 + 2\times.65 + 3\times.37 + 4\times.31}{0.46 + 1 + 0.65 + 0.37 + 0.31} = 0.42 \qquad (6.17)$$

The division by 4 in this equation is for the purpose of normalization.

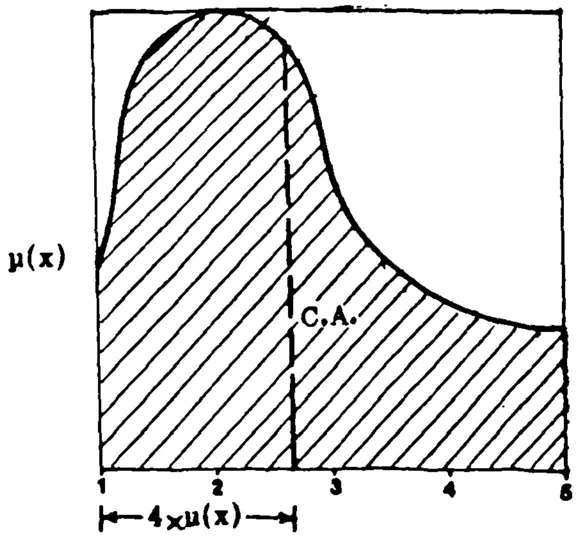


Fig.(6.7): A measure of utility to the irrigator.

In this way, and if the support functions of table (6.4) are used, the fuzzy set which can be approximated to *medium*, for example, can have a utility ranging from 0.45 to 0.55, and that which can be approximated to *high* can have a utility ranging from 0.75 to 0.92 .... and so on. Of course these ranges will depend on the support functions assigned to the original fuzzy expressions.

For the general case of a universe U of N elements, and what ever the support functions selected to represent the fuzzy sets of the initial judgements, the utility to the irrigator is given by:

$$Utility = \frac{1}{N-1} \times \frac{\sum_{i=1}^{N} (i-1) \times \mu(i)}{\sum_{i=1}^{N} \mu(i)} \qquad (6.18)$$

6.9. Computerization of the Analysis:

As can be seen from section (6.7), the calculations involved in using equation (6.15) are difficult to perform by hand. A micro-computer based program was written in LOTUS-123 for this purpose. When the program is run, an interactive subroutine is called for the data input. In this subroutine the user is presented with a menu of linguistic expressions from which he can choose the appropriate description. The user feeds the description given by the farmer to each of the three factors and their importance. Having fed the six required fuzzy expressions, the program performs all the calculations described in sections (6.7) and (6.8) and presents its output in the form of a linguistic expression describing the overall convenience of the water supply schedule to the farmer whose opinion was fed, and also the utility of the water supply schedule to that irrigator.

The model is micro-computer based to enable its use by irrigation officials at their local offices. It is written in LOTUS-123 to enable its use by people who are not familiar with computers, as the user is always presented with a menu to choose from.

Some of the problems with using LOTUS in a micro-computer are, however, the computer memory limitation and speed of execution. We note from section (6.7) that even with a universe of only 5 elements, the calculation of the fuzzy weighted mean involves manipulation of a 50x25 elements matrix in the calculation of the nominator of equation (6.15), and a 75x15 elements matrix in the division. If a 10 elements universe is used instead, these matrixes will become 200x100 and 300x30 respectively. This is the reason for the use of a universe of only 5 elements. However, because of the approximate nature of the analysis, using larger universe may not necessarily give better results and justify the additional complexity of the calculations involved.

6.10. Sensitivity Analysis:

One of the problems with the use of the fuzzy sets approach for modelling practical problems is the choice of a support function to represent a given linguistic expression. Different people may assign different support functions to represent the same linguistic expression, depending on the problem under consideration and the individual interpretation of this expression. For example, when a farmer reports his opinion on the predictability of the water supply, he may describe it to be *bad*. We may then assign any of the following support functions to the expression *bad*:

$$bad1 = \{1|1.0,\ 2|0.5,\ 3|0.1,\ 4|0.0,\ 5|0.0\}$$
$$bad2 = \{1|1.0,\ 2|0.7,\ 3|0.4,\ 4|0.1,\ 5|0.0\}$$
$$bad3 = \{1|1.0,\ 2|0.3,\ 3|0.0,\ 4|0.0,\ 5|0.0\}$$

In order to evaluate the effect of different definitions of the support functions on the analysis, the example of section (6.7) is solved here again. This time the linguistic variables of table (6.1) are made more fuzzy and assigned the support functions of table (6.4).

Table (6.4): Alternative definition of the support functions for the fuzzy expressions of table (6.1)

LINGUISTIC EXPRESSION	$\mu(1)$	$\mu(2)$	$\mu(3)$	$\mu(4)$	$\mu(5)$
(very good) or (very high)	0	.01	.16	.25	1
good or high	0	.1	.4	.7	1
(more or less good) or (more or less high)	0	.1	.5	1	.5
medium	.1	.5	1	.5	.1
(more or less bad) or (more or less low)	.5	1	.5	.1	0
Bad or low	1	.7	.4	.1	0
(very bad) or (very low)	1	.49	.16	.01	0

Using the support functions of table (6.4), the resulting overall convenience to the farmer of table (6.3) is again *MORE OR LESS BAD*, but his utility changed from 0.42 with the support functions of table (6.1) to 0.47 with the support functions of table (6.4).

When the description of predictability in table (6.3) was changed from *LOW* to *HIGH*, both support functions of table (6.1) and table (6.4) gave a result of *GOOD* water supply schedule. However, the utilities were 0.75 and 0.66 when using the support functions of table (6.1) and table (6.4) respectively. When the flow rate importance was changed from *VERY LOW* to *VERY HIGH*, both support functions of table (6.1) and table (6.4) gave a result of *MEDIUM* water supply schedule, but the utilities were 0.56 and 0.55 respectively.

From the above results, one can conclude that the description of the overall convenience is not sensitive to small variations in the support functions chosen to represent the linguistic expressions describing the individual factors or their importance. This means that whatever the farmer meant by the words *BAD* or *GOOD*, and whatever support functions we choose to represent them, the final statement about the overall convenience of the water supply schedule will have the same meaning as that intended by the farmer (provided that the choice of the support function is rational).

Differences in the choices of the support functions, however, can be felt in the value of the farmer utility. But even with this problem, more application of the method and use of professional wisdom for rational choice of the support functions can reduce the effect of this subjectivity. If the purpose of the analysis is to compare the convenience of different water supply schedules, and if the same support functions are used, then the higher the utility the better is the water supply schedule to the irrigators.

6.11. Application in the Gezira Scheme, Sudan:

To demonstrate the applicability and usefulness of the fuzzy sets approach in evaluating the convenience of the water supply schedule in practice, the irrigators in six separate farms in the Gezira scheme were interviewed. Of these six farms, farms 1 and 2 both belong to the same farmer, and farms 3 and 4 belong to another farmer. Farm 5 and Farm 6 each belongs to a separate farmer. The irrigator in each farm was asked to give a linguistic description of the suitability of each of the predictability, flow rate and timing of the water supply to his individual circumstances in his farm and another description of the importance of each of the three factors to him.

The responses of the farmers is shown in table (6.5). Together with that, at the bottom of the table, is the result of the calculation of the overall convenience using the method described previously. Table (6.6) shows the aggregation and the diversity of opinions expressed by the farmers for each of the three factors and their importance.

Table (6.5): Aggregation of opinions of individual farmers on the overall convenience of the supply schedule.

FARM NUMBER		F1	F2	F3	F4	F5	F6
	crop	wheat	cotton	wheat	sorghum	onions	wheat
PRED.	description	bad	good	v.good	v.bad	good	v.good
	importance	v.high[1]	v.high	v.high	v.high	low	v.high
FLOW RATE	description	v.good	bad	good	bad	v.good	medium
	importance	high	high	v.low	v.low	v.high	high
TIMING	description	bad	good	good	good	v.good	good
	importance	v.low	v.low	high	high	low	v.low
Overall Convenience		medium	m.l.low[2]	high	medium	high	m.l.high
Utility U(x)		0.53	0.34	0.84	0.46	0.81	0.72

Notes: 1) v.high = very high. 2) m.l. low = more or less low.

As was mentioned in Chapter 4 (section (4.2.4)), the traditional water supply schedule in the Gezira scheme consists of supplying water to each number every other week at a rate of about 116 l/sec. (for 12 hours per day). During each of the weeks in which the supply is on, and for the first half of the week, an earth dam (called sudd) is built half-way along Abu Ishreen and all the supply is diverted to the upstream half of the farmers. For the other half of the week the earth dam is removed and all the supply goes to the downstream half of the farmers. In this way, at any time during the week, the 116 l/sec. is divided between 45 feddans (nine 5-feddans plots). i.e. Each 5-feddans plot will be receiving a flow of about 13 l/sec.

In the 1989/90 season, and for the wheat crop only, the local SGB block inspector in the area decided to change this traditional method of scheduling and divert all the 116 l/sec. to only 10 feddans at a time. The objective was to supply wheat at a higher flow rate so as to achieve better field application uniformity. For the cotton and sorghum crops the traditional supply schedule was practised. The onion field was located in a number where 30 feddans of onions were grown and the rest of the number was allocated to sorghum and groundnut. By the time the crop was transplanted and started to be irrigated, sorghum and groundnut had already been harvested and, therefore, were no longer competing for water with onions.

In this way, and as far as the water supply schedule is concerned, the six farms under investigation here, can be divided into three categories: (a) The three wheat farms adopting the newly introduced schedule. (b) The cotton and sorghum farms adopting the traditional schedule. And (c) The onion farm which has less competition on water and therefore better flexibility in its water supply schedule.

Table (6.5) tells us that for those farmers, the overall convenience ranges from *high* to *more or less low* and that the farmers were happier with the newly introduced water schedule in the wheat farms than with the traditional one practised with other crops. The onion farm irrigator was more satisfied than most others, because of the large flexibility available to him resulting from reduced competition in the water supply.

It may be interesting to note here that, different farmers may all prefer (or not prefer) the same supply schedule, but each may have his own reason for his preference. For the farmers interviewed here, while the first farmer (who manages farms 1 and 2) and the second farmer (who manages farms 3 and 4), both preferred the higher flow rate of the newly introduced schedule in the wheat crop, they have different reason for their preferences. The reason given by the first farmer was that the ground level in his wheat farm is relatively higher than the rest of the number. As such he would have some difficulties irrigating it if the flow rate was lower. The reason given by the second farmer for his preference is that he is a part-time farmer and high flow rate enables him to reduce the time he needs to spend in the field to do the irrigation.

table (6.6): Aggregation and divergence of opinions on individual factors and their importance

FACTOR	DESCRIPTION			IMPORTANCE		
	Term	Utility	DI[1]	Term	Utility	DI
PREDICTABILITY	medium	0.50	0.62	high	0.67	0.57
FLOW RATE	m.l.good[2]	0.55	0.80	m.l.high	0.58	0.57
TIMING	good	0.67	0.62	m.l.low	0.42	0.62

Note: 1) DI = Diversity Index. 2) m.l.good = more or less good.

Table (6.6) indicates that, in general, and for all the six fields taken together, there are differences in the opinions of the irrigators about the way water was scheduled to them. These opinions are, however, closer in the importance attached by them to the individual factor. The table also indicates that, for the six irrigators interviewed, the most important factor was the predictability, followed by the flow rate and then the timing of the water supply. The level of suitability of these factors to the irrigators, however, goes in the reverse direction, being lower with the most important and higher with the least important factor.

6.12. Concluding Remarks:

The extent to which the water supply schedule suits the circumstances of the individual irrigator largely determines the way in which the irrigator will be able to effectively use this supply. The question of which schedule will better suit the irrigator is a complex question involving many considerations. Some of these considerations are related to the individual irrigator personal judgement and preferences in relation to the physical and socio-economic environment in which he is situated. As such, traditional quantitative techniques may fail to capture all the aspects of the question and subjective judgement is inevitable.

The size of the sample of farmers interviewed in the study is too small to enable any judgement or comment to be made about the level of convenience with which the water supplies are scheduled to the farmers in the Gezira scheme. The objective was to test the applicability and usefulness of the fuzzy sets approach in dealing with the problem at hand. The experiment indicates that the fuzzy sets mathematics offer a convenient tool for dealing with the question of the farmer convenience. Its usefulness is in its ability to accommodate human judgements and preferences expressed in a vague linguistic form. It provides an approximate, yet useful, method for understanding the irrigators requirements and enables comparison of the suitability of different water supply schedules to those irrigators. In doing that, however, we have to tolerate some degree of imprecision resulting from the qualitative nature of the judgement and the interpersonal differences in the interpretation of the meanings of different fuzzy statements.

One of the problems with using the fuzzy sets approach in modelling practical problems is the choice of the support function to represent different linguistic expressions. Different people may assign different support functions for the same expression, largely depending on their perception of the expression meaning. Although the final statement about the overall convenience may not be sensitive to small variations in the choice of the support functions, the difference can be felt more when this statement is converted into utility index. In our view rational choice of the support functions can considerably reduce this effect.

The experiment also shows that the decomposition of the question of the convenience of the water supply schedule into its components makes it quite easy for the farmer to express his opinion. In this study no problems were encountered with the farmers interviewed in responding to the questions asked.

For proper application of the approach in the evaluation of the convenience of the water supply schedule to the irrigators, a larger sample of farmers need to be interviewed. The sample should be stratified rather than random. It should include farmers from different parts of the scheme, with different holding sizes, age, crops grown ... etc. The size of the sample should be decided depending on the diversity of circumstances in which the farmers are situated and the time and resources available for the evaluation.

CHAPTER 7

OVERALL PERFORMANCE INDEX

The non-uniqueness of the set of objectives to be used in evaluating irrigation systems and the trade-offs between them was pointed out in Chapter 3 of this thesis. To evaluate the performance of any irrigation system it is, therefore, necessary first to identify the set of objectives which the system(s) is expected to achieve and then evaluate the trade-offs between them. Explicit definition of the set of objectives is particularly important in the context of developing countries' irrigation systems, where the objectives are usually unclear and judgements of how well or how poorly irrigation systems are performing are offered without specifying the criteria on which these judgements were based (Lenton, 1983; and Seckler, *et.al.* 1988). This type of judgement does not only misreport the performance but may also turnout to be misleading and counterproductive (Sampath, 1988). Even for those who are actually involved in the management of the systems, the objectives as perceived by their employers are usually unclear. They may have to devise their own objectives and preferences among these objectives and do their jobs accordingly.

In this chapter we illustrate the usefulness of the Multi-Attribute Utility Theory (MAUT) using a group of officials who are involved in the decision-making process of managing irrigation, in order to (a) explicitly spell out from them the set of objectives which the irrigation systems in their country are expected to achieve, (b) choose an appropriate scale (or attribute) for measuring the degree of achievement of each objective, (c) evaluate the trade-offs between the objectives to derive a single index which reflects the overall performance of the systems.

7.1. Motivation for MAUT:

Multiobjective and multicriterion evaluation techniques and their application in the field of water resources planning are reviewed in Chapter 2. A large number of methods is available for evaluating different water resources plans and projects which are expected to serve multiple objectives. These methods have been designed for comparing projects and plans by combining the achievements of their individual objectives into one overall measure.

Traditional approaches consist of expressing the various objectives in monetary terms and formulating the planning question into a linear optimization problem. In view of the difficulties associate with transforming some types of objective into monetary terms, alternative approaches have been developed in which the objectives are measured in different units and a weighting system is employed to reflect their relative importance. Such techniques include, for example, *goal programming*, *compromise programming* and *ELECTRE*.

One of the main shortcomings of these latter techniques is, however, that they require the decision-maker to assign weights to the different objectives in an ad hoc manner. The problem here is that as the number of objectives becomes large and unless the preferences between them are obvious, it is extremely difficult for a person to capture the evaluation of all the attributes and process the trade-offs between them simultaneously in his mind in order to give them the weights which reflect his real preferences. By nature people are poor at integrating information from different sources and simple models can be constructed to do that better than expert judgement (Fischhoff, 1976; and Dawes, 1977).

This difficulty provides motivation to consider methods which can help the decision-maker construct his preferences and express them. Both the *surrogate worth trade-off* and the MAUT provide such a method. They both break the problem into a series of evaluation of the trade-offs between pairs of objectives. i.e. They lead the decision-maker through a systematic comparison, only two objectives at a time. One of the shortcoming of the surrogate worth trade-off method, however, like all other techniques which use vector optimization, it is computationally inefficient particularly when large number of objectives is involved (Chapter 2, section (2.2)).

The MAUT differs from all other techniques mentioned above in that it aims to derive the choice principles of the decision-maker from his choice behaviour. These choice principles are then expressed in the form of a utility function $U(x_1, x_2, \dots x_N)$ where x_i is the level of achievement of the i-th objective. This utility function reflects the decision-maker's preferences between various levels of achievements of the objectives and his trade-offs between these objectives. Once this utility function is derived then we can measure the attractiveness or level of satisfaction of different alternatives without him being present in the evaluation process. This is particularly important in the context of irrigation systems performance evaluation because if the utility of the irrigation department is obtained, then individuals who are involved in the management of the irrigation systems can have a clear guide towards the way in which their performance will be evaluated.

Another advantage of the MAUT over all other techniques is that it results in a cardinal ranking of the alternatives. i.e. It does not only tell us that alternative A is better than alternative B, but also by how much. This cardinal ranking is particularly important for sensitivity analysis as will be seen later in this chapter (section. (7.4)).

The MAUT has been well developed in the literature. A detailed and complete overview of the MAUT is given by Keeney and Raiffa (1976) and summaries of the theory can be found in Farouhar (1977) and Zeleny (1982, chapter 12). The technique is found to be useful and has been applied to help in multi-criterion decision-making in a variety of settings. Keeney and Raiffa (1976) reported a number of these applications. In the field of water resources an example of using the technique was reported by Keeney and Wood (1977). They used the technique for ranking five proposed water resources plans in the Tisxa River basin, Hungary. In this work, using twelve attributes, including economic, social, environmental and technical objectives, it was possible to rank the desirability of the five alternatives to the people concerned with the development of the river basin.

7.2. Derivation of the Overall Utility Function:

In a multi-attribute situation in which the overall performance is judged by N individual attributes x_1, $x_2 \ldots x_N$, the process of deriving the overall utility function $U(x_1, \ldots\ldots, x_N)$ consists of four steps:

1- Preparation for the assessment.
2- Verification of the necessary independence conditions.
3- Assessing the individual attribute utility functions.
4- Determination of the scaling constants.

Each of these steps is discussed in some detail in the following sub-sections. Because subjective judgements from the decision-maker will be used in some of these steps it may be necessary throughout these steps to frequently check that the decision-maker being interviewed is consistent in his preferences.

7.2.1. Preparation for the Assessment:

This step is designed to introduce the decision-maker to the approach to be followed. At the end of this step we should have agreed with him on:

(1) The set of objectives which the system(s) under consideration is expected to achieve. Care should be taken to make sure that the important characteristics of the performance are considered and at the same time we should try to limit the set to the really important objectives (see Chapter 3, section (3.3) for discussion on the choice of the objectives).

(ii) The attributes to be used in measuring the level of achievement in each objective considered. It is important here to make sure that the decision-maker understands the practical meanings of different values of each of these attributes. It is always preferable to use attributes with which the decision-maker is familiar.

(iii) The expected range of achievement of each objective in the system(s) to be evaluated. Limiting the analysis to the range of achievements usually encountered in practice makes it easier for the decision-maker to give the strength of his preferences between different levels of achievements than if he is to do that with values which he rarely experiences in practice. It is not necessary to be exact in choosing the upper and lower limits of the range. The range should be large enough to include most values which can be expected in normal conditions.

7.2.2. Verification of the Necessary Independence Conditions:

To combine the achievements of a number of objectives into one overall measure (i.e. to obtain the overall utility function) we need to decide on the functional form to be used for expressing this utility function. This involves testing various independence conditions depending on the case under consideration. More details on these are given by Keeney and Raiffa (1976).

In broad terms, for the purpose of deciding on the functional form of the utility function, the MAUT distinguishes between two categories of decision problems: *decision under certainty* and *decision under uncertainty* (Fishburn, 1965). The difference between the two categories is in the type of information available to the decision-maker when he is taking the decision about the consequences of his decision. If the decision-maker knows the consequences of the decision with certainty, the decision is said to be taken under certainty. If, however, his knowledge is subject to probability the decision is said to be taken under uncertainty.

In the context of irrigation management some decisions may have to be taken under uncertainty. These include decisions on how much area to be cultivated and how much water to supply and at what time. The manager in taking these decisions have to consider some meteorological factor (rainfall and evaporation) and some hydrological factors (river flows and/or water table levels). Both of these factors are uncontrollable by the manager and are probabilistic in nature. This makes his knowledge of the consequences of his decision subject to probability. For example, the level of adequacy which can be achieved by some water supply schedule on some cropping pattern depends on the rainfall and evapotranspiration during the season. Similarly, the impact of the quantity of water to be diverted or pumped from a river or ground water on future supplies may depend on the river flows or ground water recharges. These decisions can, therefore, be classified as ones which may have to be taken under uncertainty.

In many irrigation systems, however, the uncertainty which stems from the hydrological factors does not exist. These include:

1) Systems in which the irrigation water is pumped from large rivers such that this pumped water is only a small part of the river flow
2) Systems in which large water storage facilities exist such that the irrigation supplies are secured against the river flow fluctuations.
3) Systems in which the irrigation water is pumped from an extensive ground water source not subject to rapid drawdown.

Within these systems there are many in which the rainfall does not play an important part in satisfying the crop water demands. In this type of systems, and because usually the variation in the evapotranspiration is small, the element of uncertainty is considerably smaller. In these systems decisions can be considered as ones which are taken under certainty.

In this study consideration is confined to this latter type of systems. i.e. Systems in which the element of uncertainty is small such that the manager decisions can be assumed to be taken under certainty. These conditions apply to many irrigation systems in the dry zone of the world such as in Egypt, Sudan, Iraq and most parts of Pakistan and Northern India. In fact even for the wet zone of the world, these conditions apply equally well to the dry season crops in places where separate dry season cropping is practised such as in Southern India, Sri Lanka and Philippines.

The Irrigation systems in Sudan, which are used as a case study for the application of the MAUT in this study, are described in Chapter 4. For the hydrological factors, irrigation supplies for all the Sudanese irrigation schemes are provided from the Nile and its tributaries. It has been shown that (section (4.1.4)) during the high flow period of the rivers (July - October) the flows are much higher than the irrigation demands and, therefore, the water supply is certain. During the low flow period (November - March), however, the rivers flows are less than these requirements and large part of the demands are satisfied from the limited storage available. By that time, however, (i.e. from November and onwards) the situation of water availability is usually clear. Areas to be cultivated with the winter crop (i.e. wheat) is based on the volume of water stored and the expected yield of the Blue Nile in its recession period (see section (4.2.4)). For this period the Blue Nile flows are usually small (on average about 10.5% of its annual yield) and are reasonably predictable. For these reasons, the rivers flows do not contain serious uncertainties. As for the meteorological factors, the variations in the evapotranspiration is usually small and the real uncertainty is associated with the rainfall. But the contribution of the rain in the crop water demands in the Sudanese irrigation systems is usually very small. In Chapter 5 (section (5.7.1)) it has been shown that in the Gezira scheme the total rainfall is about 14% of the irrigation supplies. Obviously, what ever the decision of the system manager, only part of this rain can be useful for satisfying the crop water demand (i.e. effective rain). Under these conditions, the element of uncertainty in these systems is sufficiently small that management decisions can be considered to be taken under certainty.

Having the attention focused on irrigation systems in which decisions can be considered to be taken under certainty, we now consider how to decide on the functional form of the overall utility function. Under condition of certainty Keeney and Raiffa (1976, pp.108-117) using results obtained by others, derived the necessary and sufficient conditions under which the overall performance measure of a multi-objective system can be expressed in a summation form. Their result states that in any multi-attribute situation, with the number of attributes greater than two, the compound utility function U(X) (where X = x_1, x_2, ... x_N) is of the additive form:

$$U(X) = \sum_{i=1}^{N} k_i \times u_i(x_i) \tag{7.1}$$

if and only if each pair of attributes x_i and x_j (where $i \neq j$) is "*preferentially independent*" of all other attributes.

In equation (7.1), $u_i(x_i)$ is the utility function of the i-th attribute, k_i is a scaling constant and U(X) and $u_i(x_i)$ are scaled between zero and one.

By definition the attributes x_i and x_j are preferentially independent if the trade-off between them is not affected by the given level of any of the other attributes (Zeleny, 1982).

To help clarify the meaning of preferential independence in the context of irrigation management, let us take the example of a farmer who judges the quality of services provided to him by the system management by three attributes: i) the volume of water provided by the system, ii) limit on credit available, and iii) restriction on area he can cultivate. For this farmer there is always trade-off between the land he can cultivate and the credit available. This trade-off may or may not depend on the volume of water supplied by the irrigation system. If another source of water is available for him his trade-off between land and credit may not be affected by the water supply. In this case land and water are said to be preferentially independent of the water supply. If, however, there is no water source other than that provided by the system then additional land above certain area is useless for him without additional water. Under these conditions his trade-off between land and credit must be affected by the level of water supply and, therefore, land and credit are not preferentially independent of the water supply.

In general, the preferential independence condition is a property of the attributes in the particular setting of the system to be analyzed. It is not determined by the subjective judgement of the decision-maker. However, and although in most case it may be obvious to tell whether the attributes are preferentially independent or not, in the general case it is the decision-maker and not the analyst who understands the system better. It is, therefore, more appropriate for the decision-maker to make the judgement on the preferential independence of the attributes.

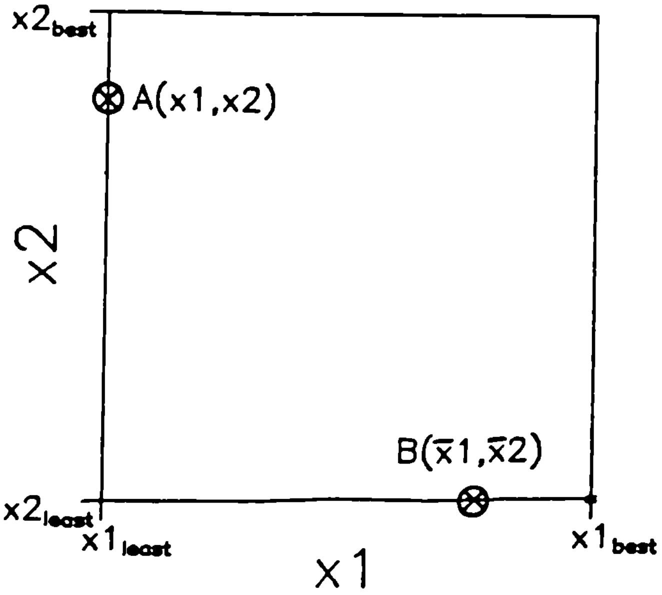
In case of uncertainty, methods for determining the functional form for expressing the overall utility functions are presented in, for example, Keeney (1974) and Keeney and Raiffa (1976). In these cases additional independence conditions have to be tested to cater for the uncertainties involved before deciding on the functional form for expressing the overall utility function.

We now go back to the certainty case. To verify that the preferential independence conditions between the attributes is satisfied we proceed as follows:

i) Start with any two attributes, say x_1 and x_2. Fix the level of their complimentary attributes x_3 ... x_n at a relatively low values.

ii) Find two points in the x_1-x_2 plane, say $A=(x_1,x_2)$ and $B=(\bar{x}_1,\bar{x}_2)$, such that the decision-maker is indifferent between them (Fig.(7.1)).

iii) Change the level of the complimentary attributes x_3....x_n to higher values. If the decision-maker is still indifferent between point A and point B then the attributes x_1 and x_2 are preferentially independent of all other attributes.



A and B are two equally preferred points.

Fig.(7.1): Verification of the independence conditions.

iv) Repeat the above steps for each of the (N-1)-pairs (x_1, x_3), (x_1, x_4) ... (x_1, x_N). This is sufficient to establish the preferential independence condition between all attributes (Keeney and Raiffa, 1976, pp.104-117).

If the preferential independence condition is not satisfied then either the attributes are to be redefined or the objectives themselves to be rearranged and the process repeated again.

7.2.3. Assessing Individual Attribute Utility Functions:

To measure the overall performance of a multi-criteria system, we need to transform all its attributes into a common scale. In the MAUT this common scale is the utilities of the attributes. In simple terms, the utility is a number between zero and one reflecting the attractiveness or degree of satisfaction of different levels of achievement in the attribute. The utility function is a relationship between the level of achievement in the attribute and its utility. Some users of the MAUT approach, simplify matters by assuming a linear relation between the level of the attribute and its utility (Turban & Metersky, 1971; and Edwards, 1977). In most applications, however, the economic principles of diminishing marginal returns is taken into consideration and a nonlinear relation is estimated. This is the approach adopted here.

To estimate the utility function of any individual attribute x, several methods are available. Fishburn (1967) reviewed and classified some of them. Of these the DIRECT MIDPOINT (or BISECTOR) method is used in this work. This method was selected because it yields cardinal ranking of different values of the attribute (Fishburn, 1988). Other methods which yield cardinal ranking are either suitable only when the attribute can only take discrete values or the method requires the decision-maker to give his preferences between lotteries. One of these latter methods was tried with one decision-maker in a preliminary experiment in this study. We found it more difficult to let him give his preferences between lotteries than between certain cases.

To derive the utility function of any individual attribute x using the direct mid-value method we proceed as follows:

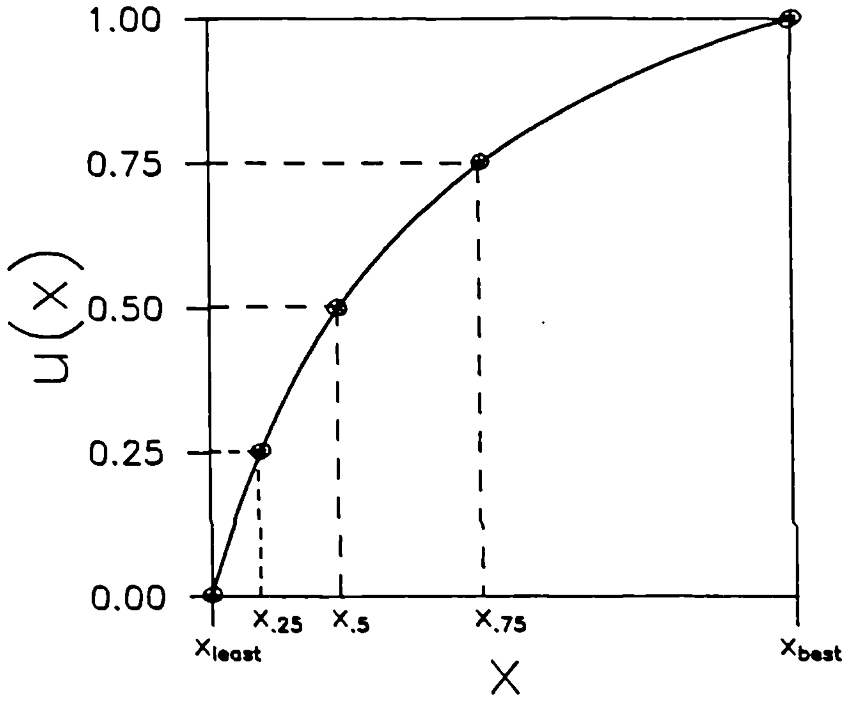


Fig.(7.2): Assessing a single utility function.

i) Set the utility of the least preferred expected level of the attribute as $U(x_{least}) = 0$ and that of the best preferred expected level as $U(x_{best}) = 1$ (fig.(7.2)).

ii) Ask the decision-maker to estimate a value $x_{.5}$ such that the intensity of his preference between x_{least} and $x_{.5}$ is the same as that between $x_{.5}$ and x_{best}. The point $x_{.5}$ is called the mid-value point between x_{least} and x_{best}.

iii) Set $U(x_{.5}) = [\ U(x_{least}) + U(x_{best})]/2 = 0.5$.

iv) Repeat steps (ii) and (iii) above to find the mid-value points between x_{least} and $x_{.5}$ and between $x_{.5}$ and x_{best}. This is repeated until sufficient number of points to sketch the shape of the utility function is obtained.

7.2.4. Determination of the Scaling Constants:

From the verification of the preferential independence conditions in section (7.2.2), two points $A = (x_1,x_2)$ and $B = (\bar{x}_1,\bar{x}_2)$ which are equally preferred by the decision-maker were found. By definition these two points have equal utility. Therefore, U(A) = U(B). Using equation (7.1) with the condition that x_3, x_4, ... x_N are the same for both pints A and B, gives:

$$k_1 \times u_1(x_1) + k_2 \times u_2(x_2) = k_1 \times u_1(\bar{x}_1) + k_2 \times u_2(\bar{x}_2) \qquad (7.2)$$

$u_1(x_1)$, $u_2(x_2)$, $u_1(\bar{x}_1)$ and $u_2(\bar{x}_2)$ are known values from the individual attribute utility functions derived in the previous sub-section.

Equation (7.2) fixes the relative values of k_1 and k_2. Similar equations can be obtained which relate the pairs (k_1,k_3), ... (k_1,k_N). This will yields (N-1)-linear equations in N-unknowns. With the additional condition that $\Sigma k = 1$, equations can be obtained and solved to yield the values of all the k_i's.

7.3. Application to the Irrigation Systems in Sudan:

To apply the procedure outlined above, eight Sudanese officials were interviewed: three engineers from the MOI field staff, two engineers from the MOI senior staff at the headquarters, one research engineer from the Hydraulics Research Station (HRS) of the MOI, one agricultural manager working for one of the agricultural corporations responsible for managing the irrigation schemes and one university academic who has a wide experience in water management in Sudanese irrigation systems.

The purposes of these interviews were:

(i) To test the applicability of the MAUT approach in evaluating the performance of the irrigation system in Sudan.

(ii) To see how decision-makers differ in their evaluation criteria and trade-offs and how this affects the performance evaluation.

The following steps describe the results of the interviews and the derived utility functions. A typical dialogue with a decision-maker is given in appendix B. Before the exact procedure given in appendix B was adopted, some preliminary discussions and interviews which were somewhat different, were carried out with some of the respondents. The interview procedure was then modified as necessary in order to overcome some of the difficulties encountered.

Step 1: Preparation for the Assessment:

The officials were interviewed separately. For each of them the purpose of the interview was explained. Ideally they should have been left to propose their own criteria. But to assist them and to ensure that criteria used could be easily measured, six criteria were suggested to them and they were left to select from them what they think are important and relevant to the Sudanese irrigation systems. The criteria suggested to them were:

x_1 = Adequacy.
x_2 = Water losses.
x_3 = Equity.
x_4 = Cost.
x_5 = Water-user convenience.
x_6 = Durability (long-term).

The meaning of each of these criteria was discussed in detail with each respondent. Out of these criteria all respondents took only the first four to be relevant and sufficient for of the evaluation of irrigation systems performance in Sudan. Water user convenience was not considered by them to be relevant because, according to them, at the heads of the minor canals the MOI supplies water to a large number of farmers who should always be able to share this supply in a way which suits them. In addition to that, the minor canals themselves act as a storage reservoir to provide the farmers with a good flexibility in their irrigation scheduling. Similarly, long-term durability or sustainability of the system, was not taken by them to be relevant because in the Sudanese irrigation systems, the deep water table and the good quality of the Nile waters removes any hazard of system deterioration due to build up of salinity, alkalinity or water-logging problems (Chapter 4, section (4.1.3)).

As part of this step we need to agree with the respondents on the attributes to be used for measuring each of the four criteria selected by them. Earlier in this study methods for measuring these criteria were introduced (adequacy, water losses and equity in Chapter 5 and cost in Chapter 3). In the interviews with the respondents in this study, however, for some of these criteria, some approximate attributes were adopted instead. The reason for this was that it is always absolutely important for the respondents to be able to grasp the meaning and practical significance of different values of each attribute. Otherwise his preferences over different levels of achievement of each objective and his trade-offs between different objectives may not reflect his real preferences. It is therefore always preferable to use attributes with which the respondent is familiar (see Chapter 3, section (3.3.1)). The literature on the application of the MAUT gives many examples where "*proxy attributes*" were used (Keeney and Raiffa, 1976, pp.55-63). A proxy attribute is an attribute which approximately indicates the level of achievement of the objective but does not completely and precisely measure that level.

Moreover, one of the purposes of the interviews was to compare the preferences of those officials. In order to do that it is necessary to use the same attributes with all of them. Not all those officials are prepared and have the time to spend in introducing new attributes in such a way that we are sure that they get the right understanding of their practical meanings.

The following are the attributes which were used in the interviews. These attributes were adopted after some initial discussion with some of them.

i) Adequacy = (x_1):

The purpose of the interview as stated to the subjects was to establish a frame by which we can measure the performance of the MOI in providing its services to the water users. As such they suggested that because the MOI is responsible for supplying water in response to an indent from the SGB, the adequacy of its supplies should be judged by comparing the supply at the head of the minor canal by the indent of the SGB block inspectors. Whether this indent is correct or not is not the responsibility of the MOI. In other words, those respondents assumed that in the Gezira scheme a demand type of scheduling is in practice.

They accepted the following attribute for measuring adequacy (x_1):

$$x_1 - 100\times\frac{Q}{I} \qquad (7.3)$$

Where

Q = Total volume of water supplied at the minor canal head during the season head.

I = Total seasonal water indent from the SGB for the minor canal.

With this definition x_1 can, theoretically, take any value between zero and ∞. The target value is $x_1 = 100$. Any value less than that means that the MOI supplies are less than adequate and a value more than 100 means these supplies are more than required.

ii) Water losses = (x_2):

This refers to the losses involved in transporting the water from the water source (dam or pump) to the head of the minor canal and measured by:

$$x_2 = 100\times\frac{(S - R)}{S} \qquad (7.4)$$

Where:

S = Total water supplied from the dam.

R = Total water received at the heads of all minor canals.

With this definition x_2 can, theoretically take any value between zero and 100. The target value is zero. Any value above that indicates corresponding percentage of water losses.

iii) Equity = (x_3):

Equal volume of water per unit of cropped area should be supplied to every minor. This is to be measured by:

$$x_3 = 100\times\frac{1 - \sum_{i=1}^{m}|q_i - Q|}{m\times Q} \qquad (7.5)$$

Where

q_i = Volume of water per unit cropped area served by the i-th minor.

Q = Average q_i to all minors sampled.

m = Number of minors sampled.

This is the same as the measure of equity introduced in Chapter 5 (section (5.7), equation (5.12)) with q_i here defined differently. With this definition x_3 can take any value between zero (when only 50% of the minors take all the flow) and 100 (when all minors receive equal volume per unit area).

(iv) Cost = (x_4):

This is the annual cost to the MOI for operating the system per unit cropped area. Items of expenditure to be included in the cost are discussed in Chapter 3 (section (3.5)). In the interviews with those officials it was assumed that all the irrigation systems in Sudan had already paid back their capital costs and investments on major improvements and rehabilitations are to be annualized.

Using the above definitions, the respondents agreed on the ranges of values given in table (7.1) as the best and worst levels of achievement in each objective.

Table (7.1): Expected range of the attributes

Attribute	Definition	Best level	Worst level	Units
x_1	Adequacy	95	50	%
x_2	Water losses	5	30	%
x_3	Equity	90	60	%
x_4	Cost	50	150	Ls*/feddan

* Note: Ls = Sudanese pounds

Again, ideally each respondent should be left to choose the range with which he is familiar, but to be able to compare their preferences it was necessary to use the same ranges with all of them. To achieve that, after some initial discussion with some of them and consultation of some of the data available, we suggested to them the ranges given in table (7.1) and they accepted them. In choosing these ranges we deliberately made them wide enough to include any range which may be suggested by the respondents

Step 2: Verification of the Independence Condition:

When x_3 (equity) and x_4 (cost) were fixed at their worst levels, the first of our respondents indicated that in the x_1-x_2 (adequacy-water losses) plane he is indifferent between the two points A and B (Figs. (7.3.a)). He also indicated that his indifference between these points does not change if the levels of the attributes x_3 (equity) and/or x_4 (cost) are changed (an outline of a dialogue with the respondent to arrive at these points is given in appendix B). This shows that for this respondent x_1 (adequacy) and x_2 (water losses) are preferentially independent of x_3 (equity) and x_4 (cost). In addition to that we now have two points (i.e. A and B) with equal utility to that respondent.

The same procedure was followed with the same respondent for the pairs of attributes (x_2,x_3) and (x_2,x_4). They were also found to be preferentially independent of their complimentary attributes and yielded the pair of indifferent points shown in fig.(7.3.b) and fig.(7.3.c).

In deriving the points of fig.(7.3) two points are worth mentioning:

Firstly, as can be seen from fig.(7.3), *in deriving these points we* always compare between x_2 (water losses) and some other attribute. The attribute x_2 here was chosen randomly. It could be any of the other attributes. What is important is to consider three different combinations in order to yield three different relations between the four attributes.

Secondly, the choice of the indifferent points is determined by the subjective judgement of the respondent. There is no absolutely correct or absolutely wrong choice. In order to ensure that these points are not

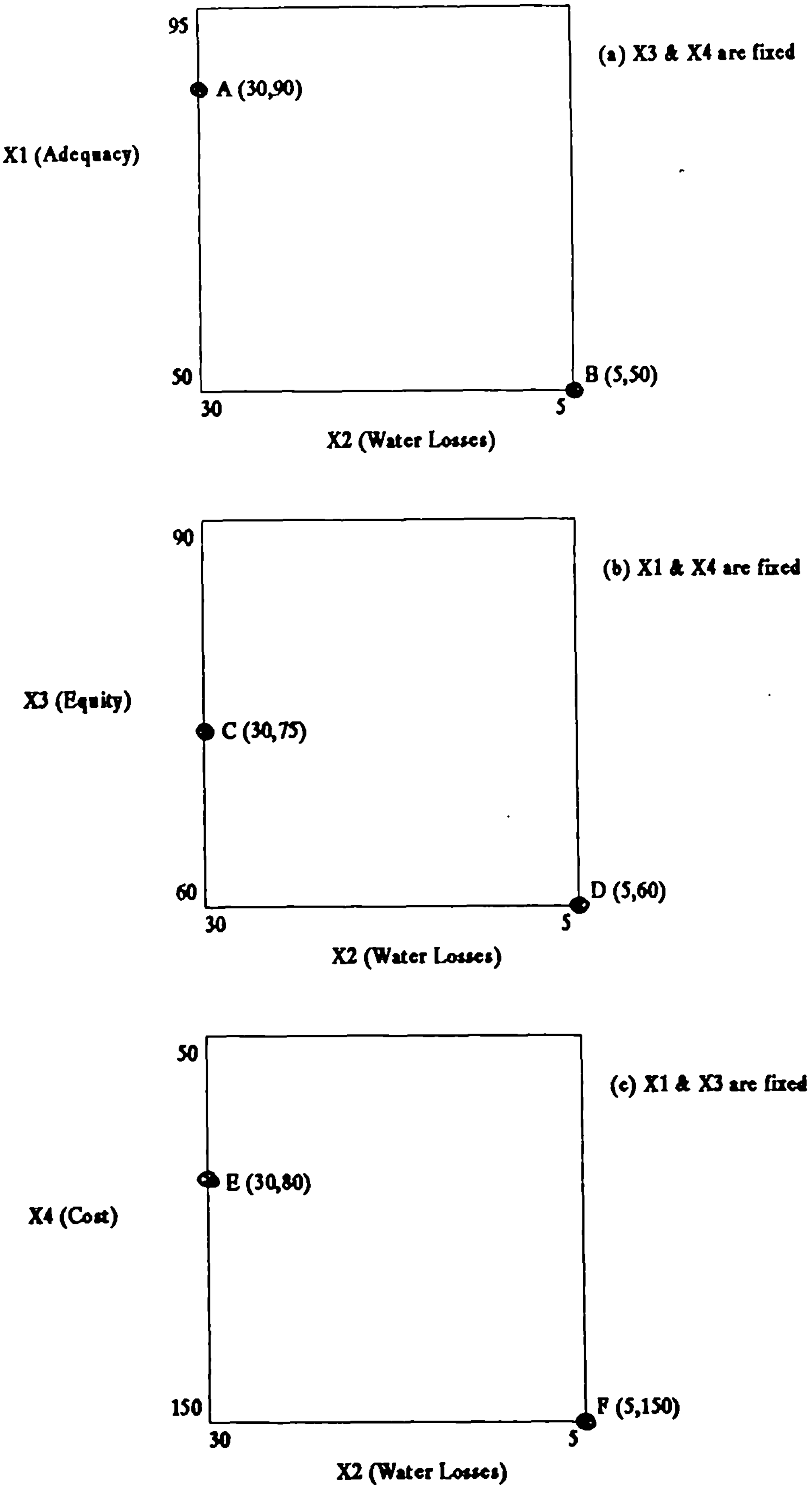
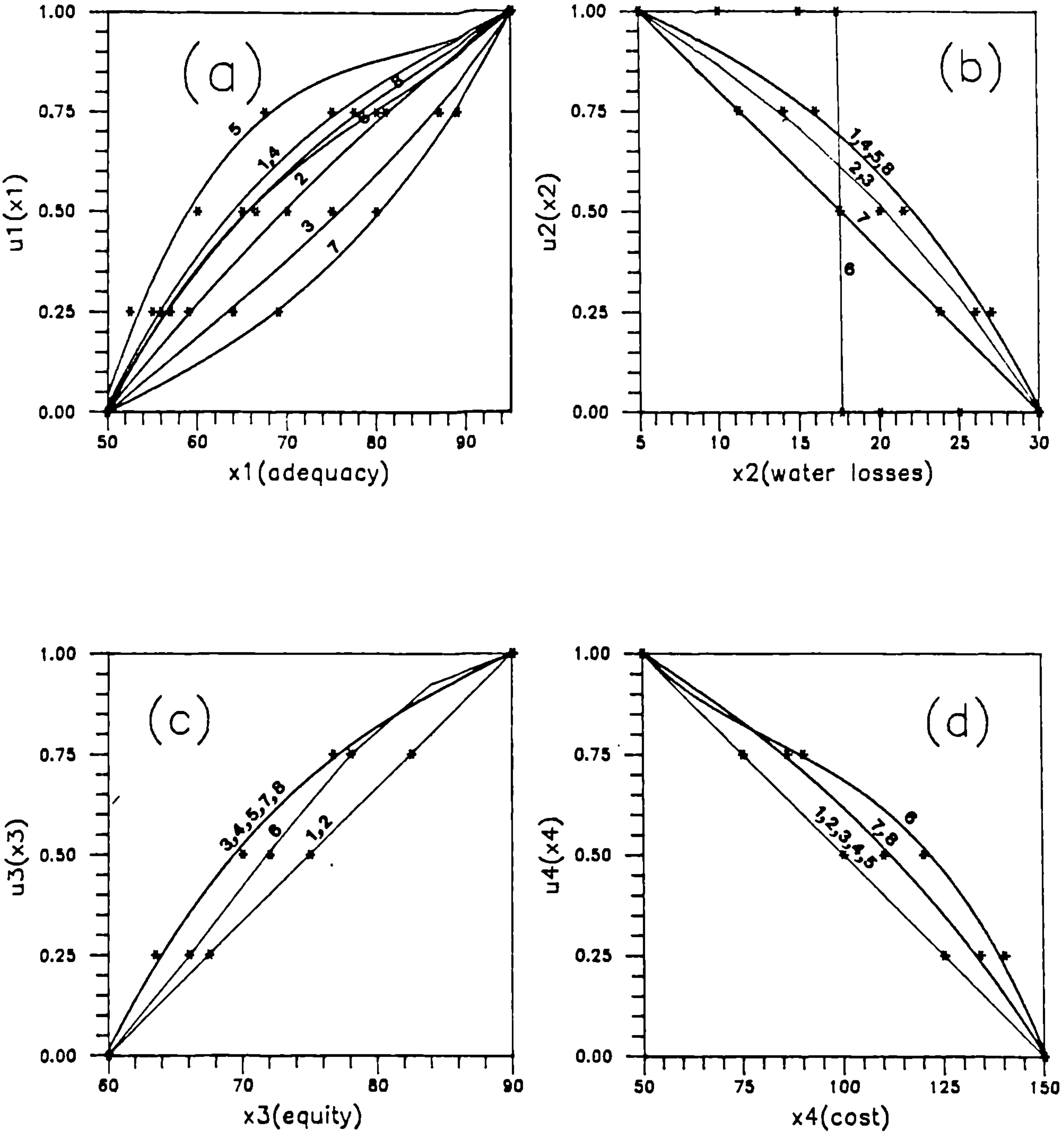


Fig.(7.3): Trade-offs of the first respondent far from representing the preference of the respondent, additional pairs of points could be determined to be used in a consistency checks. For example, for this respondent, we can find pairs of indifferent points for the pairs of attributes (x_1,x_3), (x_1,x_4) and (x_3,x_4). As will be seen in step 4, these should yield the same relations between the scaling constants as that to be derived from (x_2,x_1), (x_2,x_3) and (x_2,x_4). If large differences are encountered the choice of the indifferent points should be revised with the respondent. This consistency checks is particularly important if the respondent is uncomfortable with his answers.

The same procedure was followed with each of the other respondents. Because the attributes were originally selected to be preferentially independent, all respondents assured that they are. In addition to that, for each respondent, the procedure yielded pairs of indifferent points. The respondents gave their answers with varying degree of confidence, but in general no real difficulties were encountered.

Step 3: Estimation of Individual Attribute Utility Functions:

For each respondent the utility function of each of the four attributes was assessed using the method outlined earlier (an outline of the dialogue with a respondent to derive his utility function for one attribute is given in appendix B). The derived utilities for all attributes for all respondents are shown in figs.(7.4.a - 7.4.d). Again, in deriving these utility curves, we are using the subjective judgements of the respondents. The shape of the derived curves can be discussed with the respondent to make sure that it represents his preferences. Again the respondents gave their answers with varying degrees of confidence but no real difficulties were encountered.



Note: Numbers on the curves correspond to respondent number.

Fig.(7.4): Utility curves for the individual attributes.

The shape of the utility curves has some significance. It reflects the attitude of the subject towards different values of the attribute. Concave curves indicate that he is prepared to give more efforts to improve the performance, by some fixed amount, when this performance is at a lower level than to achieve the same amount of improvement when the performance is at a higher level. With two exceptions, all the curves in fig.(7.4) follow this pattern. Respondents 3 (MOI field engineer) and Respondent 7 (agricultural manager) have convex utility curves for adequacy reflecting what can be described as a "*gambler behaviour*". They argued that when the adequacy is low, the crop may be seriously affected. Improvement in adequacy under this condition will not be as profitable to the farmer as when the adequacy is already at a high level. This is because for the farmer there is certain limit of yield which he must achieve before he starts to make a profit. This yield limit is the yield required to cover the cost of the inputs provided by the government. This is because whatever the yield obtained the government first deducts its full charges from the sales of the crop and then if there is a profit the farmer can have it. Other respondents took the attitude that low level of the attribute is psychologically uneasy to live with because it attracts the attention of critics.

We also note that Respondent 6 (HRS researcher) demonstrated an unusual utility function for water losses. He argued that only part of that loss can be recovered by an improved management and that this part is very small since a large proportion of the losses is due to the unavoidable evaporation from the open water surface of the canal network. According to his utility curve, if the water loss is less than 17% he considers the performance to be perfect (i.e. utility = 1). Any value above that is unacceptable and should be given zero utility.

Using a commercially available computer software a best fit equation was fitted to the data points for each utility curve. Equations (7.6.a) - (7.6.d) are the utility functions for the four attributes for the first respondent.

$$u_1(x_1) = 1.77 - \frac{57.57}{x} - \frac{1535}{x^2} \qquad (7.6.a)$$

such that $50 \leq x_1 \leq 95$

$$u_2(x_2) = 0.9975 + 0.0065x_2 - 0.0013x_2^2 \qquad (7.6.b)$$

such that $5 \leq x_2 \leq 30$

$$u_3(x_3) = -2 + 0.033x_3 \qquad (7.6.c)$$

such that $60 \leq x_3 \leq 90$

$$u_4(x_4) = 1.5 - 0.01x_4 \qquad (7.6.d)$$

such that $50 \leq x_4 \leq 150$

Step 4: Determination of the Scaling Constants:

From the result of step 2 above the preferential independence condition implies that the overall utility function is of the form:

$$U(x_1 .. x_4) = k_1u_1(x_1) + k_2u_2(x_2) + k_3u_3(x_3) + k_4u_4(x_4) \qquad (7.7)$$

Points A and B of fig.(7.3.a) were found to be equally preferred by the first respondent, therefore:

$$U(A) = U(B) \tag{7.8}$$

For both points A and B, x_3 and x_4 are fixed at their worst levels. This means:

$$u_1(x_3) = u_2(x_3) = u_1(x_4) = u_2(x_4) = 0$$

Substituting this and equation (7.8) in equation (7.7) gives:

$$k_1u_1(90) + k_2u_2(30) = k_1u_1(50) + k_2u_2(5)$$

Substituting $u_1(90)$, $u_2(30)$, $u_1(50)$ and $u_2(5)$ from equations (7.6.a) and (7.6.b) gives:

$$k_2 = 0.94k_1 \tag{7.9}$$

Similarly, U(C) = U(D) (fig.(7.3.b)) gives:

$$k_2 = 0.5k_3 \tag{7.10}$$

And U(E) = U(F) (fig.(7.3.c)) gives:

$$k_2 = 0.7k_4 \tag{7.11}$$

The relations between k_1, k_2, k_3, and k_4 given by equations (7.9) - (7.11) should be the same for any three pairs of attributes used in step 2 above. This is where some consistency checks could be done to ensure that the respondent answers reflect his preferences.

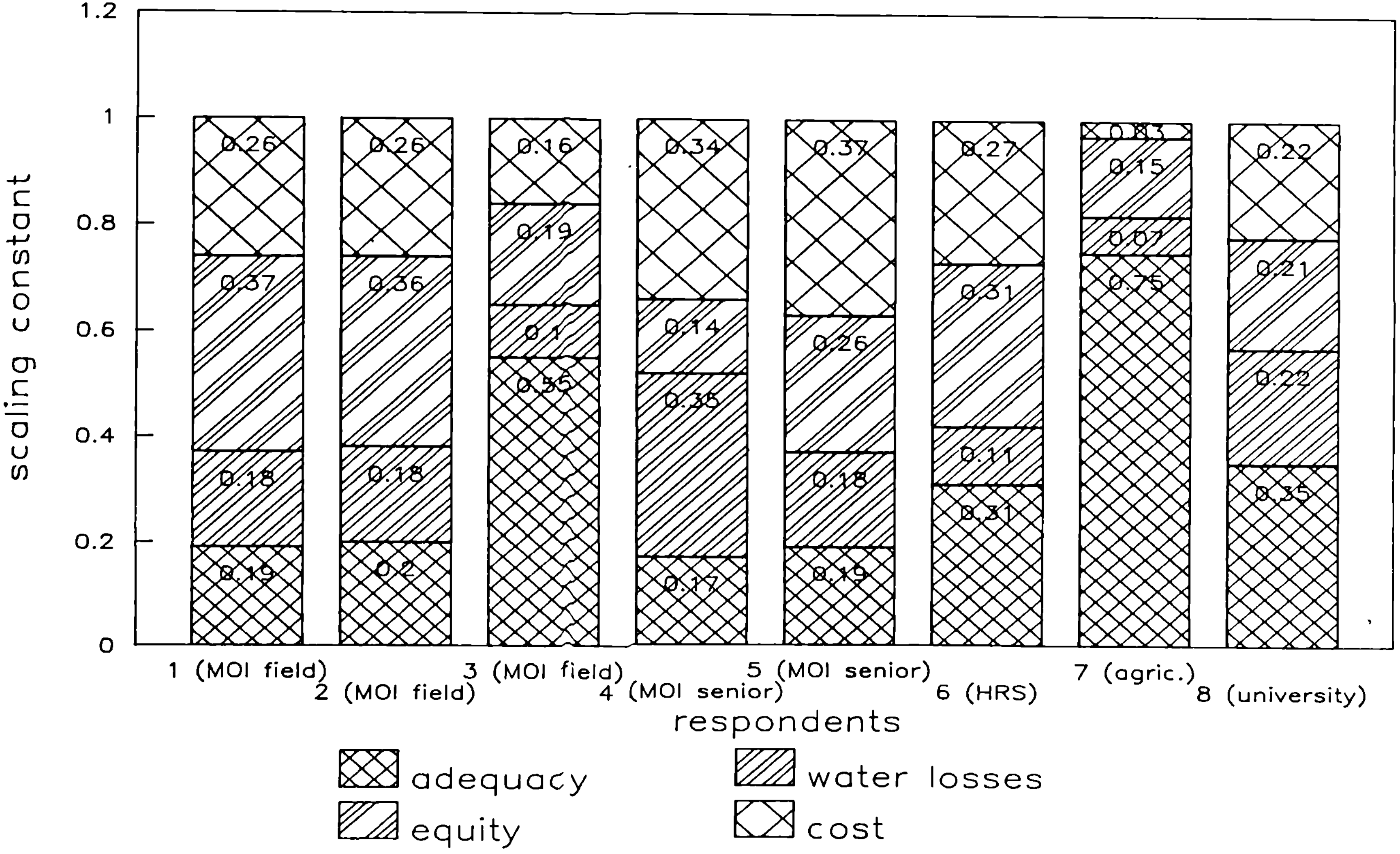
Solving equations (7.9) - (7.11) with the condition $\Sigma k_i = 1$, yields the values of the four scaling constants. A similar procedure was followed with all respondents. The values of the scaling constants are given in fig(7.5).

Generally the scaling constants cannot be taken as a direct measure of the relative importance which the subject interviewed gives to the respective objectives. Their values depend on the ranges of operation of the attributes selected for the analysis. Changing any of these ranges will necessarily change the values of the scaling constants. For example, Respondent 1 has $k_2 = 0.18$ and $k_3 = 0.36$. It doesn't follow that equity for him is twice as important as water losses. What it means is that improving the adequacy from its lowest level of 50% to its best level of 95% is twice as preferable to him as reducing the water losses from its worst level of 30% to its best level of 5%. In general the scaling constant for any of the attributes is exactly equal to the increase in the overall utility which would result from changing the level of the attribute from its worst level to its best level. This means that the smaller the operating range selected for the attribute the smaller will be the scaling constant of that attribute relative to the others.

For the eight respondents here the operation range selected for each attributes is the same. In this case it can be shown that the scaling constant for any particular objective reflects the relative importance of that objective to the respondent as compared with the importance of the same objective to the other respondents. In this way we can say that Respondents 1, 2 and 5 gave equal weights to the water losses, but Respondent 4 gave it twice that weight (fig.(7.5)).

Clearly fig.(7.5) shows that the trade-offs differ widely between the officials interviewed. In general the MOI senior engineers at the headquarters put more emphasis on water losses and cost as compared with the MOI field engineers

Fig.(7.5): Values of the scaling constants for the eight respondents



who are more concerned about adequacy and equity. This is probably because of their immediate contact with the water users, unlike the senior MOI officials who are exposed to the pressures from the financing authorities. The agricultural manager showed very little concern about water saving or cost and is greatly preoccupied with the adequacy of supply.

7.4. Overall Performance Index:

Having the individual attributes utility functions (equations (7.6.a) - (7.6.d)) and the scaling constants fig.(7.5) we can now have the overall utility function for the first respondent. The procedure was followed with other respondents. Equations (7.12) - (7.19) are the overall utility functions for the eight respondents. These functions were obtained by combining the individual attribute utility functions of fig.(7.4) with the scaling constants of fig.(7.5). All equations (7.12) - (7.19) are valid for:

$$50 \leq x_1 \leq 95; \quad 5 \leq x_2 \leq 30; \quad 60 \leq x_3 \leq 90; \quad 50 \leq x_4 \leq 150.$$

Respondent 1:

$$U(x_1 \ldots x_4) = 0.19\times(1.77 - \frac{57.57}{x_1} - \frac{1535}{x_1^2}) + 0.18\times(1 + 0.0065x_2 - 0.0013x_2^2) + 0.37\times(-2 + 0.033x_3) + 0.26\times(1.5 - 0.01x_4) \qquad (7.12)$$

Respondent 2:

$$U(x_1 \ldots x_4) = 0.20\times(-1.71 + 0.04x_1 - 0.0001x_1^2) + 0.18\times(1.09 - 0.01x_2 - 0.0007x_2^2 + 0.36\times(-2 + 0.03x_3) + 0.26\times(1.5 - 0.01x_4) \qquad (7.13)$$

Respondent 3:

$$U(x_1 \ldots x_4) = 0.55\times(-0.47 + 0.003x_1 + 0.0001x_1^2) + 0.10\times(1.09 - 0.01x_2 - 0.0007x$$

$$+ 0.19\times(0.89 + \frac{133.6}{x_3} - \frac{11110}{x_3^2}) + 0.16\times(1.5 - 0.01x_4) \quad (7.14)$$

Respondent 4:

$$U(x_1 \ldots x_4) = 0.17\times(1.78 - \frac{57.57}{x_1} - \frac{1535}{x_1^2}) + 0.35\times(1.02 + 0.002x_2 - 0.001x_2^2)$$

$$+ 0.14\times(0.80 + \frac{148.4}{x_3} - \frac{11720}{x_3^2}) + 0.34\times(1.5 - 0.01x_4) \quad (7.15)$$

Respondent 5:

$$U(x_1 \ldots x_4) = 0.19\times(0.46 + \frac{131.1}{x_1} - \frac{7603}{x_1^2}) + 0.18\times(1.05 - 0.005x_2 - 0.001x_2^2)$$

$$+ 0.26\times(0.89 + \frac{133.6}{x_3} - \frac{11110}{x_3^2}) + 0.37\times(1.5 - 0.01x_4) \quad (7.16)$$

Respondent 6:

$$U(x_1 \ldots x_4) = 0.31\times(2.08 - \frac{103.9}{x_1}) + 0.11\ (\mathit{if}, 17.5 \ge x_2 \ge 5)$$

$$+ 0.31\times(-5.09 + 0.12x_3 - 0.0006x_3^2) + 0.27\times(0.92 + 0.005x_4 - 0.00007x_4^2)$$

$$(7.17)$$

Respondent 7:

$$U(x_1 \ldots x_4) = 0.75\times(0.60 - 0.03x_1 + 0.0004x_1^2) + 0.07\times(1.2 - 0.04x_2)$$

$$+ 0.15\times(0.81 + \frac{147.6}{x_3} - \frac{11730}{x_3^2}) + 0.03\times(1.16 - 0.0009x_4 - 0.00005x_4^2) \qquad (7.18)$$

Respondent 8:

$$U(x_1 \ldots x_4) = 0.35\times(2.09 - \frac{104.4}{x_1}) + 0.22\times(1 + 0.01x_2 - 0.001x_2^2)$$

$$+ 0.21\times(0.75 + \frac{156.7}{x_3} - \frac{12070}{x_3^2}) + 0.22\times(1.16 - 0.0009x_4 - 0.00005x_4^2) \qquad (7.19)$$

Now with equations (7.12) - (7.19), if we measure the performance level in each of the four individual criteria (adequacy, water losses, equity and cost) in any irrigation system (or part of it) in Sudan, the attractiveness of the performance of that system to each of the officials interviewed can be calculated.

7.5. Application in the Gezira Scheme, Sudan:

To demonstrate the usefulness of the approach, the performance of two major canals in the Gezira scheme was estimated. Zananda major and Gamosia major (see location map fig.(5.11)). Table (7.2) gives the values of the four attributes for each of the two majors. The data in table (7.2) is for the 1987/88 season. The levels of the attributes were estimated using the definitions used in the interviews with the respondents (section (7.3)).

Table (7.2): Values of the attributes for two majors

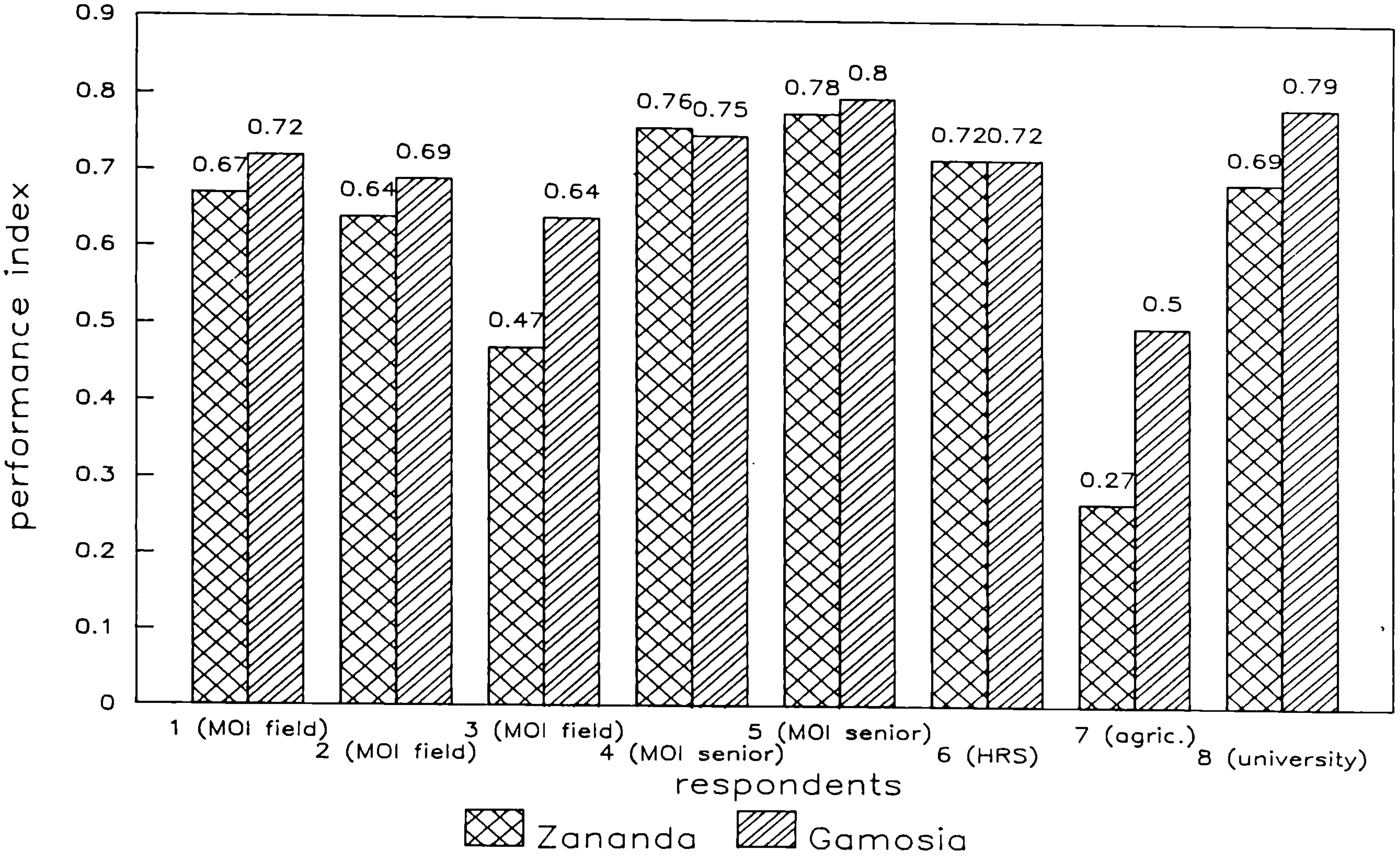
MAJOR	ADEQUACY %	W.LOSSES %	EQUITY %	COST Ls/feddan
1 (Zananda)	61	15.5	79	60.28
2 (Gamosia)	77	18.5	81	69.68

In table (7.2), figures for adequacy and equity were derived from data taken from Francis, *et.al.* (1988) for the period of November-December 1987. Information on cost for individual majors were not available. Cost figures here were based on the estimated cost of removing the silt deposited on each major (and its minors) added to that equal vales of Ls 28.68 per feddan for each major to cover all other operation and maintenance costs. Estimates of the silt deposited for the two majors were also derived from data given by Francis, *et.al.* (1988). Due to non-availability of water losses estimates for the major canals an estimated average value was used. Added to that is another quantity to cater for the open water surface evaporation losses in each major. These latter quantities were estimated based on the distances of the major off-take from the water source at the dam.

As can be seen from table (7.2), the preference between the two majors is not obvious. While Zananda major is performing better with respect to water losses and cost, Gamosia major is performing better at adequacy and equity.

Fig.(7.6) is a plot of the performance index for the two majors as calculated

Fig.(7.6): Performance index for two majors in the Gezira scheme (1987/88 season)



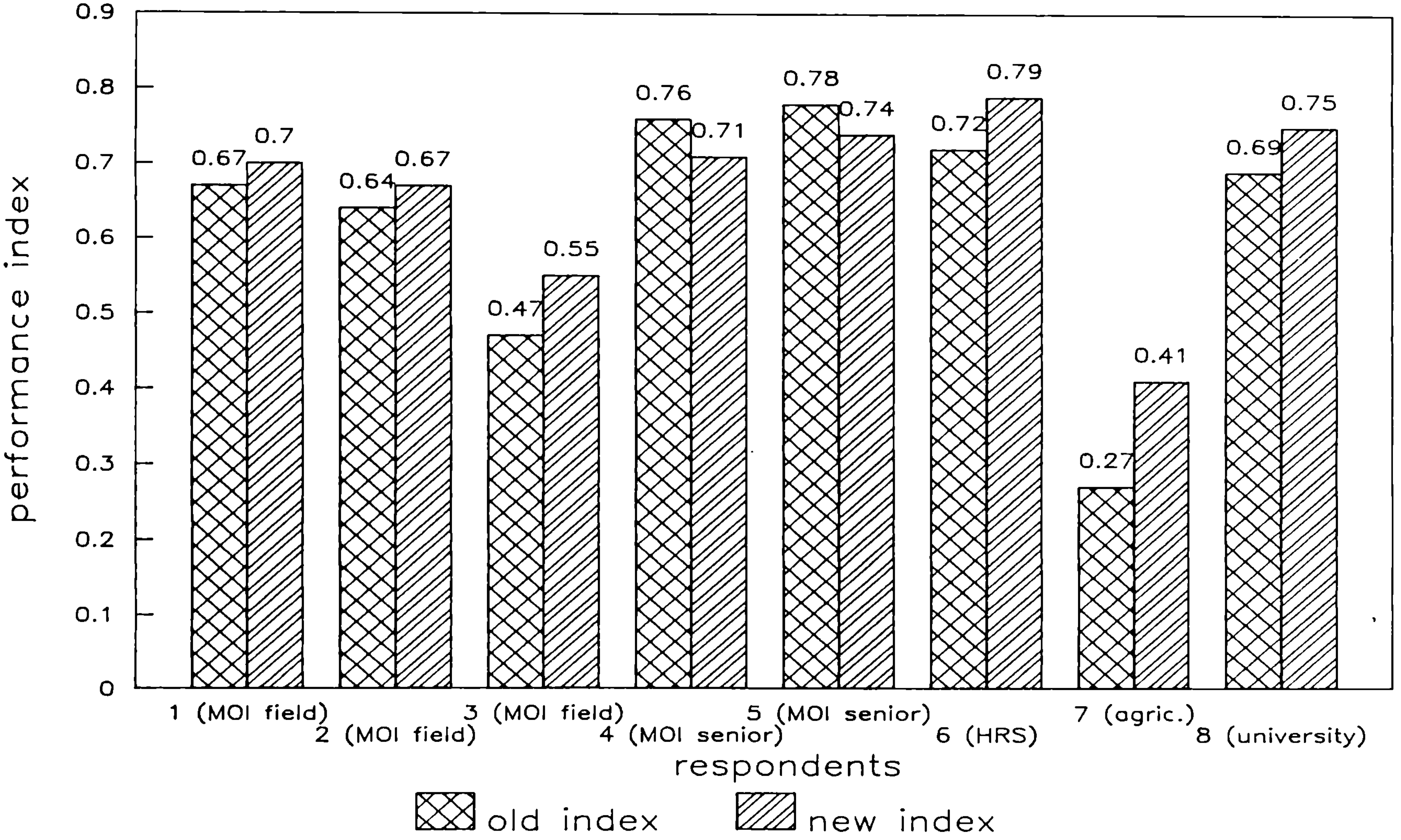
using the utility functions of equations (7.12) - (7.19). From fig.(7.6), clearly for all of them, except Respondents 4 and 6, Gamosia major is performing better than Zananda major. Respondents 3 and 7 are less satisfied with the performance in both majors than all other respondents, because of the higher priority given by them to adequacy.

Another possible use of the derived utility functions is in decisions concerning proposed investments for improvement. We refer here to a hypothetical case of chemical treatment for weed control in Zananda major costing 30 Ls/feddan/season. This investment is expected to improve adequacy by 10% and equity by 5%. The old and new overall performance index for Zananda major for each respondent are plotted in fig.(7.7).

Clearly from fig.(7.7), an investment like this will be accepted by all except Respondents 4 and 5. i.e. The two MOI senior engineers. This is because they were more concerned about cost than all others. The approach also permits sensitivity analysis. For example, it is possible to calculate how far this investment is from being accepted by Respondents 4 and 5. This can be done by decreasing the cost, holding the three other attributes fixed until the overall utilities of those respondents are equal to their old utilities. This particular investment will be feasible for Respondent 4 only if he can get the same effect at a cost of 15 Ls/feddan/season or less. Similarly, the maximum cost which Respondent 5 will be willing to pay for this improvement in performance is 19 Ls/feddan/season.

This sensitivity analysis is made possible by the fact that the individual attributes utility functions as well as the overall utility function resulting from the application of the MAUT are cardinal indexes.

Fig.(7.7): Old and new performance indexes for Zananda major



7.6. Concluding Remarks:

The officials interviewed in this work do not necessarily represent the organizations they are working for, and the time spent with them, ranging from two to fours hours each (most of it spent on the definition of the attributes and the practical significance of different values of these attributes) was probably too short to be able to fully elicit their preferences. It was, however, all the time they could possibly spare for us. Because the concept of comprehensive evaluation of irrigation systems performance in general and the evaluation of the trade-offs between the objectives in particular are new to the respondents, more time should have been spent with them. For example, in this experiment not enough consistency checks were made due to shortage of time. For these reasons, it cannot be suggested that the utility functions derived here could be used as they are in an practical evaluation of the performance of the irrigation systems in Sudan. They should be taken as preliminary ones. Nevertheless, the experiment shows that the MAUT approach is a very useful tool for the problem at hand.

As seen from the case study described, although people involved in the management of irrigation can easily agree on the objectives of their system(s), wide variations between individuals can be encountered in the relative importance attached by each of them to each of the objectives. Management priorities for any official involved in irrigation are strongly affected by his position in the management hierarchy and the pressures exerted on him by his immediate surroundings, i.e. the farmers, the boss, the financing circles, public opinion ....etc.

The utility function reflects these management priorities. It is a measure of the attractiveness of different performance levels to the decision-maker. This is a personal value judgement and as such it is in essence subjective. The MAUT approach cannot do any thing about this subjectivity. All it can do is to provide a systematic step-by-step procedure which can help us construct the preferences of a cooperative decision-maker and make them explicit. Because subjective judgement must be involved, some degree of imprecision is inevitable and must be accepted.

The interest of the decision-maker in the analysis and his willingness to think hard enough to give the answers which reflect his real feeling are crucial requirements for correct results. It is always possible for an uninterested decision-maker to give any answers which can easily distort the results of the analysis or may even lead to meaningless and misleading results.

In irrigating several group of individuals are involved and concerned about how well the irrigation system is performing. Within each group, individuals differ in their preferences. The question arises then is on whose preferences should the evaluation be based.

One way out is to let some national body consider the interest of all parties concerned and translate that into irrigation management policy. In our view the Irrigation Department (or its equivalent) is a potential candidate for this job. What is important here is that this management policy must be presented in an explicit form and made public. If this is done then, individuals involved in the implementation of this policy can clearly know what their targets are and their performance can be measured against a clearly defined yardstick. Moreover, it is only fair for the beneficiaries of the irrigation system to know what they should expect from their system. If the management policy is explicit and made public then it can be debated and all beneficiaries can campaign in order to have their opinions taken into consideration. By beneficiaries here it is meant, not only the farmers, but also people like local politicians, farm labourers, local merchants and all others involved in businesses related to the irrigation schemes.

The MAUT is exactly useful here. It provides a convenient means for expressing the Irrigation Department management policy in terms of explicit objectives and trade-offs between these objectives. However, the main problem with the MAUT approach in this respect is that it is designed to work with a single person decision-maker. Within the Irrigation Department, like any other public organization, a single person decision-maker who dictates the policy may not exist. At least in theory, in public sector the general policy is derived by a group of experts or a selected committee. Some way of combining the preferences of several people in a group utility is, therefore, needed. The MAUT in itself does not provide such a facility. In our view, however, a combination of the MAUT with Delphi method (Dinius, 1987) can provide a method for deriving such a consensus utility. This has not been done in this study because of time limitations.

Delphi method is a procedure for obtaining a compromise agreement between a number of people without having them meeting together. If it is to be applied with the officials interviewed in this study, the individual attributes utility functions of fig.(7.4) and the pair of equally preferred points of fig.(7.3) derived from all respondents are to be presented, possibly with some statistics on them, to each of the respondents. In the light of this new information respondents may change their opinions to be closer to that of the others. The process may be repeated as necessary till some compromise agreement between all of them is reached. When the respondent is presented with the opinions of the others, he may not be informed about who are the others. In this way the method replaces the committee meeting and has the advantage of avoiding the biasing effect of the influential members.

An important issue concerning the stability of the utility function has been raised during the interviews. In Chapter 3 (section (3.2.2)) we referred to this as the short-term variability of the objectives and the trade-offs between them. One of the officials interviewed in this study indicated that his trade-offs between water losses and any of the other attributes depends on the river yield. Even for the same season, in Sudan water losses during the flood period may not have the same value as during the low flow period (see Chapter 4, section (4.1.4)). In deriving the utility functions in this study, normal river yield was assumed and water losses were taken as average for the whole season.

The point to be made here is that the management policy may have to be different for different conditions. Whether to make the average condition policy as applicable always or to allow for some changes to cater for up normal conditions depends on the variability of the conditions from season to season or from part of the season to the other.

CHAPTER 8

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1. Summary:

The work reported in this thesis was motivated by the widely recognized lack of comprehensive methodologies by which the performance of irrigation schemes can be measured. The objective of the study was to develop a systematic methodology by which some use can be made of the large quantities of data already routinely collected in irrigation schemes for the purpose of regular seasonal or annual evaluation of their performance. Specific consideration was given to the developing countries' irrigation schemes where, in recent years, concern has been widely expressed about the performance of particularly their main irrigation systems and large sums of money have been injected into their rehabilitation. For this reason the focus of attention in the study was confined to the performance of the main irrigation system of the bureaucratically-managed, small-holders, canal-fed irrigation systems. These are the most common in developing countries. An evaluation methodology was developed, tested and is reported in this thesis.

The approach followed in the study consists of first identifying the criteria which we believe to be sufficient for characterizing the important features of the performance of any irrigation system of the type considered in this study. Using hierarchical structure of objectives, six criteria were identified for this purpose. These are: *water supply adequacy*, *equity*, *water losses*, *water user convenience*, *cost* and *durability*. The idea is that the performance of any irrigation system can be adequately characterized by a subset from these criteria. The question of which of these six criteria is to be considered in evaluating any particular system(s) and the trade-offs between them is best determined by the decision-maker in the particular system(s) to be evaluated.

New methods were developed for measuring the system performance with respect to each of *water supply adequacy*, *equity* and *water user convenience*. Data from the Gezira scheme, Sudan, was used for testing the applicability of these methods.

The characterization of water supply adequacy, equity and water losses involves the development of a LOTUS micro-computer soil moisture simulation model for the scheme (or the part of the scheme) to be evaluated. Such a model was developed and validated using field data from the Gezira scheme. The model simulates the variation of the daily average soil moisture level in the crop root zone and the actual crop evapotranspiration. Two methods for characterizing adequacy were suggested. One method is through constructing a graph which summarizes the intensity-duration characteristics of the stress experienced by the crop during the season. This is done from the time variation of the soil moisture level in the crop root zone. The other method consists of formulating a procedure through which all the characteristics of the water supply adequacy are combined into a single index which we called "*Irrigation Adequacy Index* (IAI)". In addition to the variation of the soil moisture level in the crop root zone, the IAI value takes into consideration the characteristics of the crops grown (i.e. their root development patterns, their stress sensitivities and their relative importance to the system manager). Using this latter method, the IAI at three levels in the irrigation system of the Gezira scheme was calculated (at the dam headwork for eight seasons, at the off-takes of 9 minor canals for one season and at 9 field outlets supplied from the same minor canal using data for one season). The results were reported and discussed.

For characterizing equity, it was argued that a better picture of the differences in the quality of services provided by the irrigation system to different parts of the scheme could be obtained if equity is characterized in terms of the differences in the adequacy of the water supply to these parts, rather than in terms of the differences in the total depth of water supplied during the season. Equity in terms of adequacy and in terms of the total depth supplied was calculated between the 9 minor canals and the 9 field outlets mentioned previously. The results were reported and discussed.

For characterizing the *water user convenience*, which is a measure of the appropriateness of the water supply schedule to the irrigator, the concept of the fuzzy sets theory was used. Three factors were taken to determine the level of this convenience. These are: *predictability*, *timing of the water supply* and *flow rate*. It was argued that for any of these factors it is difficult to find an objective numerical scale by which the appropriateness of the water supply schedule can be measured. The fuzzy sets mathematics was, therefore, used to estimate a linguistic statement about the overall convenience from linguistic judgements given by a sample of farmers to each of the three factors and their importance. A method was also developed to convert linguistic judgements into numerical scales. A LOTUS micro-computer based program was written to perform the required calculations. The method of characterizing the water user convenience was tested with a sample of four farmers in six separate farms in the Gezira scheme.

In order to evaluate any particular irrigation system(s) using the method developed in this study we need to let the decision-maker in the system(s) identify the set of criteria relevant to his system(s) and spell out his preferences between these criteria. The criteria chosen by the decision-maker will then be combined into one overall performance index using his preferences. This was achieved through the use of the multi-attribute utility theory. The irrigation systems in Sudan were taken as an example case study. Eight Sudanese officials who are involved in some way or another in the decision-making in irrigation were interviewed. The purpose of the interviews was to explicitly derive from those decision-makers the objectives which they would like the irrigation systems in their country to achieve and their trade-offs between these objectives. The overall utility function for each of them was then derived. The results of these interviews and the derived utility functions were reported and their usefulness was discussed.

8.2. Conclusions and Contributions of the Study:

The main conclusions obtained from the study can be divided into two categories: a) conclusions of general nature, and b) conclusions applicable to the particular case study examined.

8.2.1. General Conclusions:

1) A more accurate analysis of the adequacy of the water supply, to the scheme or any area of it, can be achieved by consideration of the characteristics of the soil and crops grown in the area under consideration, rather than just through the comparison of the water supply and the meteorologically imposed crop water demands. Crops characteristics here include their root development patterns, their stress sensitivities and their

relative importance to the system manager.

2) A better picture of the differences in the quality of services provided by the irrigation system to different part of the scheme or different water users can be obtained by characterizing equity in terms of the differences in the water supply adequacy to those users rather than by comparing the total depth of water supplied during the season to each of them.

3) The appropriateness of a water supply schedule to the water users is a complex question involving many considerations. It depends on the specific physical and socio-economic environment in which individual farmers are situated and is, therefore, best determined by the farmers own judgements. The fuzzy sets mathematics offer a useful approach for estimating the level of convenience with which the water supplies are scheduled to the farmers. The usefulness of the approach is in its ability to accommodate personal judgements and preferences expressed in vague linguistic expressions and to aggregate the opinions of a number of people into one statement about the overall appropriateness of the water supply schedule. This overall judgement can be obtained in the form of a linguistic statement or can be converted into a numerical scale (which we call here *farmer utility*).

4) The use of the fuzzy set theory in modelling any practical problem involves assigning support functions to represent linguistic expressions. Different people may assign different support functions to represent the same linguistic expression. In this study it was shown that the final expression describing the overall convenience is not sensitive to small variations in the choices of these support functions. The value of the farmer convenience, however, is more sensitive to these variations.

5) An adequate evaluation of the irrigation systems performance requires the use of a set of criteria each characterizing different aspect of the performance and also requires the evaluation of the trade-offs between these criteria. However the set of criteria to be used in evaluating any specific system(s) and the trade-offs between them are system-specific. They are dictated by the physical, economic, social, political and environmental conditions in which the system(s) is operating. The purpose of the evaluation may also guide the choice of the type and set of criteria to be used.

6) In order to fully assess the performance with respect to multiple criteria it is sometimes useful to combine them into a single overall performance index. Such an index is useful, for example, for comparing the performance of different systems or of the same system overtime. The multi-attribute utility theory provides a step-by-step method for deriving such an index in the form of the utility function of the decision-maker. This utility function measures the overall satisfaction to the decision-maker of the system performance with respect to all criteria. However, in combining the performance with respect to all criteria into a single index, some information must necessarily be masked. Sometimes the performance with respect to individual criteria is also required.

7) Irrigation management policy should be explicitly presented in a form of objectives and trade-offs between these objectives. If this is done then individuals involved in the implementation of this policy can have clear targets against which their performance is going to be judged and all beneficiaries of the system(s) can campaign in order to have their opinions taken into consideration.

8) Data collection in irrigation schemes is a demanding task consuming an

important part of the management staff time. Considerable part of these data may not be used or may not even be usable because of its poor quality. The fact that the data collected is not being used may also affect the level of care taken by those who collect it to improve its quality. For these reasons the items of data to be collected and the location and frequency of the readings should be guided by the intended use of the data. Data should not be collected for the sake of collecting it.

8.2.2. Conclusions Related to the Case Study:

1) In Sudan large quantities of data related to the irrigation schemes performance are routinely collected. The quality and reliability of these data vary considerably from one scheme to the other and also depend on the organization collecting the data. For the analysis proposed in this study, the only item of data which may not be routinely collected or if found it may be of low quality is the data on water discharges. Particularly at lower levels of the irrigation system.

2) Analysis of the water supply from the dam headwork to the whole Gezira scheme for the eight seasons (1980/81 to 1987/88) and the 9 minor canals for one season (1987/88) was found to be highly adequate. The average IAI's were 96% and 95% for the two levels respectively. However, the level of adequacy at the field outlet level was found to be far lower. The close values of adequacies at the dam headwork and the minor canals' off-takes confirms the assumption generally made in the Gezira scheme about the absence of any transmission losses other than direct evaporation from the canal network surface.

3) At the three levels of the system (i.e. the dam headwork, the minor canals' off-takes and the field outlets) a positive correlation was found to exist between the percentage of water losses and the level of adequacy achieved (i.e. a negative correlation between adequacy and efficiency). However, for achieving the same level of adequacy the percentage water losses increases as we go down the system levels (fig.5.14).

4) Analysis of equity between the 9 minor canals mentioned above and between the 9 field outlets which are supplied from the same minor indicated that although some farmers may be receiving more water than others, this additional water was not fully reflected in the level of adequacy they were able to achieve. This result suggests that at least part of this additional water was not intentionally taken by the farmers because they needed it, but rather an over supply at the wrong time.

5) The inequity problems was felt much more between field outlet pipes supplied from the same minor than between the minor canals themselves or between the major canals.

6) Although the eight officials interviewed in this study agreed on the objectives which they would like their systems to achieve, considerable variations were found to exist in their preferences between these objectives. Each was affected by his position in the management hierarchy and the pressure exerted on him by his immediate surroundings, i.e. the farmers, the boss, the financing circles or public opinion. Similar variations were also detected in the priorities given by them to the irrigation of different crops grown.

8.2.3. Contributions of the Study:

The main contributions of the study are the following:

1) Development of a conceptual frame work for identifying the performance evaluation criteria for any irrigation system.
2) Development and testing of a methodology for measuring the adequacy of the water supply. The methodology takes into consideration the characteristics of the water supply, climate, soil and crops and is applicable to multi-crop irrigation systems.
3) Development and testing of a methodology for measuring the convenience of the water supply schedule to the water users through the use of the concept of fuzzy set theory.
4) Evaluation of the trade-offs between the irrigation performance criteria through the use of the multi-attribute utility theory.

8.3. Appraisal of the Study:

The objective of the study was reasonably achieved. The evaluation methodology developed can be applicable in a wide variety of irrigation systems and can be useful for a number of purposes including:

1) Seasonal or annual evaluation of irrigation systems. For example, for the purpose of preparing annual reports similar to what is done in almost any company.
2) Evaluation of improvements in system performance brought about by an investment in rehabilitation.
3) Evaluation of different design approaches and management policies.

This is important for the purpose of transferring successful experiences between systems.

For the last two purposes the evaluation may take place as a research undertaking. As such it may deserve a specialized data collection program. Seasonal or annual evaluation, however, must rely on the data routinely collected, but must have some implication on that data. On one hand, the fact that some use will be made of the data is expected to be an incentive for those who collect it to improve its quality. On the other hand, the extent of the coverage of the evaluation will guide the data to be collected.

Some points on the limitation of the study must be noted:

1) At the outset of this study the intention was to develop an evaluation methodology which is suitable for seasonal evaluation and which relies on the type of data routinely collected. This was achieved with *adequacy* and *equity* (provided that reliable water discharge records exist). As concerning the *water user convenience*, however, this is not the case. Firstly, its characterization requires special data collection program. Secondly, it may not need to be measured on seasonal basis. It is a useful criterion for comparing different designs and operation policies. As such it may need to be measured only within long time intervals. Say once every five or ten years or when some changes in the management policy have taken place.

2) Distinction should be made between the performance of the irrigation system and the performance of its manager. The methodology developed in this study was designed to measure the quality of services provided to the water users. This is the outcome of the efforts of the manager given the physical

and management facilities in the system. Such facilities differ widely between systems. For example, some systems have a storage dam which provides the manager with much better control over the quantity and timing of the water supply as compared with run-of-the-river systems. Some systems are subject to severe budgetary constraints, others are not. We cannot expect the same level of performance from all these systems.

Sometimes the performance of the manager (or the managing body) alone may need to be measured. For example, for the purpose of incentives or promotions. The methodology developed in this study may not be suitable for such purpose. With this methodology, comparison of the performance of different managers can only be possible within similar systems or within the same system over time.

3) In deriving the overall performance index, consideration was confined to irrigation systems in which the uncertainties associated with the river flows and rainfall are small. This limits the scope of the study because in many irrigation systems these uncertainties are large and have their impact on the management decisions. Formal consideration of these uncertainties within the framework of the MAUT is possible but involves some changes in the approach to be followed: 1) additional independence conditions need to be tested before deciding on the functional form of the overall utility function, and 2) a certain method for deriving the individual utility function has to be used. Each of these requires the decision-maker to state his preference between lotteries. In a preliminary experiment in this study this was tried with one respondent. He was found to have more difficulties stating his preference between lotteries than between values known for certain

8.4. Recommendations for Other Studies:

Several issues have arisen during the course of this study and were left unresolved, mainly due to time limitations. The following are those which we believe deserve separate studies:

1) In this study, in dealing with the durability criterion, distinction was made between long-term and short-term durability. By long-term durability it is referred to the environmental deterioration of the irrigation schemes resulting from specifically the build up of the problems of salinity, alkalinity and water logging. Characterization of long-term durability was not considered in this study. The main reason for that was the fact that the impact of these factors is generally slow, it may take several years before it can be realized, and the main emphasis in this study was on methodologies for the purpose of annual or seasonal evaluation.

In our view, methodologies for assessing the impact of different design approaches and management policies on long-term durability of irrigation schemes are urgently needed. Studies in the development of such methodologies should, therefore, be given high priority. Such studies may involve the development of computer simulation models which can predict the water and salt movements in the soil and the water-table levels for different design and management alternatives. Makin and Goldsmith (1987) have developed such a model for an irrigation scheme in India.

2) The multi-attribute utility theory was designed to be used with a single person decision-maker. In the public sector the decision-making process is complicated and such a single person decision-maker may be difficult to

identify. This applies to irrigation management in which several groups of people are involved and concerned about the performance of the irrigation systems. In this study it was argued that it is the job of the irrigation department (or its equivalent) to consider the interest of all the beneficiaries of the irrigation systems in his policy. The question which was not answered is: how can the irrigation department define his policy? This involves deriving a consensus utility function of irrigation department officials. Some work needs to be done on how to combine the preferences of several people into some social utility function. A combination of the multi-attribute utility theory and the Delphi method was suggested as a candidate for this. A study on deriving the utility function of a group of people is recommended.

3) In this study some sophisticated methods were developed for characterizing each of adequacy and equity. In the interviews with the officials for deriving their utility functions, however, for reasons mentioned elsewhere (Chapter 7, section (7.3)), some simpler proxy attributes were adopted for these two criteria. The question which may arise is: can the overall utility function derived using these proxy attributes be used with values of adequacy and equity calculated using the more sophisticated definitions? In our view this is a valid premise. However, it need to be confirmed.

A study is recommended in which some people are to be interviewed with both definitions of the attributes to see if there are any significant differences in the resulting scaling constants and the individual attribute utility functions.

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APPENDIX A

Simulated average soil moisture level graphs for different levels in the Gezira irrigation system, plotted from the soil moisture simulation model output.

Fig.(A.1): Average soil moisture

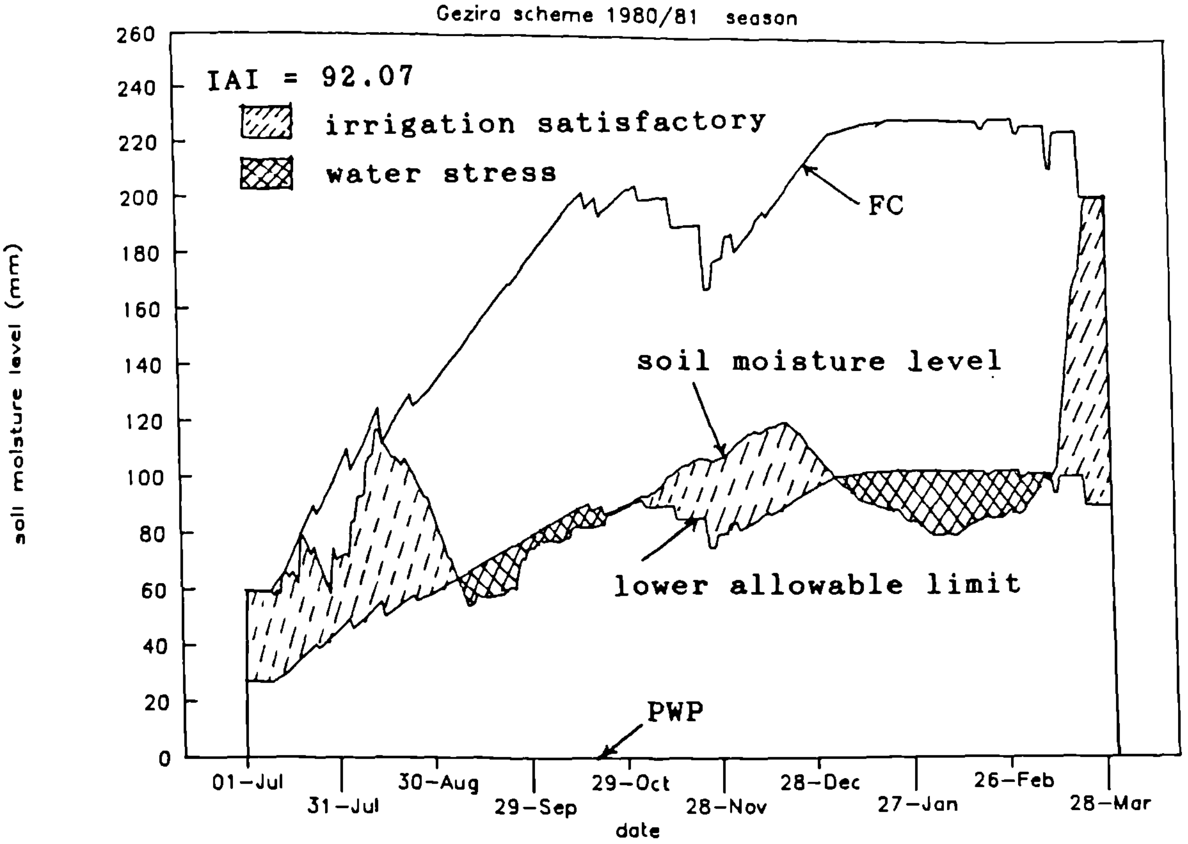

Gezira scheme 1980/81 season

Fig.(A.2): Average soil moisture

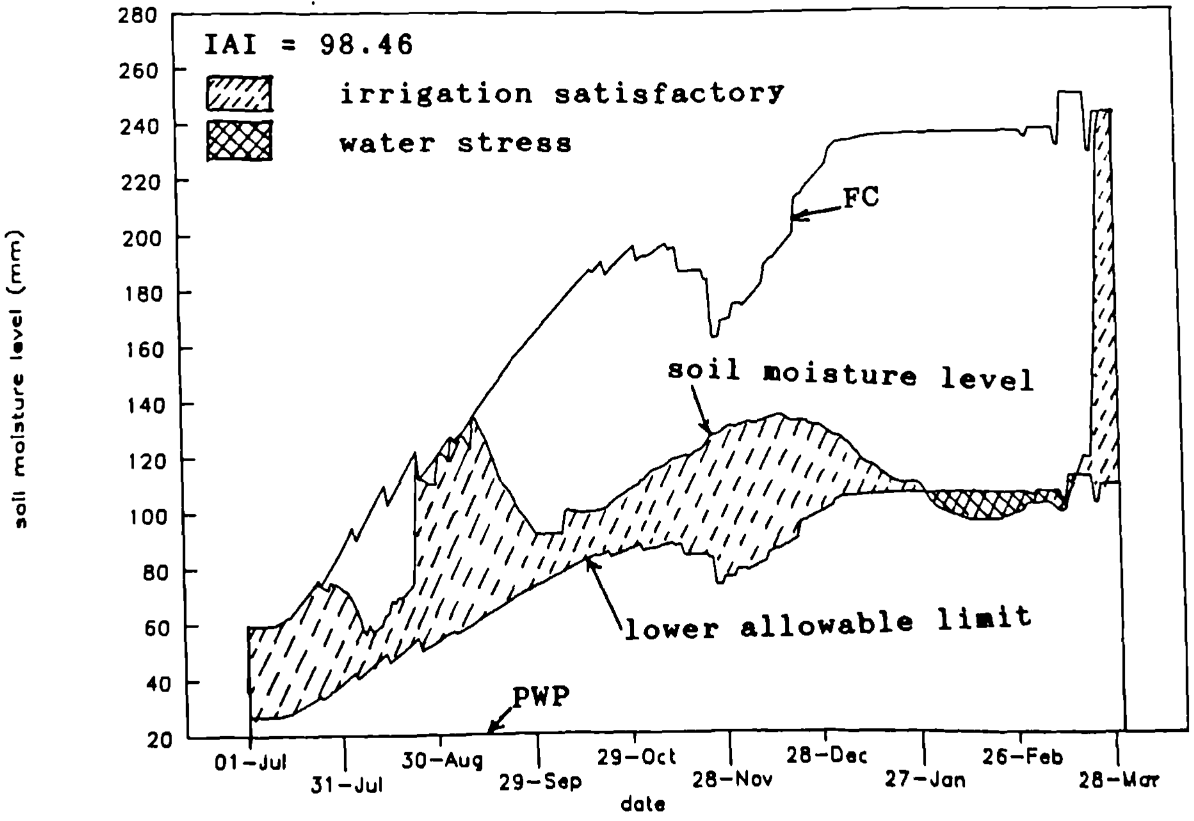

Gezira scheme for the 1981/82 season

Fig.(A.3): Average soil moisture

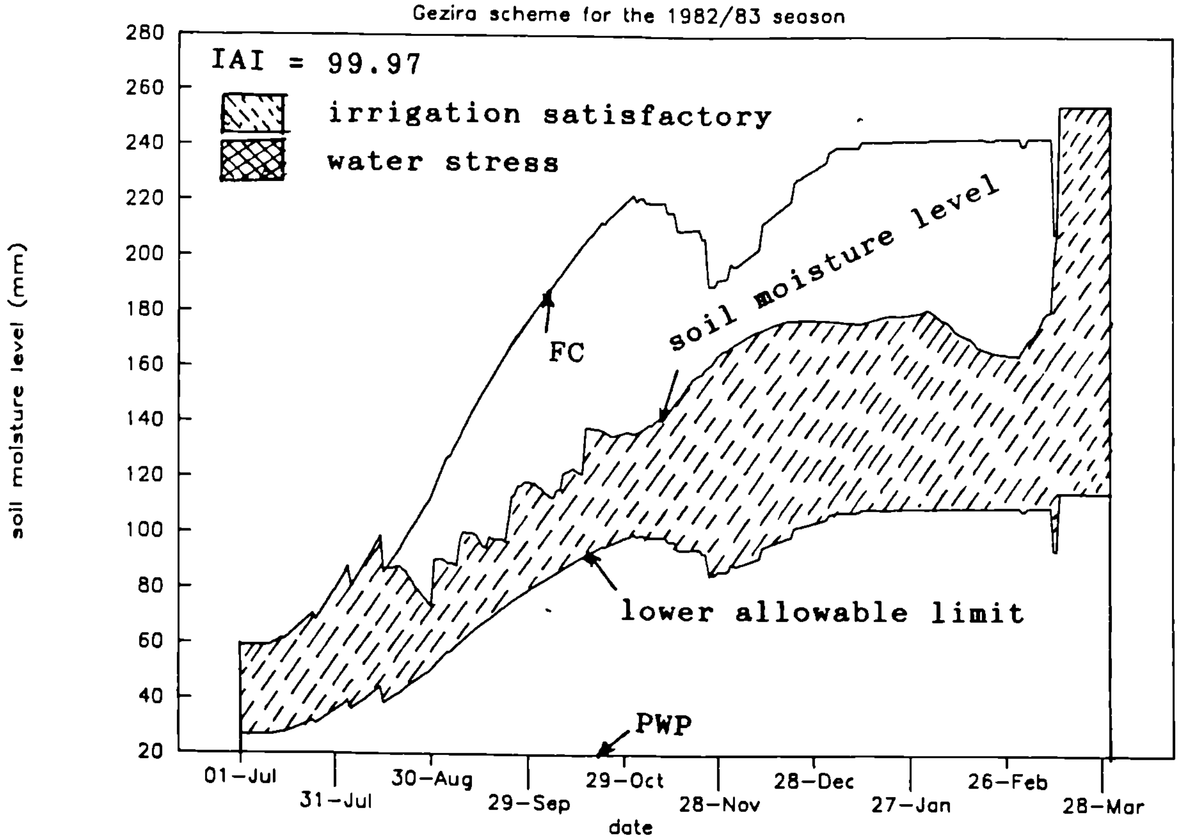


Fig.(A.4): Average soil moisture

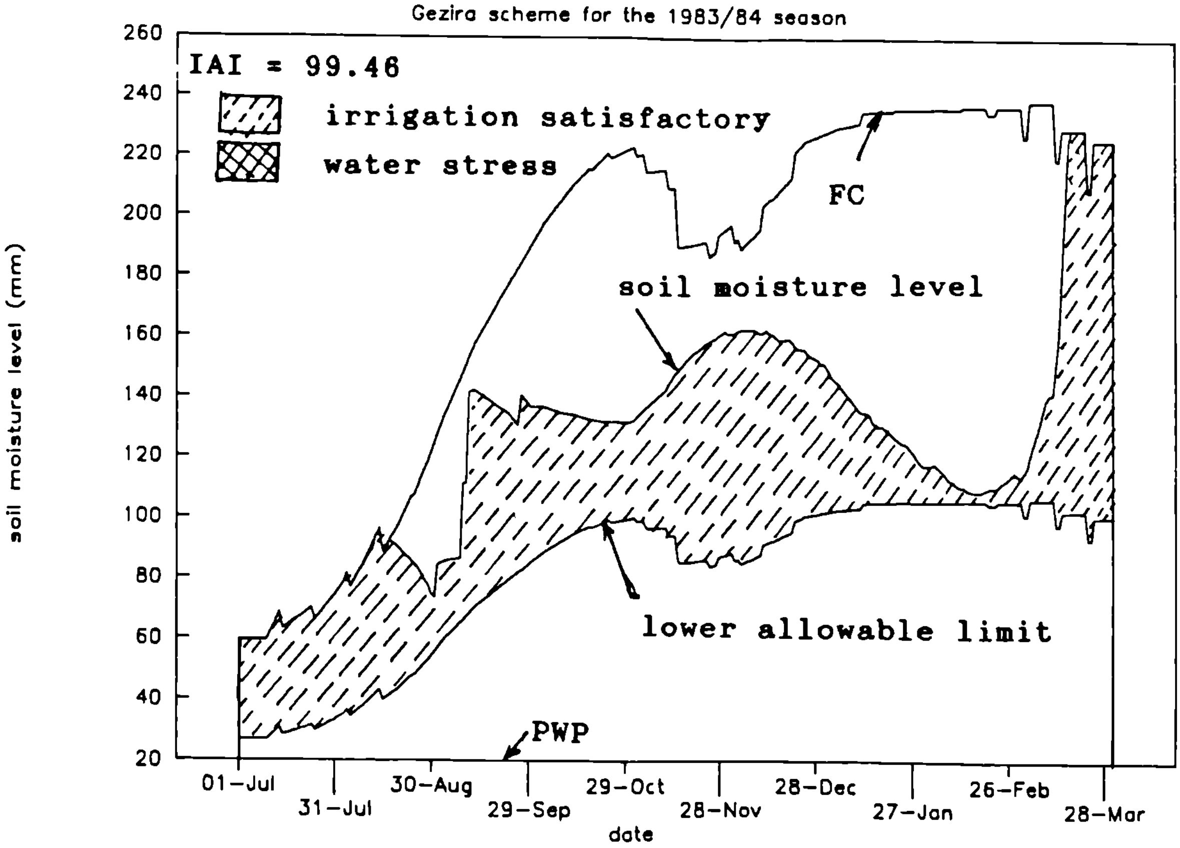


Fig.(A.5): Average soil moisture

Gezira scheme for the 1984/85 season

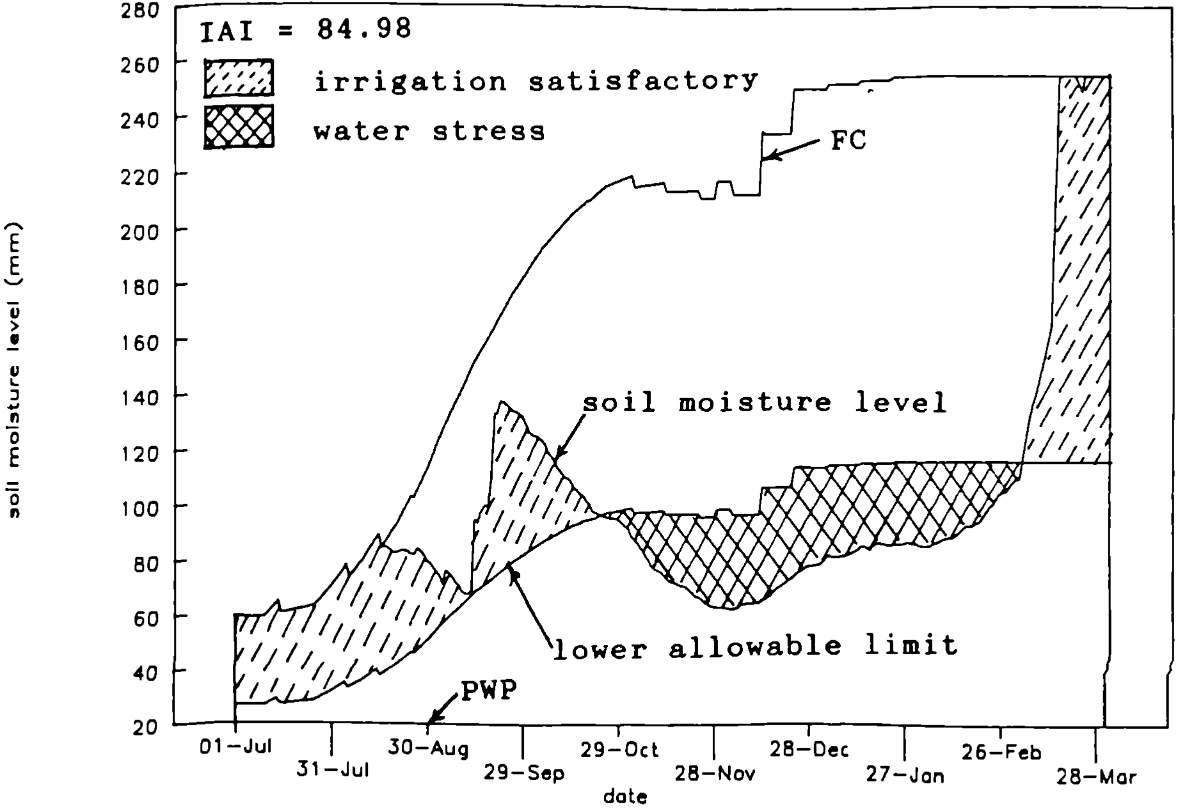


Fig.(A.6): Average soil moisture

Gezira scheme for the 1985/86 season

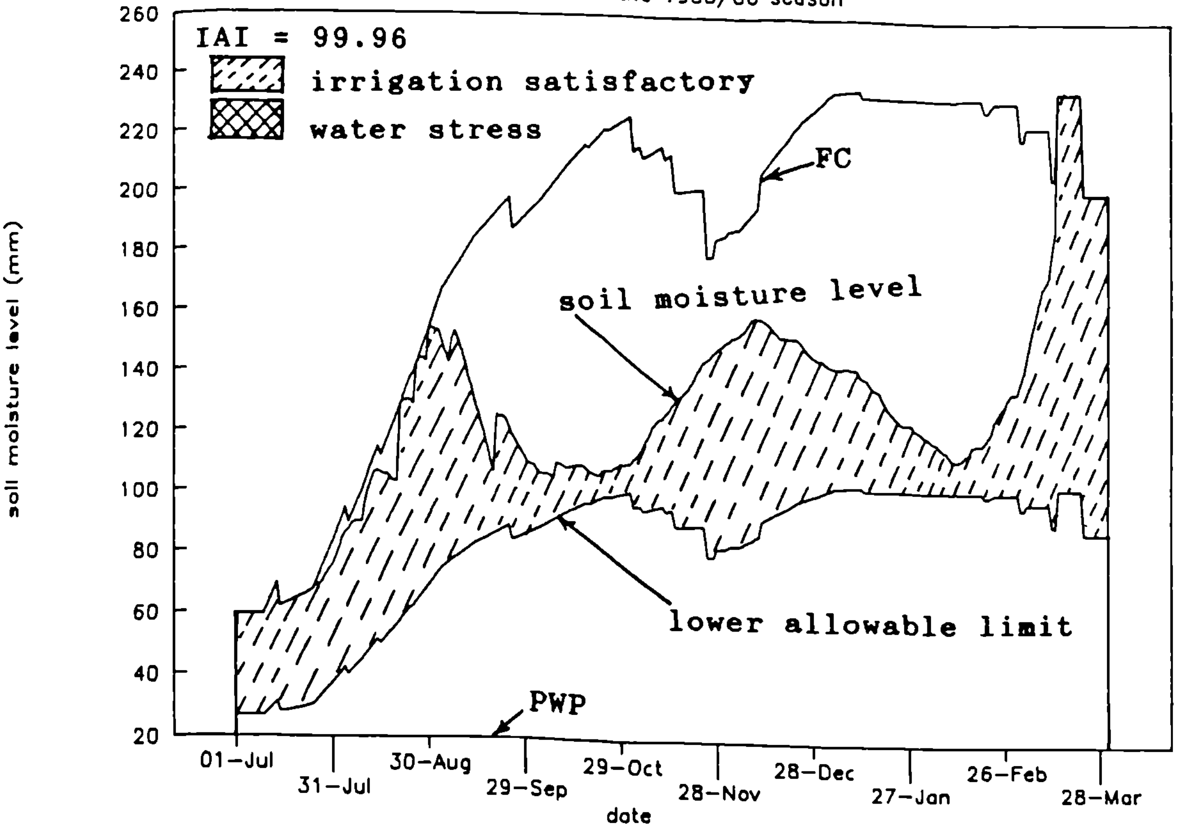


Fig.(A.7): Average soil moisture

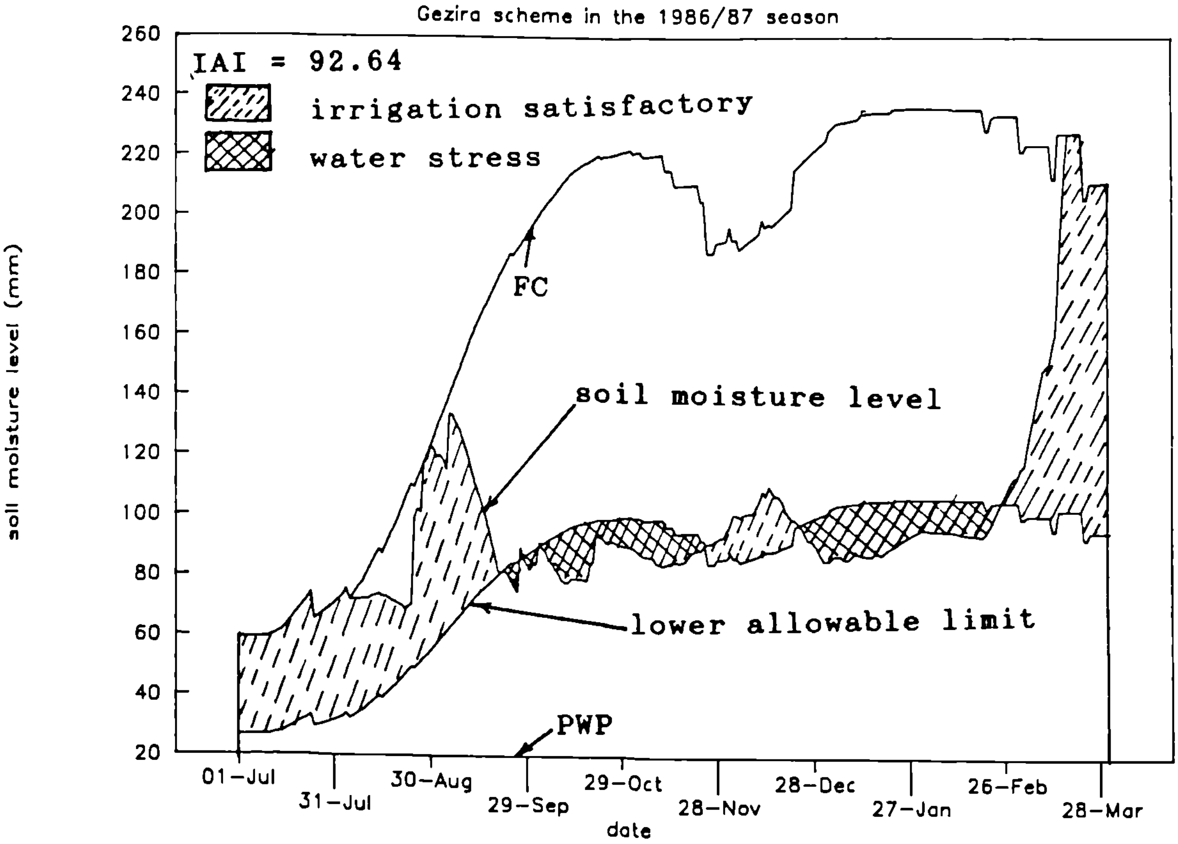


Fig.(A.8): Average soil moisture

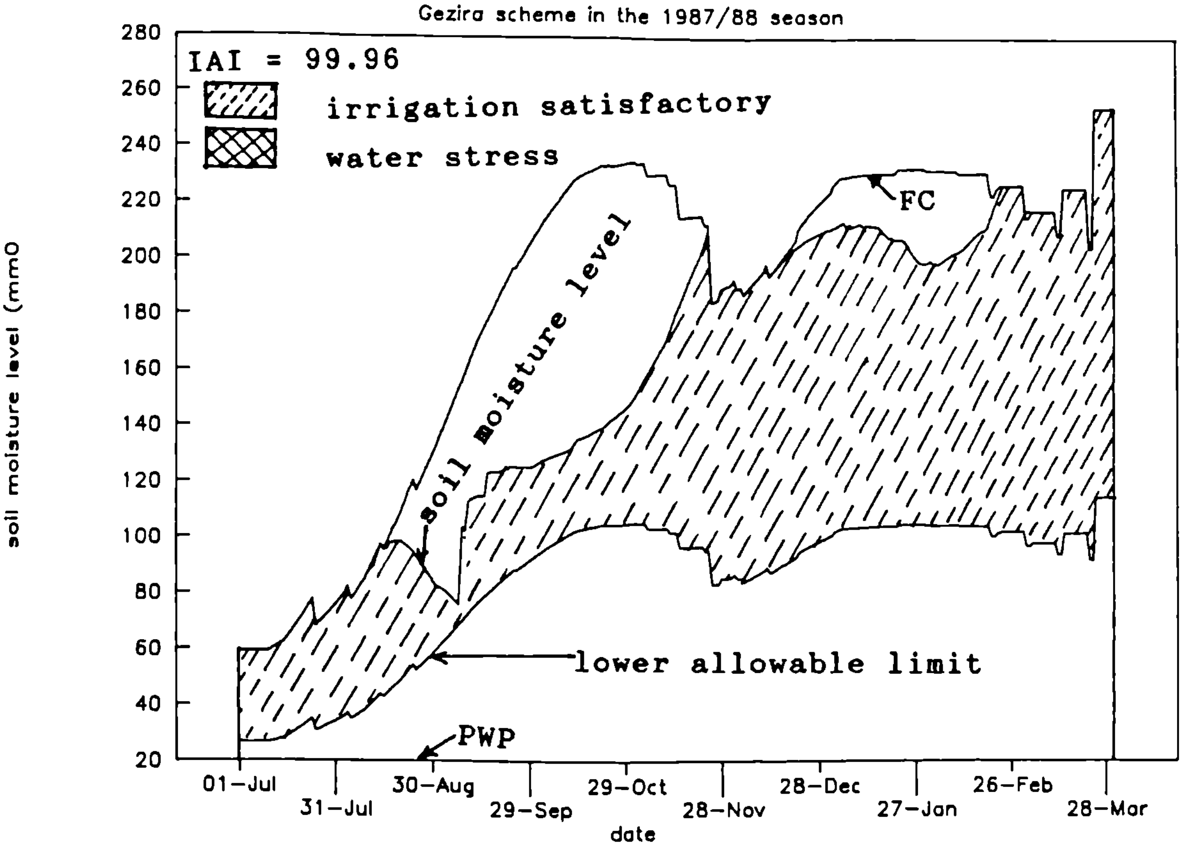


Fig.(A.9): Average soil moisture

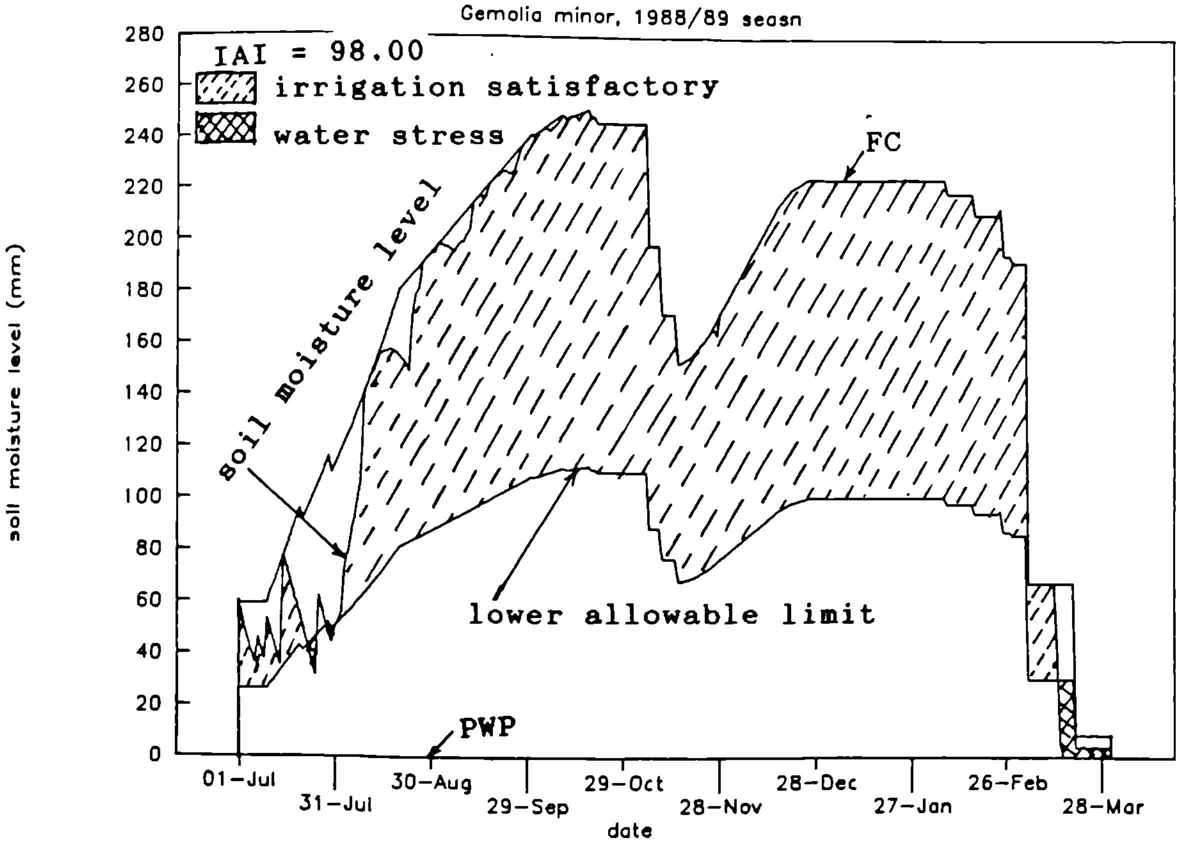


Fig.(A.10): Average soil moisture

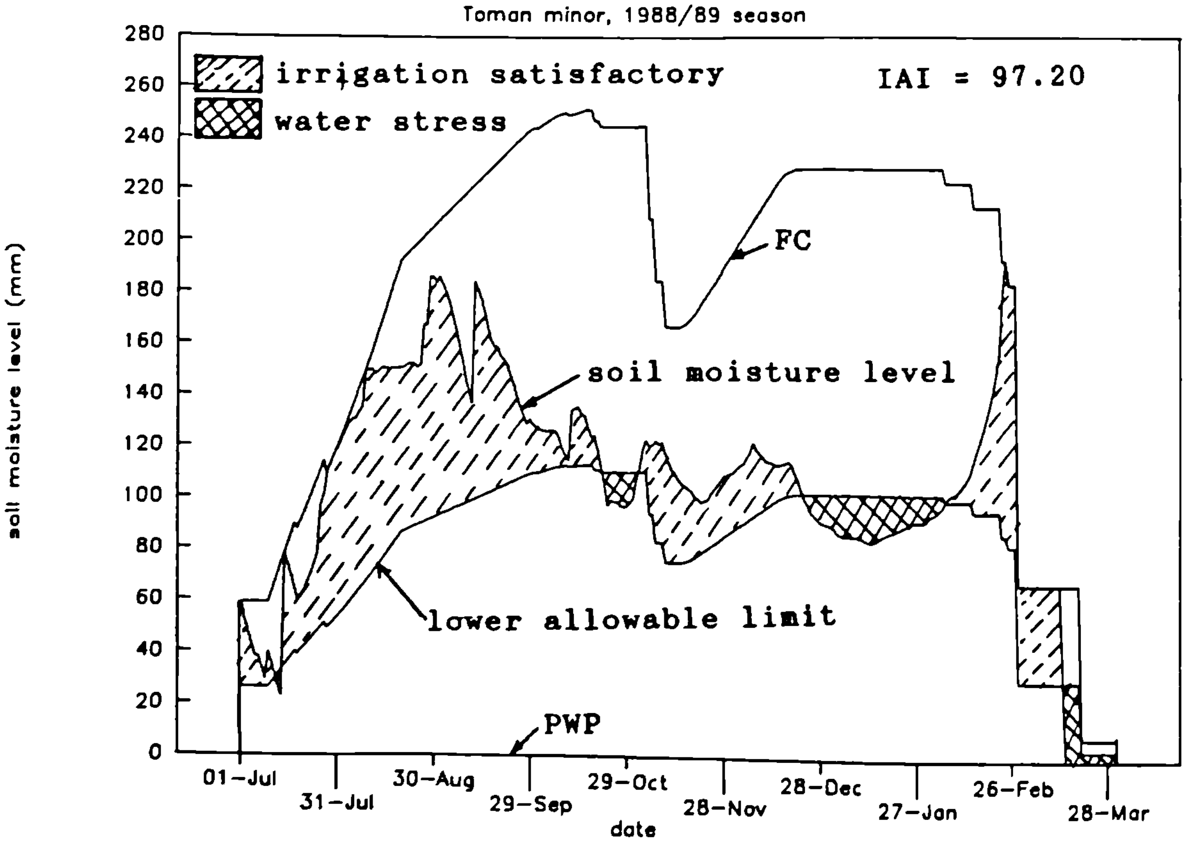
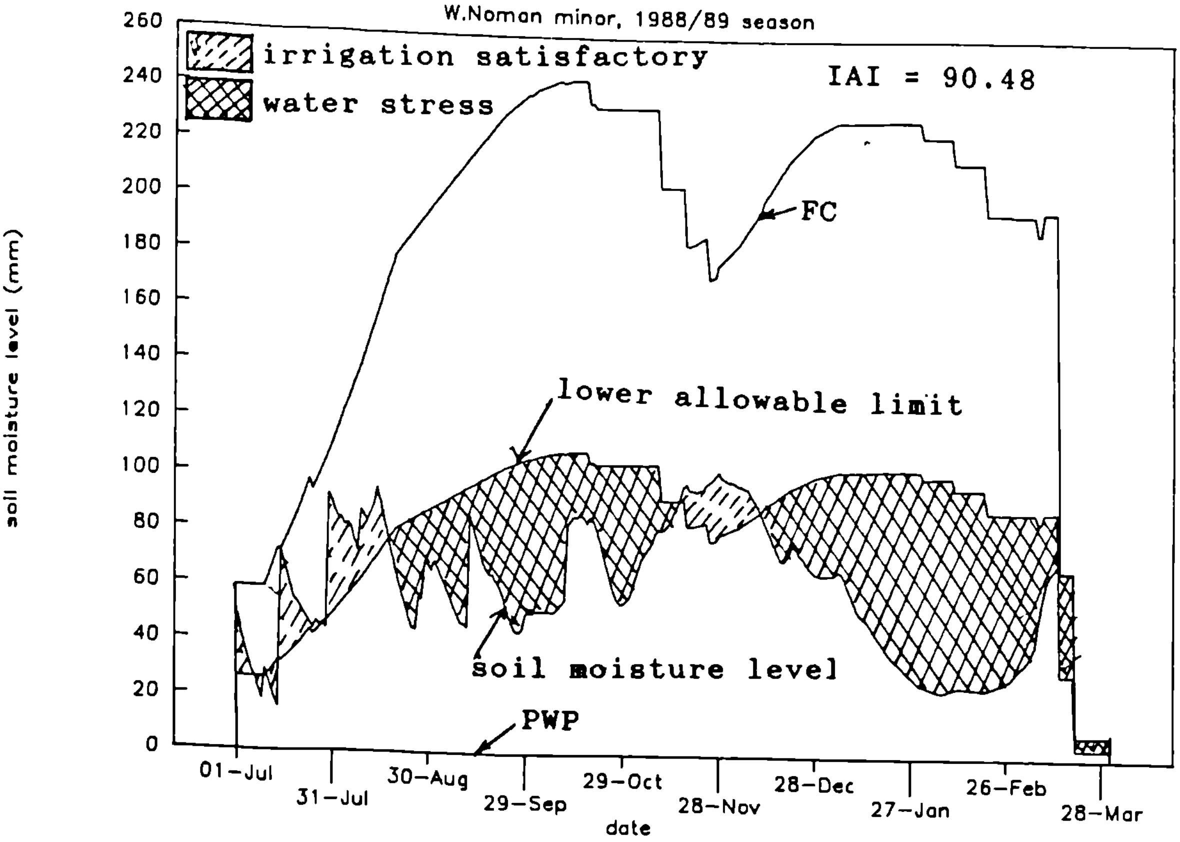
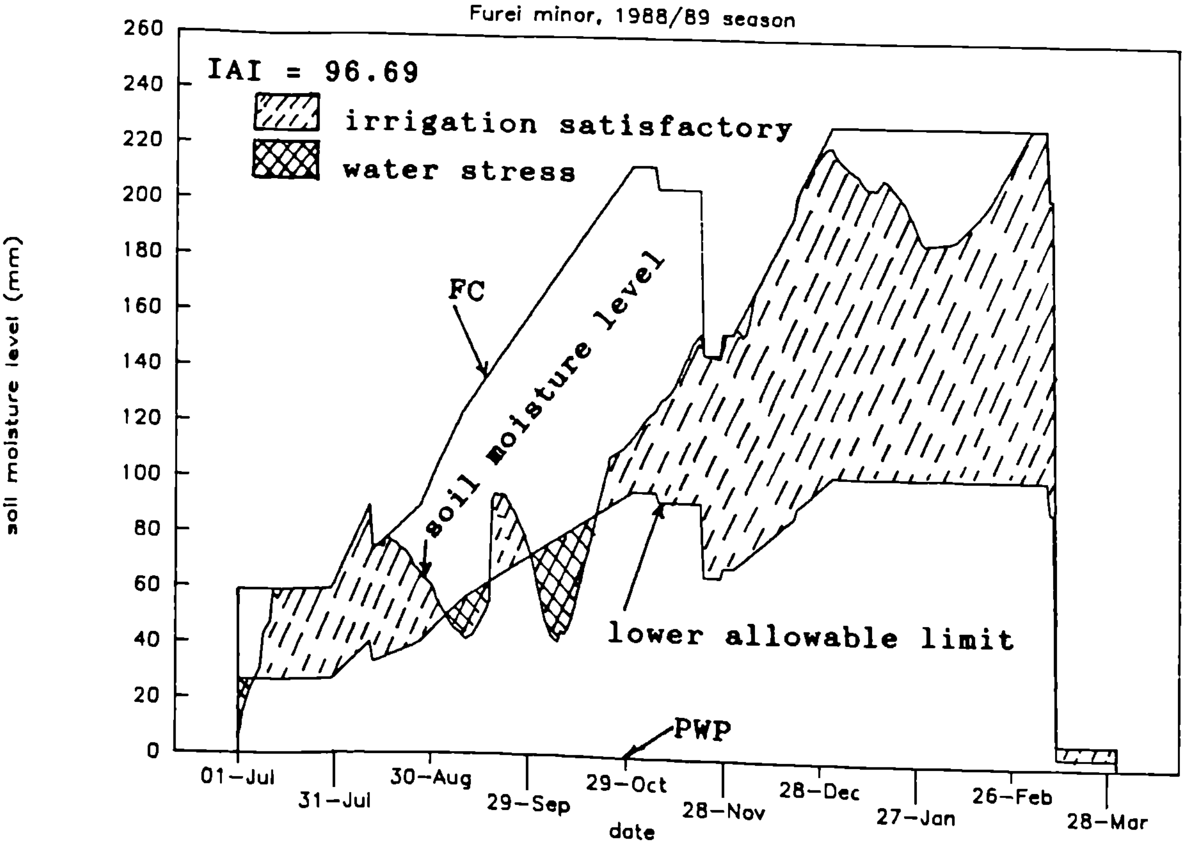


Fig.(A.11): Average soil moisture



W.Noman minor, 1988/89 season

Fig.(A.12): Average soil moisture



Furei minor, 1988/89 season

Fig.(A.13): Average soil moisture

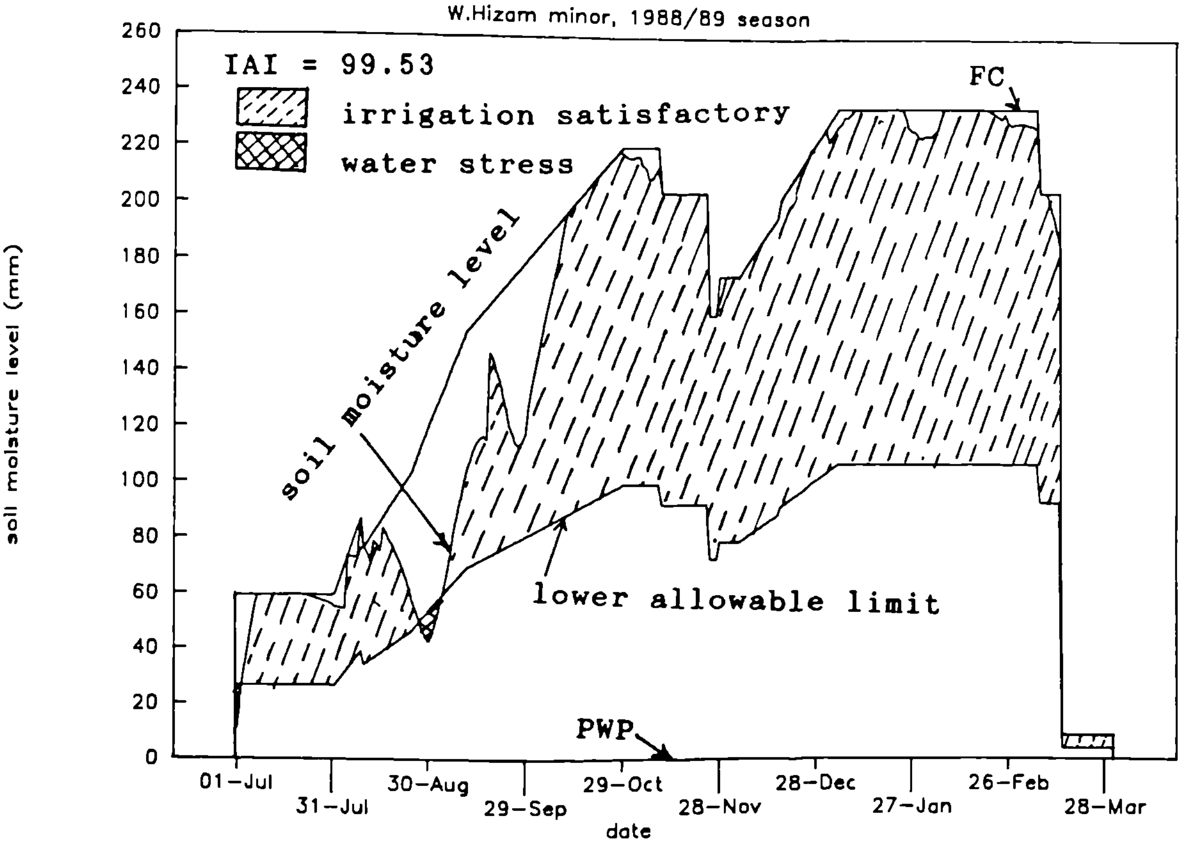

W.Hizam minor, 1988/89 season

Fig.(A.14): Average soil moisture

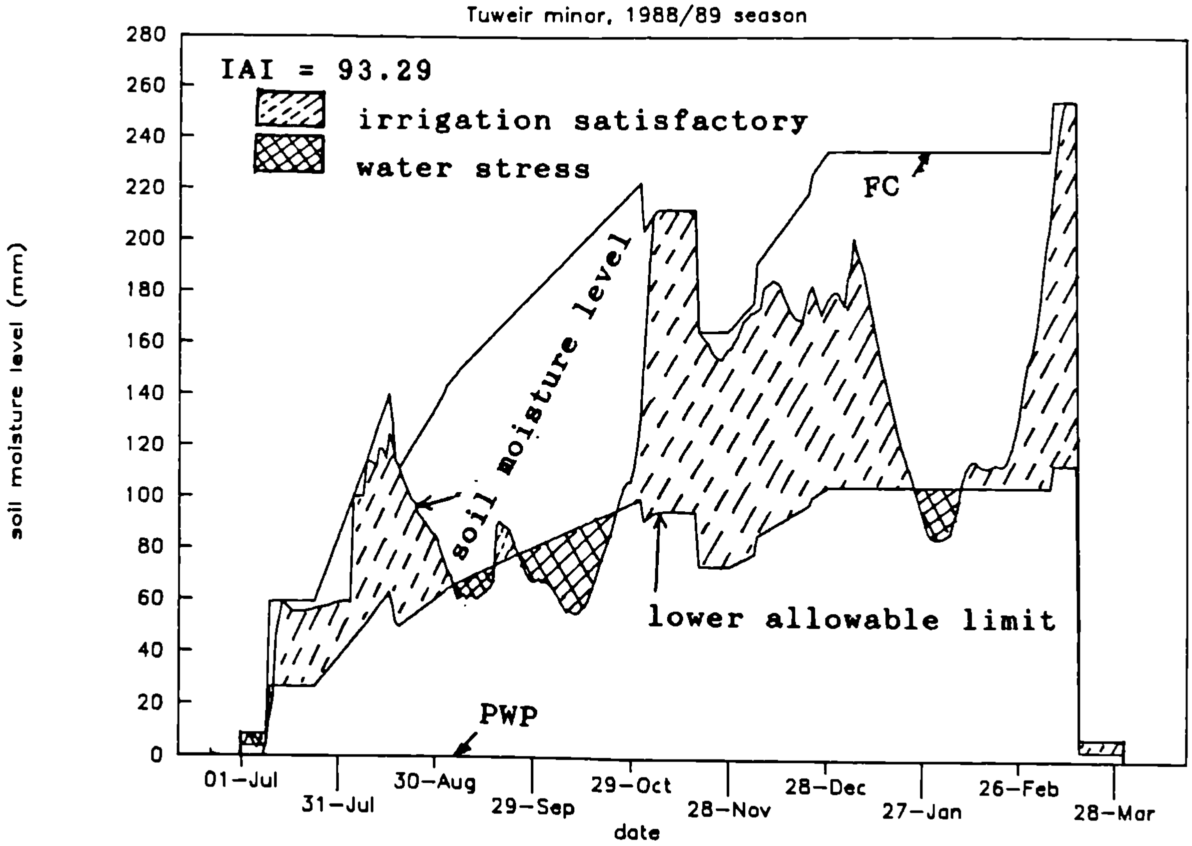

Tuweir minor, 1988/89 season

Fig.(A.15): Average soil moisture

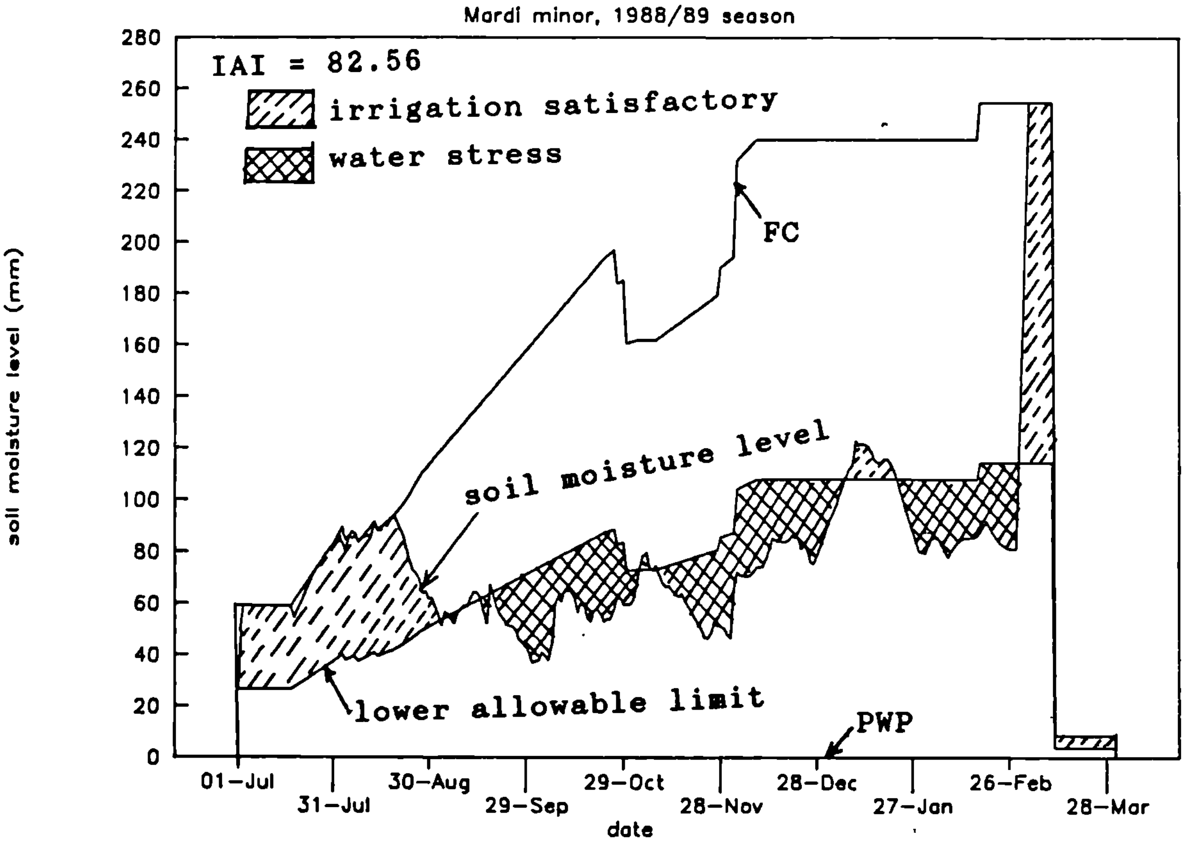


Fig.(A.16): Average soil moisture

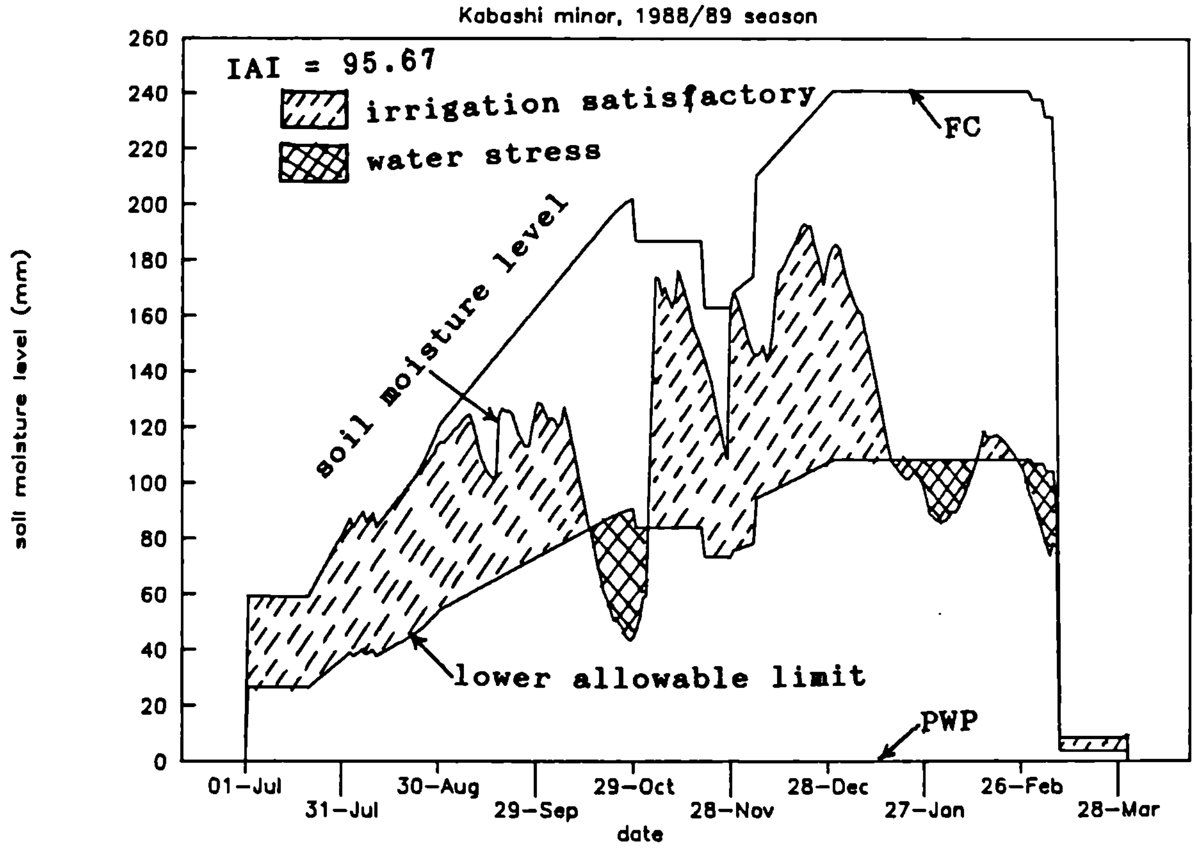


Fig.(A.17): Average soil moisture

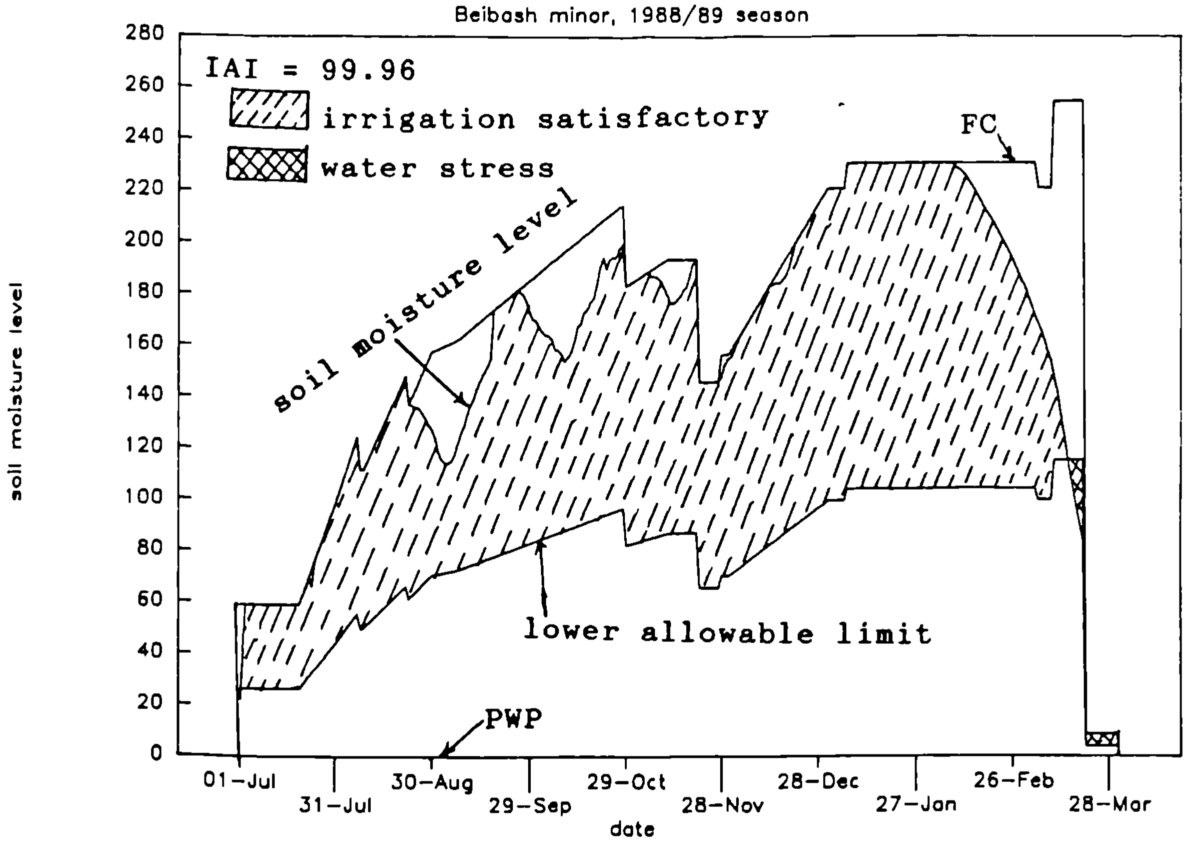


Fig.(A.18): Average soil moisture

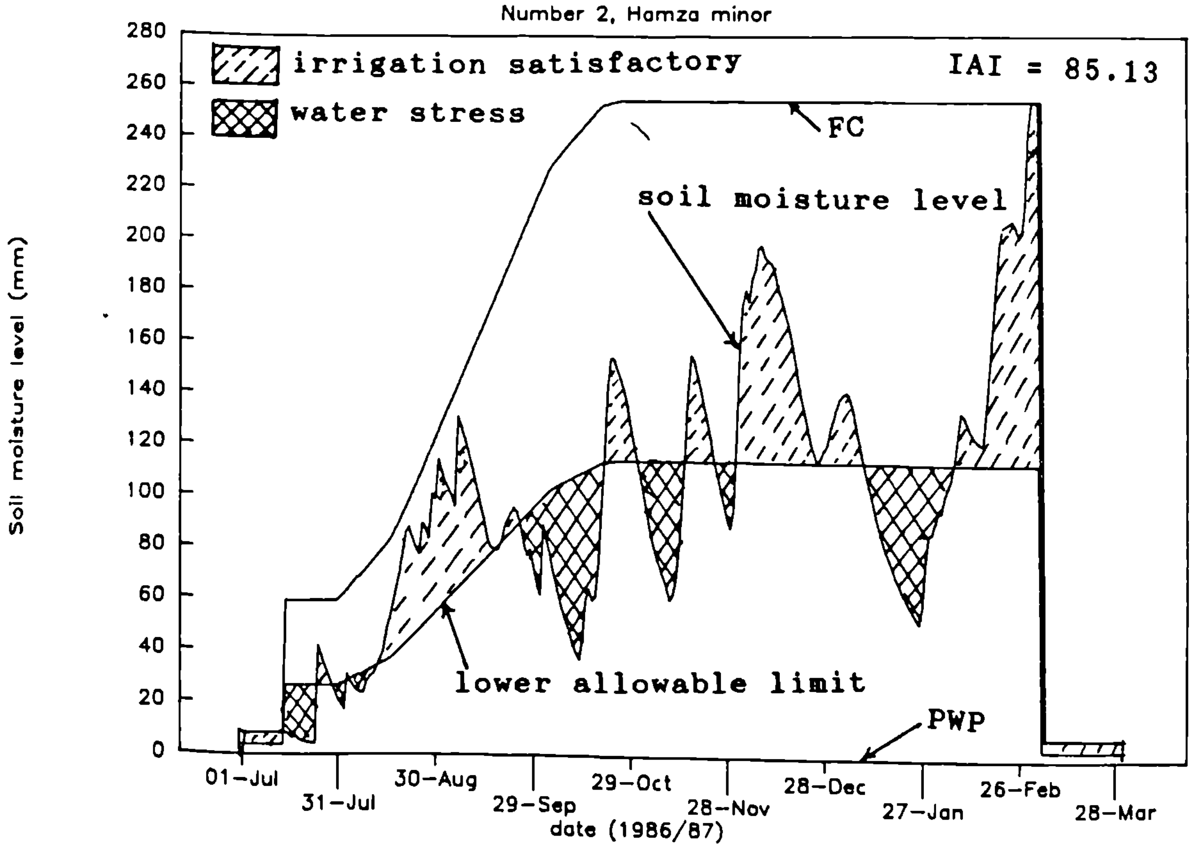


Fig.(A.19): Average soil moisture

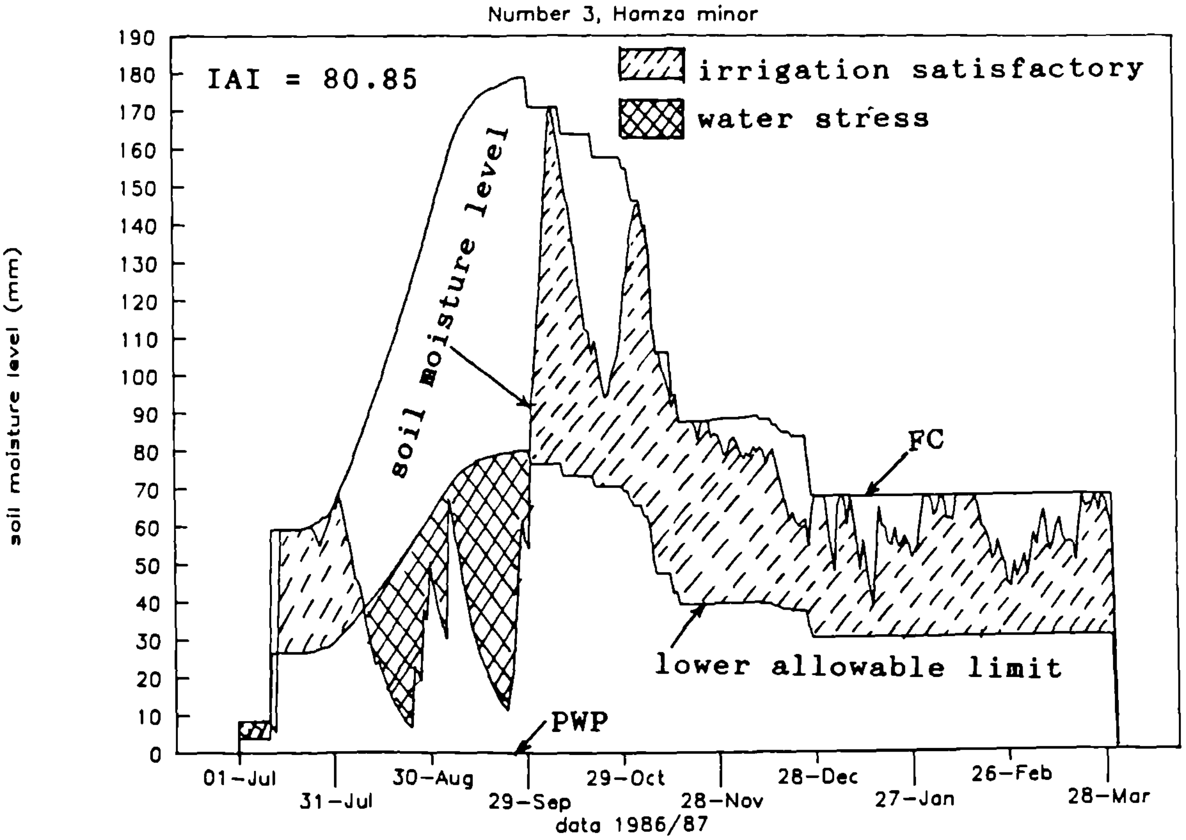


Fig.(A.20): Average soil moisture

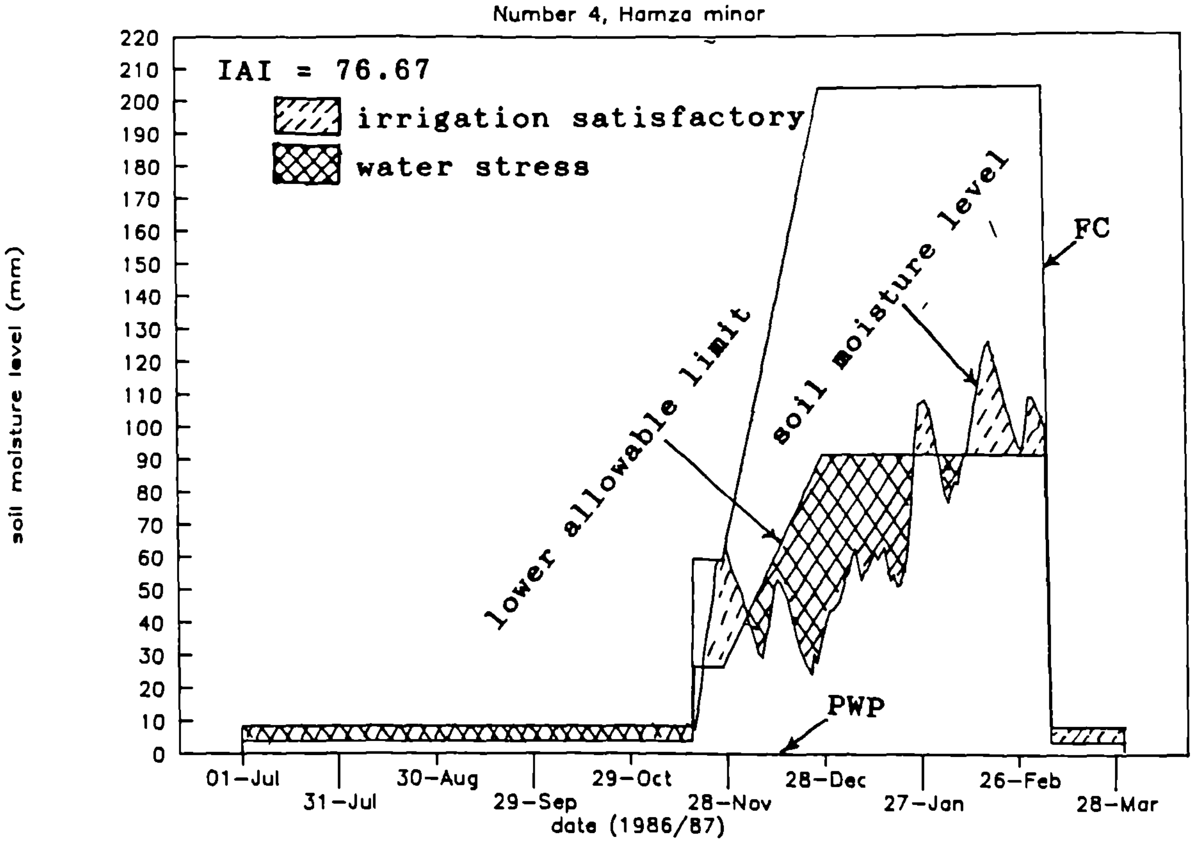


Fig.(A.21): Average soil moisture

Number 15, Hamza minor

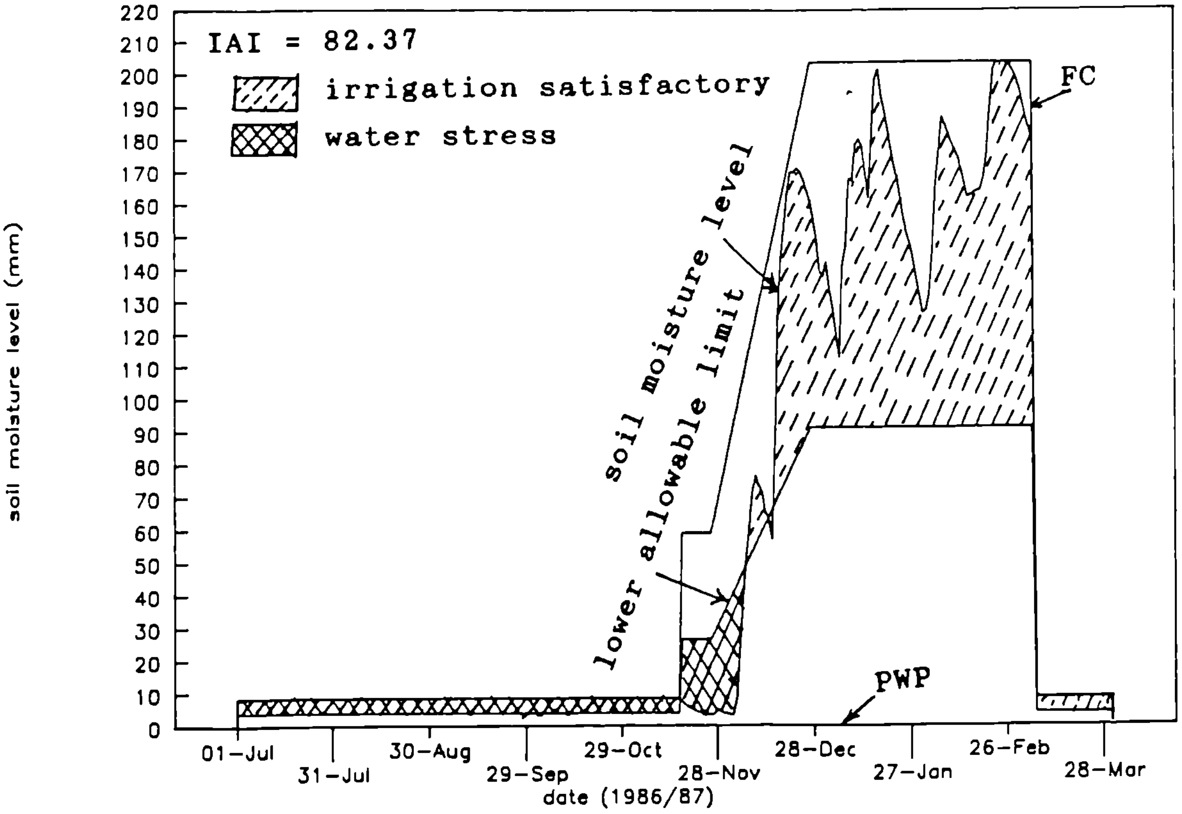


Fig.(A.22): Average soil moisture

Number17, Hamza minor

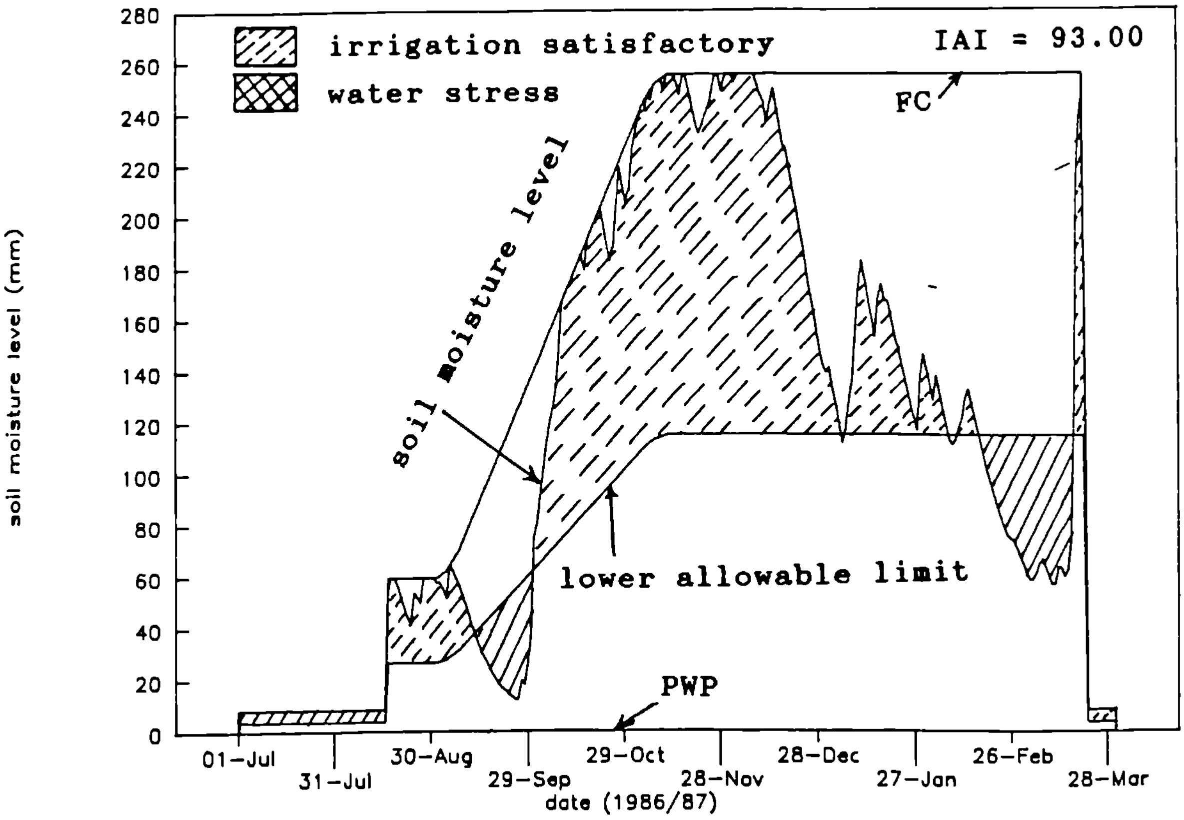


Fig.(A.23): Average soil moisture

Number. 18, Hamza minor

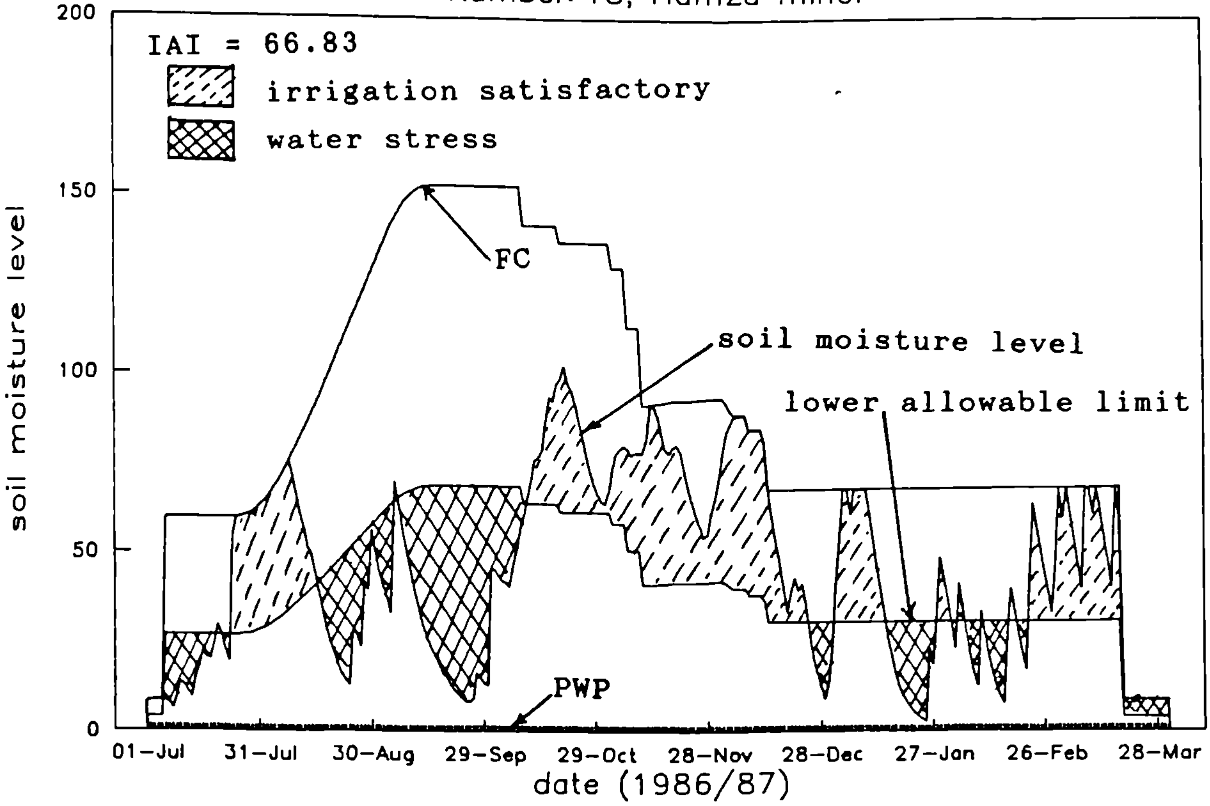


Fig.(A.24): Average soil moisture

Number 23, Hamza minor

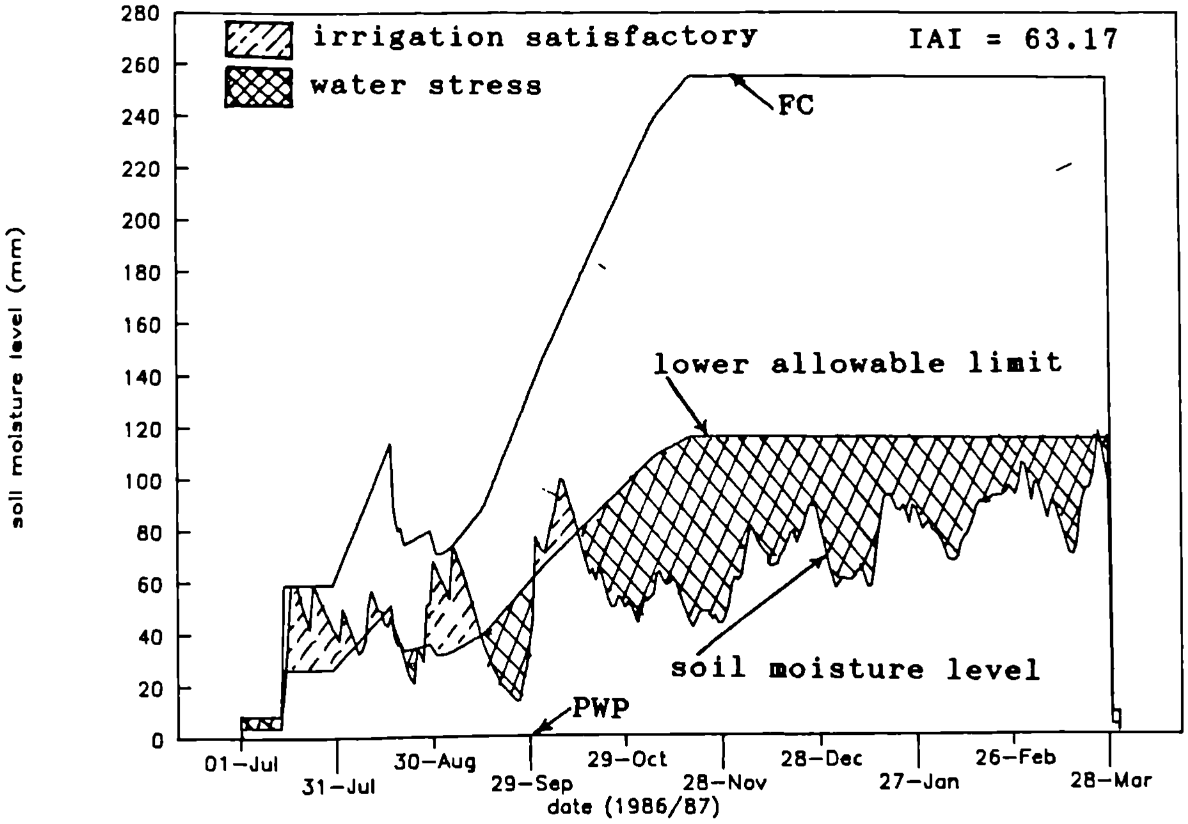


Fig.(A.25): Average soil moisture

Number 24, Hamza minor

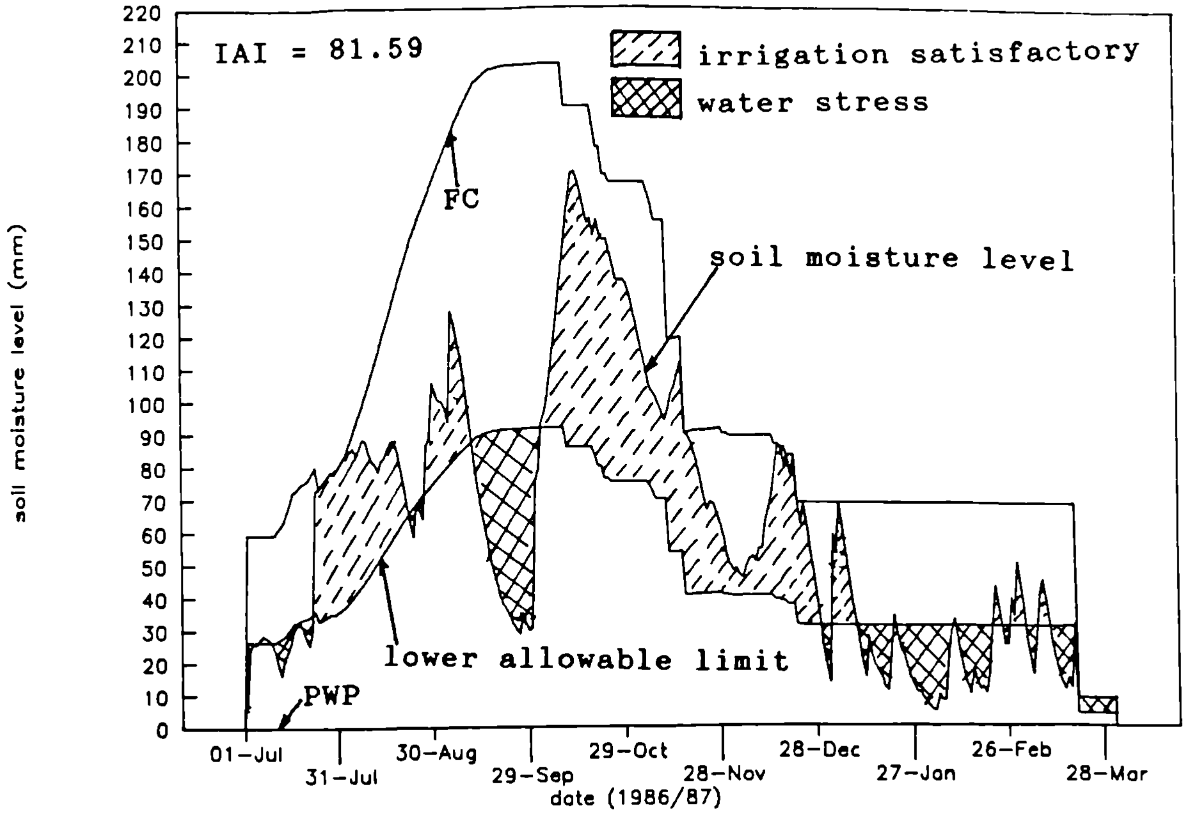
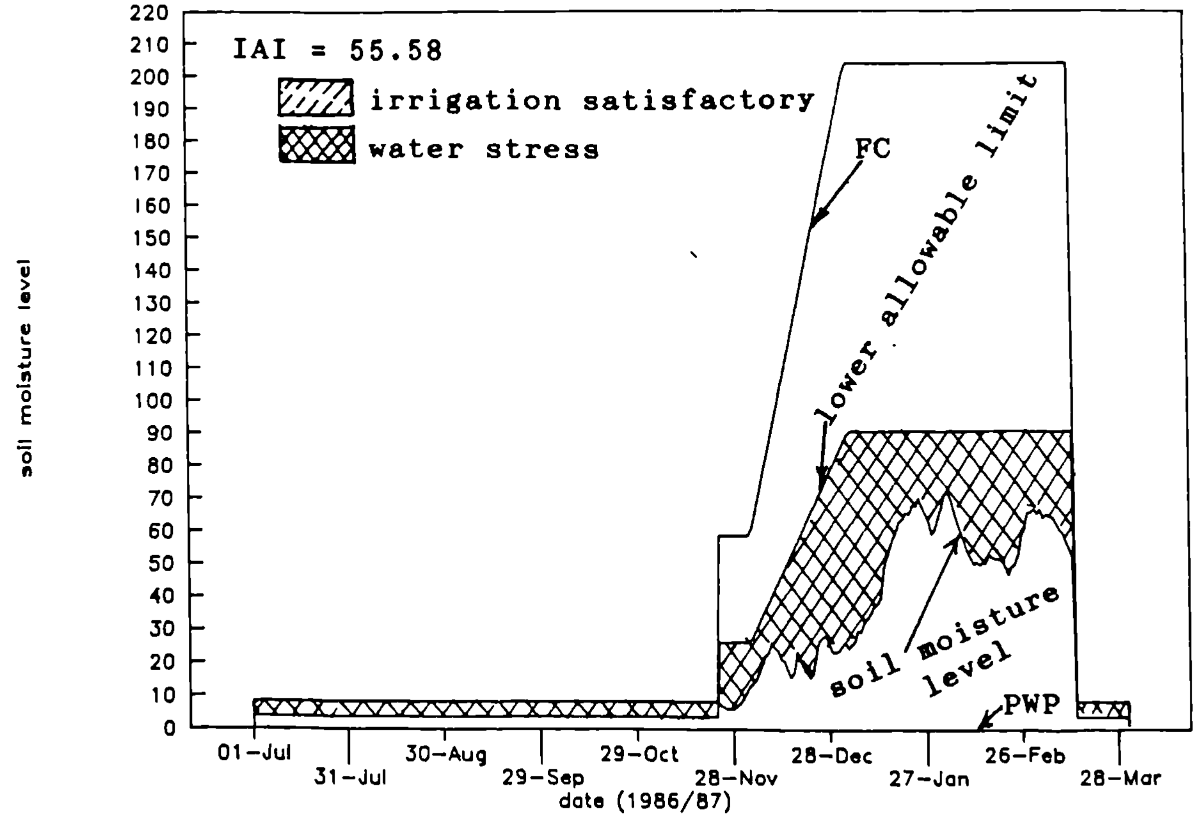


Fig.(A.26): Average soil moisture

Number 26, Hamza minor



APPENDIX B

AN INTERVIEW WITH A DECISION-MAKER

There is no single procedure which should be followed in the interview with a decision-maker in order to derive his utility function. The following is an outline of a dialogue followed with one of the subjects in the interview:

Step (1): Preparation for the Interview:

ANALYST:

You may agree that irrigation systems performance should be measured against a number of criteria. The purpose of this interview is to assess how you, as a decision-maker in the field of irrigation in your country, feel about various values of irrigation systems performance indicators. Our ultimate objective in this interview is to be able to use your judgement to compare the performance of different irrigation systems (or parts of these system) Sudan.

To start with, we should agree on what are the important characteristics of good performance. I am suggesting here some criteria, let us discuss them first and then see whether they are all relevant and sufficient for the purpose. If so, then, we should agree on how to measure each of them.

[*The six criteria: adequacy, water losses, equity, cost, water user convenience and durability were discussed in detail with the subjects. He stated that only the first four criteria are relevant to the Sudanese systems and that they are sufficient for the purpose. The attributes defined in Chapter 7 were agreed on . Each of them was discussed in detail with the subject to make sure that* *he has the right feeling of the practical meanings of different levels of achievements of each of these attributes*]

ANALYST:

Now, we cannot expect an irrigation system in which the water supply is 100% equitable, or with an adequacy of only 10%. It would be better if we limit our discussion to the range of values of the attributes usually attainable in practice in the irrigation schemes in Sudan.

[*We agreed with the subject on the operating ranges given in table (7.1)*]

Step (2): Verification of the Preferential Independence Conditions:

ANALYST:

Now, let us concentrate on only two of the attribute at a time. Let us start with x_1 (adequacy) and x_2 (water losses). Consider this figure:

[*Figure (B.1) was drawn in a piece of paper.*]

ANALYST:

Let us assume that at the end of this season, we are evaluating the performance of an irrigation scheme, say the Gezira scheme, and let us assume that x_3 (equity) and x_4 (cost) were found to be at a relatively low level. Now, if we measure x_1 (adequacy) and x_2 (Water losses), their values can be represented by a point in this figure (fig.(B.1)).

[*At this stage we made sure that the subject knows what is the physical meaning of each point in the figure.*]

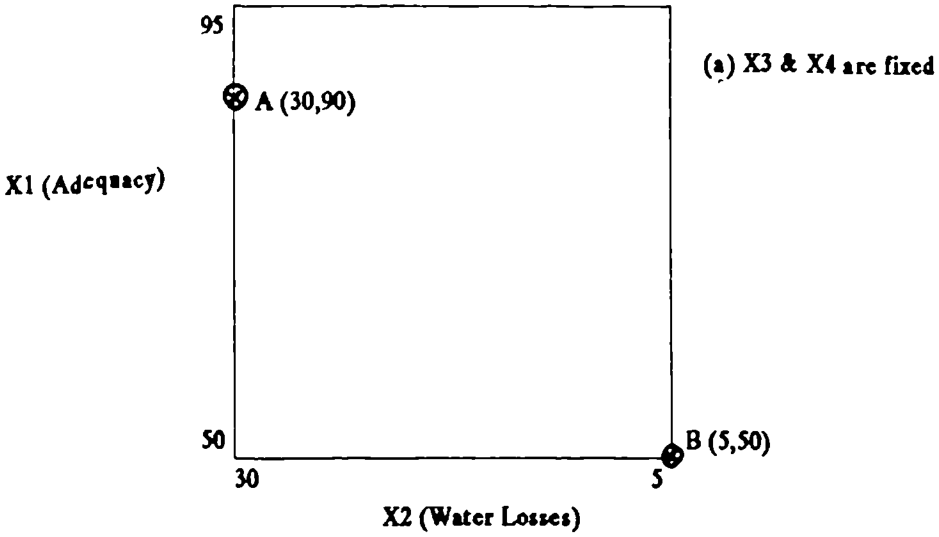


Fig.(B.1): Two equally preferred points.

ANALYST:

Now, you may be able to tell me how do you feel, about different points in this figure. What we want to know is your personal feeling. It is a subjective judgement. What is important here is that you are required to think hard and try to give the answers which reflect your real feeling.

Let us take a situation in which x_1 = 50% and x_2 = 50%, i.e. both are at their worst level. Now, if you can change the level of only one of them to its best level, do you prefer to improve adequacy from 50% to 95% or decrease water losses from 50% to 5% ?.

SUBJECT:

I would prefer to improve the adequacy from 50% to 95%.

ANALYST:

If the adequacy cannot be improved to its best level of 95%. It can only be improved to 75%. Would you still chose to improve it to 75% of prefer to decrease water losses to 5% ?.

SUBJECT:

In this case I would rather prefer to reduce water losses.

ANALYST:

Can you give me a value of adequacy, say θ, such that you are indifferent between changing the level of adequacy from 50% to θ or decreasing water losses from 50% to its best level of 5% ?

SUBJECT:

I would say 90%.

ANALYST:

Now, all this assuming that x_3 (equity) and x_4 (cost) are at relatively low levels. What will happen if their values were at a higher level? Will your choice of the value of θ be affected ?

SUBJECT:

No. I will still chose $\theta = 90\%$.

[*Here we concluded that* x_1 *(adequacy) and* x_2 *(water losses) are preferentially independent of* x_3 *(equity) and* x_4 *(cost). We also identified two points in the* x_1-x_2 *plane which are equally preferred by the subject.*]

Similar Procedure was followed with pairs of attributes (x_2,x_3) and (x_2,x_4).

Step (3): Assessing the Individual Attributes Utility Functions:

ANALYST:

Now, let us concentrate on one attribute at a time. Let us start with adequacy. If we measure the adequacy in any irrigation system (or part of it), this adequacy can be represented as a point in this line.

[*At this stage line figure (B.3) was drawn in a piece of paper.*]

ANALYST:

Let us assume that in one of our irrigation schemes you have two equal areas. Say area A and area B, each supplied from a separate major canals (fig.(B.2). Both majors are silted up so that they cannot convey the full water indent. In area A the major can supply only 50% of the indent. In area B, things are pit better and the major can supply up to 75% of the indent.

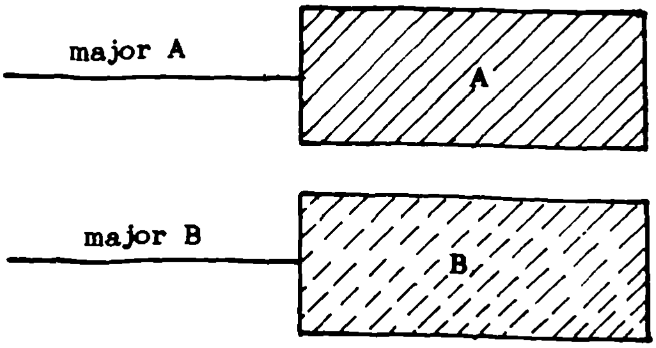


Fig.(B.2): Two equal areas supplied from separate majors.

Now, you have enough resources to desilt only one of these majors. If you invest on major A, its adequacy will be improved from 50% to 75%. If you invest in major B, its adequacy will increase from 75% to 95%. The two investments costs the same. Which major would you go for ?

SUBJECT:

I would go for major A.

ANALYST:

This means that you are more concerned to improve adequacy when it is at a low level?

SUBJECT:

Yes.

ANALYST:

What if by desilting major A the adequacy can be raised from 50% to only 60%, and by the same investment, you can improve the adequacy of major B from 60% to 95%? Which major would you go for?

SUBJECT:

In this case I would go for major B.

ANALYST:

Can you give me a point x^* such that you are indifferent between desilting major A to improve its adequacy from 50% to x^* or desilting major B to raise its adequacy from x^* to 95%?

SUBJECT:

I would say 65% is a reasonable point.

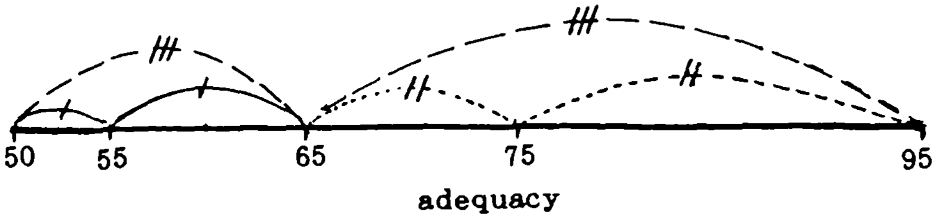


Fig.(B.3): Derivation of the utility function for adequacy: First respondent.

[*At this stage the point 65% was drawn in fig.(B.3).*]

ANALYST:

Now, raising adequacy level from 50% to 65% is equally preferable to you as improving it from 65% to 95%. In utility terms the point 65% is called the mid-value point between 50% and 95% [*Fig.(B.3) was used here*]. What is your mid-value point between 50% and 65% ?.

SUBJECT:

I would say 55%.

ANALYST:

And your mid-value point between 65% and 95% ?.

SUBJECT:

Say 75%.

[From fig.(B.3), the utility curve for adequacy for this subject is drawn fig.((B.4))]

Similar procedure was followed with the other attributes.

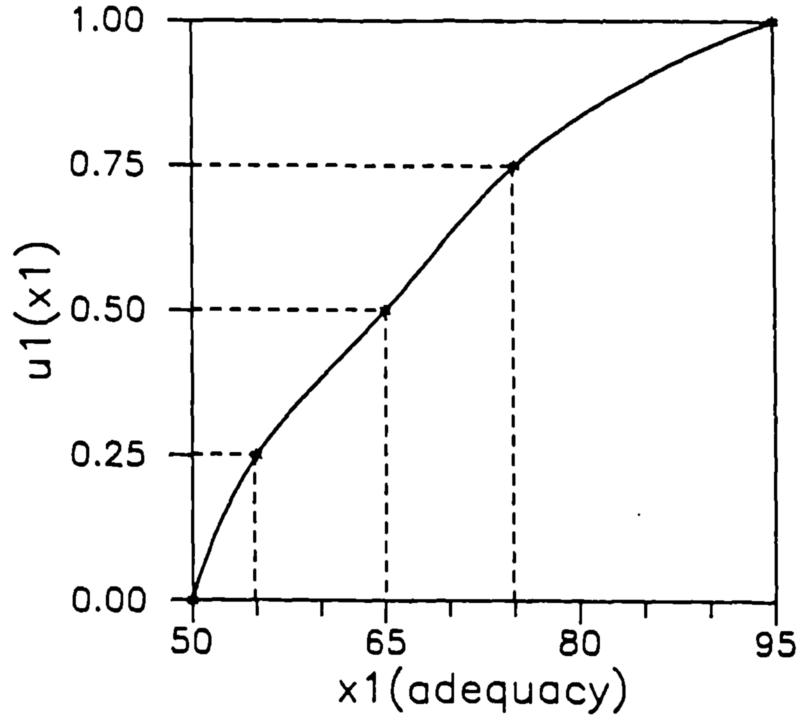


Fig.(B.4): Utility curve of adequacy for the first respondent.

APPENDIX (C.1)

SOIL MOISTURE SIMULATION WORKSHEET

```
\B      /wgrm~
        /reAA1.AA4~
        /reX5.Y280~
        /reL5.O280~
        {goto}R5~+S5*(-1)~
        /c~R6.R280~
        {goto}T5~+U5*(-1)~
        /c~T6.T280~
        {goto}X5~+X5+W5~
        /c~X6.X280~
        {goto}P4~
        {for DATE,31959,32233,1,SUB1}
        {goto}Y5~@if(U5>0,X5/U5,0.05)~
        /c~Y6.Y280~
        {goto}L5~@if(U5>0,S5/(U5*4.2),0)~
        {right}@if(O4>(0.45*170*Y5),L5,N5)~
        {right}@if(O4<0,0,(L5*O4)/(0.45*170*Y5))~
        {right}@if((O4+H5+K5-M5)>(170*Y5),(170*Y5),@if((O4+H5+K5-M5)>0,(O4+H5+K5-M5),0))~
        /cL5.O5~L6.O280~
        {calc}
        /wgra~
        {quit}


SUB1    {down}
        {let AREA,@index(DATA,1,(DATE-31959))}
        {if AREA>0}{branch SUB2}
GGG     {let AREA,@index(DATA,2,(DATE-31959))}
        {if AREA>0}{branch SUB3}
SSS     {let AREA,@index(DATA,3,(DATE-31959))}
        {if AREA>0}{branch SUB4}
WWW     {let AREA,@index(DATA,4,(DATE-31959))}
        {if AREA>0}{branch SUB5}
OOO     {let AREA,@index(DATA,5,(DATE-31959))}
        {if AREA>0}{branch SUB6}
        {return}


SUB2    /reP5.P280~
        {let AREASUM,(AREASUM+AREA)}
        {let CROP,COTTON}
        /cAQ5.AQ214~~
        {calc}
        /rvQ5.Q280~R5.R280~
        {calc}
        /reR5.R280~
        /cAREA~{right 4}.{pgdn 10}{down 9}~
        {calc}
        /reT5.T280~
        /cAV5.AV214~{right 6}~
        {calc}
        /reV5.V280~
        {branch GGG}
```

```
SUB3    /reP5.P280~
        {let AREASUM,(AREASUM+AREA)}
        {let CROP,GROUNDNUT}
        /cAR5.AR154~~
        {calc}
        /rvQ5.Q280~R5.R280~
        {calc}
        /reR5.R280~
        /cAREA~{right 4}.{pgdn 7}{down 9}~
        {calc}
        /reT5.T280~
        /cAW5.AW154~{right 6}~
        {calc}
        /reV5.V280~
        {branch SSS}


SUB4    /reP5.P280~
        {let AREASUM,(AREASUM+AREA)}
        {let CROP,SORGHUM}
        /cAS5.AS114~~
        {calc}
        /rvQ5.Q280~R5.R280~
        {calc}
        /reR5.R280~
        /cAREA~{right 4}.{pgdn 5}{down 9}~
        {calc}
        /reT5.T280~
        /cAX5.AX114~{right 6}~
        {calc}
        /reV5.V280~
        {branch WWW}


SUB5    /reP5.P280~
        {let AREASUM,(AREASUM+AREA)}
        {let CROP,WHEAT}
        /cAT5.AT114~~
        {calc}
        /rvQ5.Q280~R5.R280~
        {calc}
        /reR5.R280~
        /cAREA~{right 4}.{pgdn 5}{down 9}~
        {calc}
        /reT5.T280~
        /cAY5.AY114~{right 6}~
        {calc}
        /reV5.V280~
        {branch OOO}


SUB6    /reP5.P280~
        {let AREASUM,(AREASUM+AREA)}
        {let CROP,ONION}
        /cAU5.AU154~~
        {calc}
        /rvQ5.Q280~R5.R280~
        {calc}
        /reR5.R280~
        /cAREA~{right 4}.{pgdn 7}{down 9}~
        {calc}
        /reT5.T280~
        /cAZ5.AZ154~{right 6}~
        {calc}
        /reV5.V280~
        {return}
```

Description of the Worksheet:

The irrigation season is taken to be 275 days long (July - March, inclusive). In this way the worksheet hight is 275. The tables given here are part of the worksheet. The figures are either input data or a result of a formula.If a cell contains a formula, all cells in the same column contain similar formulae. The following is a list of these formulae for row 19:

Cell I19: 4.2*H19*U19

Where 4.2 is a conversion factor from mm.feddan to cubic meters.

Cell K19: @if(U19>0,20.57*(J19-I1*G19/G19)/U19,0)

Where cell I1 = Canal surface area (m_2).
20.57 = Conversion factor from l/sec to mm/day.
86.4 = Conversion factor from mm.m_2/day to l/sec.

Cell L19: @if(U19>0,S19/(U19*4.2),0)

Where 4.2 is as defined for cell I19.

Cell M19: @if(O18>0.45*170*Y19),L19,N19)

Where 0.45 = (1 - P) and 170 = Sa.

Cell N19: @if(O18<0,0,(L19*O18)/(0.45*170*Y19)

Where 0.45 and 170 are as defined for cell M19.

Cell O19: @if(O18+H19+K19-M19)>(170*Y19),(170*Y19),
@if((O18+H19+K19-M19)>0,(O18+H19+K19-M19,0))

Where 170 is as defined for cell N19

Cell Q19: 4.2*AA$2*G19*P19

Where 170 is as defined for cell I19 and AA2 is a range named AREA.

Cell S19: +S19+R19

Cell U19: +U19+T19

Cell W19: AA$2*V19

Where cell AA2 is as defined for cell Q19.

Cell X19: +X19+W19

Cell Y19: @if(U19>0,X19/U19,0.05)

Where 0.05 is any small value greater than zero (this is to avoid division by zero in other cells).

Cell Z19: 170*0.45*Y19

Where 170 and 0.45 are as defined for cell I19.

Cell AA19: 170*Y19

Where 170 is as defined for cell I19.

A	B	C	D	E	F	G	H	I
DATE 1986	COTTON AREA (feddan)	G/N AREA (feddan)	SORGHUM AREA (feddan)	WHEAT AREA (feddan)	ONION AREA (feddan)	ETo (mm)	RAIN (mm)	RAIN (m ^ 3)
01-Jul						7.20	8.20	0.00
02-Jul						7.70		0.00
03-Jul						8.40	15.20	0.00
04-Jul						7.60		0.00
05-Jul						9.80		0.00
06-Jul		10.00				10.00		0.00
07-Jul		10.00				11.90		0.00
08-Jul		5.00				13.00		0.00
09-Jul						9.20		0.00
10-Jul						9.40		0.00
11-Jul						10.50	1.20	126.00
12-Jul		10.00				8.70		0.00
13-Jul						9.30		0.00
14-Jul						11.20	7.20	1058.40
15-Jul						5.80		0.00
16-Jul		5.00	5.00			8.30		0.00
17-Jul		10.00				9.20	1.80	415.80
18-Jul						9.00		0.00
19-Jul						9.10		0.00
20-Jul			10.00			10.70	0.20	54.60
21-Jul						11.10		0.00
22-Jul						8.40		0.00
23-Jul						8.00		0.00
24-Jul			10.00			9.70	38.00	11970.00
25-Jul						7.90	0.20	63.00
26-Jul						8.30		0.00
27-Jul						5.70		0.00
28-Jul						6.90		0.00
29-Jul						7.90	1.20	378.00
30-Jul						7.90		0.00
31-Jul						4.80	0.20	63.00
01-Aug						6.40		0.00
02-Aug						8.50	16.40	5166.00
03-Aug						7.50		0.00
04-Aug						8.20		0.00
05-Aug						8.20		0.00
06-Aug						8.90		0.00
07-Aug						8.80		0.00
08-Aug						8.70	3.80	1197.00
09-Aug						8.00	0.20	63.00
10-Aug						9.30		0.00
11-Aug						8.70		0.00
12-Aug						7.40		0.00
13-Aug						8.80		0.00
14-Aug						7.60	3.40	1071.00
15-Aug						8.80		0.00
16-Aug						7.50		0.00
17-Aug						8.40		0.00
18-Aug						8.60		0.00
19-Aug						8.30		0.00
20-Aug						8.10		0.00
21-Aug						9.20		0.00
22-Aug						10.00		0.00
23-Aug						8.80	0.20	63.00
24-Aug						6.20		0.00
25-Aug						10.40	17.20	5418.00

J	K	L	M	N	O	P	Q	R
IRRIG (l/s)	IRRIG (mm)	ETm (mm)	ETa (mm)	VALUE	SOILMOIT (mm)	Kc (temp.)	Q (temp.)	Q (copy)
					0.00			
0.00	0.00	0.00	0.00	0.00	8.20		0.00	
0.00	0.00	0.00	0.00	0.00	8.20		0.00	
0.00	0.00	0.00	0.00	0.00	8.50		0.00	
0.00	0.00	0.00	0.00	0.00	8.50		0.00	
0.00	0.00	0.00	0.00	0.00	8.50		0.00	
0.70	1.45	5.00	1.59	1.59	8.36		0.00	
1.16	1.20	5.95	1.86	1.86	7.70		0.00	
0.42	0.34	6.50	1.87	1.87	6.17		0.00	
5.42	4.46	4.60	1.06	1.06	9.57		0.00	
6.88	5.66	4.70	1.68	1.68	13.55		0.00	
0.84	0.69	5.25	2.66	2.66	12.78		0.00	
0.69	0.40	4.35	2.08	2.08	11.11		0.00	
0.61	0.36	4.65	1.93	1.93	9.54		0.00	
0.18	0.11	5.60	2.00	2.00	14.85		0.00	
7.91	4.65	2.90	1.61	1.61	17.89		0.00	
15.64	7.15	4.21	2.81	2.81	22.23		0.00	
0.82	0.31	4.70	3.90	3.90	20.43		0.00	
8.78	3.28	4.62	3.53	3.53	20.19		0.00	
19.83	7.42	4.67	3.52	3.52	24.08		0.00	
32.28	10.21	5.47	4.92	4.92	29.57		0.00	
9.72	3.08	5.68	5.68	6.27	26.97		0.00	
0.76	0.24	4.34	4.34	4.37	22.88		0.00	
0.86	0.27	4.13	3.53	3.53	19.62		0.00	
2.39	0.65	4.99	3.65	3.65	54.62		0.00	
35.83	9.83	4.06	4.06	8.28	59.52		0.00	
20.55	5.64	4.38	4.38	9.67	59.84		0.00	
43.37	11.90	3.07	3.07	6.80	60.16		0.00	
38.70	10.61	3.75	3.75	8.29	60.47		0.00	
17.98	4.93	4.29	4.29	9.48	60.84		0.00	
11.56	3.17	4.35	4.35	9.51	59.66		0.00	
32.31	8.86	2.64	2.64	5.58	62.74		0.00	
37.41	10.26	3.57	3.57	7.82	63.69		0.00	
32.08	8.80	4.74	4.74	10.38	64.69		0.00	
68.31	18.74	4.24	4.24	9.19	66.28		0.00	
49.53	13.58	4.63	4.63	10.05	67.86		0.00	
30.74	8.43	4.84	4.84	10.52	69.45		0.00	
33.07	9.07	5.43	5.43	11.78	71.22		0.00	
49.74	13.64	5.43	5.43	11.74	73.18		0.00	
21.25	5.83	5.37	5.37	11.60	75.24		0.00	
3.73	1.02	5.09	5.09	11.02	71.37		0.00	
1.07	0.29	5.92	5.92	11.83	65.75		0.00	
2.40	0.66	5.64	5.64	10.13	60.76		0.00	
2.26	0.62	4.80	4.80	7.75	56.58		0.00	
0.98	0.27	5.88	5.88	8.61	50.96		0.00	
0.92	0.25	5.08	5.08	6.53	49.53		0.00	
1.93	0.53	6.20	6.20	7.54	43.87		0.00	
0.80	0.22	5.47	5.47	5.75	38.62		0.00	
0.57	0.15	6.18	5.57	5.57	33.20		0.00	
0.76	0.21	6.33	4.78	4.78	28.64		0.00	
0.93	0.26	6.37	4.04	4.04	24.85		0.00	
0.00	0.00	6.22	3.34	3.34	21.51		0.00	
1.05	0.29	7.19	3.26	3.26	18.54		0.00	
1.36	0.37	7.81	2.98	2.98	15.93		0.00	
1.96	0.54	7.16	2.29	2.29	14.37		0.00	
0.06	0.02	5.04	1.43	1.43	12.97		0.00	
2.52	0.69	8.82	2.20	2.20	28.66		0.00	

S	T	U	V	W	X	Y	Z	AA
Q (final)	A (copy)	A (final)	D (temp.)	D*A (temp.)	D*A (SUM)	D (final)	MIN. SOILMOIT.	MAX. SOILMOIT.
0.00		0.00		0.00	0.00	0.05	3.83	8.50
0.00		0.00		0.00	0.00	0.05	3.83	8.50
0.00		0.00		0.00	0.00	0.05	3.83	8.50
0.00		0.00		0.00	0.00	0.05	3.83	8.50
0.00		0.00		0.00	0.00	0.05	3.83	8.50
210.00		10.00		0.00	3.50	0.35	26.78	59.50
499.80		20.00		0.00	7.00	0.35	26.78	59.50
682.50		25.00		0.00	8.75	0.35	26.78	59.50
483.00		25.00		0.00	8.75	0.35	26.78	59.50
493.50		25.00		0.00	8.75	0.35	26.78	59.50
551.25		25.00		0.00	8.75	0.35	26.78	59.50
639.45		35.00		0.00	12.25	0.35	26.78	59.50
683.55		35.00		0.00	12.25	0.35	26.78	59.50
823.20		35.00		0.00	12.25	0.35	26.78	59.50
426.30		35.00		0.00	12.25	0.35	26.78	59.50
794.81		45.00		0.00	15.75	0.35	26.78	59.50
1085.78		55.00		0.00	19.25	0.35	26.78	59.50
1067.85		55.00		0.00	19.25	0.35	26.78	59.50
1079.72		55.00		0.00	19.25	0.35	26.78	59.50
1494.26		65.00		0.00	22.75	0.35	26.78	59.50
1550.12		65.00		0.00	22.75	0.35	26.78	59.50
1183.64		65.00		0.00	22.75	0.35	26.78	59.50
1127.28		65.00		0.00	22.75	0.35	26.78	59.50
1570.53		75.00		0.00	26.25	0.35	26.78	59.50
1279.09		75.00		0.00	26.26	0.35	26.79	59.52
1378.71		75.00		0.00	26.40	0.35	26.93	59.84
968.37		75.00		0.00	26.54	0.35	27.07	60.16
1180.94		75.00		0.00	26.68	0.36	27.21	60.47
1352.09		75.00		0.00	26.84	0.36	27.38	60.84
1368.68		75.00		0.00	27.26	0.36	27.81	61.79
831.60		75.00		0.00	27.68	0.37	28.23	62.74
1124.93		75.00		0.00	28.10	0.37	28.66	63.69
1494.05		75.00		0.00	28.54	0.38	29.11	64.69
1334.03		75.00		0.00	29.24	0.39	29.82	66.28
1458.53		75.00		0.00	29.94	0.40	30.54	67.86
1525.69		75.00		0.00	30.64	0.41	31.25	69.45
1712.00		75.00		0.00	31.42	0.42	32.05	71.22
1709.40		75.00		0.00	32.29	0.43	32.93	73.18
1689.98		75.00		0.00	33.20	0.44	33.86	75.24
1604.40		75.00		0.00	34.10	0.45	34.79	77.30
1865.12		75.00		0.00	35.01	0.47	35.71	79.36
1777.67		75.00		0.00	35.92	0.48	36.64	81.42
1512.04		75.00		0.00	36.91	0.49	37.65	83.66
1853.54		75.00		0.00	37.90	0.51	38.66	85.91
1600.79		75.00		0.00	38.89	0.52	39.67	88.16
1951.49		75.00		0.00	39.89	0.53	40.68	90.41
1723.05		75.00		0.00	40.92	0.55	41.74	92.75
1947.46		75.00		0.00	42.03	0.56	42.87	95.28
1993.82		75.00		0.00	43.15	0.58	44.01	97.81
2007.94		75.00		0.00	44.27	0.59	45.15	100.34
1959.55		75.00		0.00	45.38	0.61	46.29	102.87
2264.30		75.00		0.00	46.50	0.62	47.43	105.40
2461.20		75.00		0.00	47.62	0.63	48.57	107.93
2254.56		75.00		0.00	48.73	0.65	49.71	110.46
1586.44		75.00		0.00	49.85	0.66	50.85	112.99
2778.05		75.00		0.00	50.97	0.68	51.99	115.52

AP	AQ	AR	AS	AT	AU	AV	AW	AX
CROP AGE (days)	Kc (cotton)	Kc (G/N)	Kc (sorghum)	Kc (wheat)	Kc (onion)	D (cotton)	D (G/N)	D (sorghum)
1	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
2	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
3	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
4	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
5	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
6	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
7	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
8	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
9	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
10	0.50	0.50	0.50	0.50	0.50	0.35	0.35	0.35
11	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.38
12	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.41
13	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.44
14	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.46
15	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.49
16	0.50	0.53	0.55	0.66	0.50	0.35	0.35	0.52
17	0.50	0.53	0.55	0.66	0.50	0.37	0.35	0.55
18	0.50	0.53	0.55	0.66	0.50	0.39	0.35	0.58
19	0.50	0.53	0.55	0.66	0.50	0.40	0.35	0.60
20	0.50	0.53	0.55	0.66	0.50	0.42	0.35	0.63
21	0.53	0.59	0.70	0.87	0.74	0.44	0.35	0.66
22	0.53	0.59	0.70	0.87	0.74	0.46	0.35	0.69
23	0.53	0.59	0.70	0.87	0.74	0.47	0.35	0.72
24	0.53	0.59	0.70	0.87	0.74	0.49	0.35	0.74
25	0.53	0.59	0.70	0.87	0.74	0.51	0.35	0.77
26	0.53	0.59	0.70	0.87	0.74	0.53	0.35	0.80
27	0.53	0.59	0.70	0.87	0.74	0.54	0.35	0.83
28	0.53	0.59	0.70	0.87	0.74	0.56	0.35	0.86
29	0.53	0.59	0.70	0.87	0.74	0.58	0.35	0.88
30	0.53	0.59	0.70	0.87	0.74	0.60	0.35	0.91
31	0.58	0.68	0.94	1.07	0.94	0.62	0.35	0.94
32	0.58	0.68	0.94	1.07	0.94	0.63	0.36	0.97
33	0.58	0.68	0.94	1.07	0.94	0.65	0.37	1.00
34	0.58	0.68	0.94	1.07	0.94	0.67	0.37	1.02
35	0.58	0.68	0.94	1.07	0.94	0.69	0.38	1.05
36	0.58	0.68	0.94	1.07	0.94	0.70	0.39	1.08
37	0.58	0.68	0.94	1.07	0.94	0.72	0.40	1.11
38	0.58	0.68	0.94	1.07	0.94	0.74	0.41	1.14
39	0.58	0.68	0.94	1.07	0.94	0.76	0.42	1.16
40	0.58	0.68	0.94	1.07	0.94	0.77	0.42	1.19
41	0.65	0.78	1.10	1.15	1.05	0.79	0.43	1.22
42	0.65	0.78	1.10	1.15	1.05	0.81	0.44	1.25
43	0.65	0.78	1.10	1.15	1.05	0.83	0.45	1.28
44	0.65	0.78	1.10	1.15	1.05	0.85	0.46	1.30
45	0.65	0.78	1.10	1.15	1.05	0.86	0.47	1.33
46	0.65	0.78	1.10	1.15	1.05	0.88	0.47	1.36
47	0.65	0.78	1.10	1.15	1.05	0.90	0.48	1.39
48	0.65	0.78	1.10	1.15	1.05	0.92	0.49	1.42
49	0.65	0.78	1.10	1.15	1.05	0.93	0.50	1.44
50	0.65	0.78	1.10	1.15	1.05	0.95	0.51	1.47
51	0.81	0.91	1.12	1.18	1.05	0.97	0.52	1.50
52	0.81	0.91	1.12	1.18	1.05	0.99	0.52	1.50
53	0.81	0.91	1.12	1.18	1.05	1.00	0.53	1.50
54	0.81	0.91	1.12	1.18	1.05	1.02	0.54	1.50
55	0.81	0.91	1.12	1.18	1.05	1.04	0.55	1.50
56	0.81	0.91	1.12	1.18	1.05	1.06	0.56	1.50

AY	AZ
D (wheat)	D (onion)
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.35	0.35
0.38	0.35
0.40	0.35
0.43	0.35
0.46	0.35
0.49	0.35
0.51	0.35
0.54	0.35
0.57	0.35
0.60	0.35
0.62	0.35
0.65	0.35
0.68	0.35
0.71	0.35
0.73	0.35
0.76	0.35
0.79	0.35
0.82	0.35
0.84	0.35
0.87	0.35
0.90	0.35
0.93	0.35
0.95	0.35
0.98	0.35
1.01	0.35
1.04	0.36
1.06	0.36
1.09	0.37
1.12	0.38
1.15	0.39
1.17	0.39
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40
1.20	0.40

APPENDIX (C,2)

IRRIGATION ADEQUACY INDEX WORKSHEET

```
\B      {let AREA,0}
        /reP5.S32~
        {goto}R5~+R5+Q$1*P5~
        /cR5~R6.R32~
        {goto}P4~
        {for PERIOD,1,28,1,SUB1}
        {goto}S5~
        +R5/R$33~
        /cS5~S6.S32~
        {quit}


SUB1    {down}
        {let AREA,0.181*(@index(DATA,0,(PERIOD-1)))}
        {if AREA>0}{branch SUB2}
GGG     {let AREA,0.131*(@index(DATA,1,(PERIOD-1)))}
        {if AREA>0}{branch SUB3}
SSS     {let AREA,0.107*(@index(DATA,2,(PERIOD-1)))}
        {if AREA>0}{branch SUB4}
WWW     {let AREA,0.373*(@index(DATA,3,(PERIOD-1)))}
        {if AREA>0}{branch SUB5}
OOO     {let AREA,0.207*(@index(DATA,4,(PERIOD-1)))}
        {if AREA>0}{branch SUB6}
        {return}


SUB2    /cBA5.BA25~~
        /reP5.P32~
        {branch GGG}


SUB3    /cBB5.BB19~~
        /reP5.P32~
        {branch SSS}


SUB4    /cBC5.BC15~~
        /reP5.P32~
        {branch WWW}


SUB5    /cBD5.BD15~~
        /reP5.P32~
        {branch OOO}


SUB6    /cBE5.BE19~~
        /reP5.P32~
        {return}
```

A	B	C	D	E	F	J	K
10-DAY PERIOD	COTTON AREA (feddan)	G/N AREA (feddan)	SORGHUM AREA (feddan)	WHEAT AREA (feddan)	ONION AREA (feddan)	ETm (total) (mm)	ETa (total) (mm)
1						26.75	8.05
2		25.00	15.00			46.43	29.13
3		25.00	10.00			45.67	43.68
4						49.26	49.26
5						58.18	50.80
6						74.83	37.39
7						71.32	53.43
8						83.21	30.89
9						79.83	12.46
10					10.00	81.26	51.85
11					5.00	66.35	66.01
12						64.08	64.08
13						57.36	57.36
14						53.19	53.19
15						48.34	48.34
16						39.41	39.41
17						61.18	61.18
18						79.28	56.81
19						69.51	69.51
20						66.68	47.91
21						65.46	36.57
22						69.35	56.59
23						65.32	42.72
24						49.14	46.37
25						75.10	75.10
26						51.25	51.25
27						0.00	0.00

All figures in these columns contain input data. Columns J and K resulted from the soil moisture simulation model described in the previous section.

N	R	S	X
ETa/ETm	SUM OF Ci*aij*Ki	WEIGHT wj	IA
			1.00
0.30	0.00	0.00	1.00
0.63	0.98	0.01	0.99
0.96	1.85	0.02	0.99
1.00	1.85	0.02	0.99
0.87	1.85	0.02	0.99
0.50	2.65	0.03	0.97
0.75	5.15	0.06	0.95
0.37	7.03	0.08	0.88
0.16	6.98	0.08	0.75
0.64	7.91	0.09	0.72
0.99	7.72	0.09	0.72
1.00	6.34	0.07	0.72
1.00	5.54	0.07	0.72
1.00	4.74	0.06	0.72
1.00	3.79	0.04	0.72
1.00	3.79	0.04	0.72
1.00	3.14	0.04	0.72
0.72	2.48	0.03	0.72
1.00	2.48	0.03	0.72
0.72	2.48	0.03	0.71
0.56	2.48	0.03	0.70
0.82	1.45	0.02	0.69
0.65	0.93	0.01	0.69
0.94	0.93	0.01	0.69
1.00	0.31	0.00	0.69
1.00	0.00	0.00	0.69
1.00	0.00	0.00	0.69
	0.00	0.00	69.00
	84.86		

All cells in these columns contain formulae. All cells in the same column have similar formulae. The following is a list of these formulae for raw 19:

Cell N19: @if(J19>0,K19/J19,1)

Cell R19: +R19+Q$1*P19 Where cell Q1 is a range named AREA.

Cell S19: +R19/R$33 Where cell R33 = @sum(R32..R5).

Cell X19: +X18*(N19^S19)

Cell X33 contains the reqired value of IAI.

AZ	BA	BB	BC	BD	BD
10-DAY PERIOD	Ki (cotton)	Ki (G/N)	Ki (sorghum)	Ki (wheat)	Ki (onion)
1	0.20	0.20	0.20	0.20	0.45
2	0.20	0.20	0.20	0.20	0.45
3	0.20	0.20	0.20	0.20	0.45
4	0.20	0.20	0.20	0.20	0.45
5	0.20	0.20	0.70	0.20	0.80
6	0.20	0.80	0.70	0.20	0.80
7	0.50	0.80	0.65	0.60	0.80
8	0.50	0.80	0.65	0.60	0.80
9	0.50	0.80	0.65	0.50	0.80
10	0.50	0.60	0.65	0.50	0.80
11	0.50	0.60	0.20	0.50	0.80
12	0.50	0.60			0.80
13	0.50	0.20			0.30
14	0.75	0.20			0.30
15	0.75	0.20			0.30
16	0.75				
17	0.75				
18	0.25				
19	0.25				
20	0.25				
21	0.25				

All figures in these columns are an input data.