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A canal irrigation water allocation model

Akhand, Md Nurul Alam, Ph.D.

The University of Arizona, 1992
A CANAL IRRIGATION WATER ALLOCATION MODEL

by

Md Nurul Alam Akhand

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
WITH A MAJOR IN IRRIGATION ENGINEERING
In the Graduate College
THE UNIVERSITY OF ARIZONA

1992
As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Md Nurul Alam Akhand entitled A CANAL IRRIGATION WATER ALLOCATION MODEL and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director: Dennis L. Larson
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Date: July 9, 1992
STATEMENT BY AUTHOR

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SIGNED: Nurul A. Akhand
ACKNOWLEDGEMENTS

I would like to extend my appreciation to Dr. Dennis L. Larson who not only directed this dissertation research and provided me with extensive knowledge of agricultural systems engineering, but also was patient and willing to help me during every phase of this study. I am deeply grateful to Dr. Donald C. Slack, major professor and research co-director for his dedication and patience in guiding me throughout my entire graduate study program.

My special thanks are due to Dr. Robert L. Roth for his guidance in the data collection phase of my research. I especially thank Dr. Gary D. Thompson for his assistance in solving the allocation model with GAMS. My thanks are also due to Dr. Paul N. Wilson for his valuable suggestions on the manuscript.

Many people have aided in various aspects of this work. The field work was accomplished with the aid of numerous people including Dr. Thomas Scherer and Mr. Pat Murphree of the Maricopa Agricultural Center. Mr. Buddy Ekholt of Irrigation Management Service provided irrigation system data from their studies at MAC. Mr. Brian Betcher of the Maricopa-Stanfield Irrigation and Drainage District provided data on irrigation water supply. Dr. Gary Merkley of Utah State University generously contributed suggestions for modification of the canal delivery model for use at MAC.

My thanks also are expressed to Winrock International for awarding me the scholarship from 1986 to 1990.

My deepest appreciation goes to my wife and son, Fatema and Fahim, for their love, encouragement and understanding without which the completion of this graduate study would not have been possible.
DEDICATED TO

My mother who died in 1986.
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A water allocation model was developed to assist with allocation of canal water to competing crop irrigation demands. Multi-period linear programming was utilized to optimally allocate water in both time and space to maximize benefits for an irrigated farm. Irrigation scheduling, crop response and canal water delivery models were used to support the water allocation decisions. The irrigation scheduling model supplied information on crop evapotranspiration and soil water storage. The crop response model predicted crop yield in response to the irrigation water applications. The canal delivery model checked the feasibility of supplying the allocation quantities through the control structures and turnouts.

The allocation model was evaluated by tests of water allocation for the University of Arizona, Maricopa Agricultural Center demonstration farm. In crop scenarios which emphasized cotton production, the model recommended deficit irrigation for the barley, cotton, grapes and wheat fields during periods when the quantity of irrigation water demanded was greater than that supplied. Analysis of the effects of changes in water cost and crop returns showed the basis of the solution remained unchanged for a wide range of data. The basis was, however, found to be unstable with very limited water supplies. In addition to serving as a planning tool, the allocation model could be used as a real time management tool. It is believed to have broad applicability to other irrigation projects in other areas.
with characteristics similar to Arizona test conditions.
CHAPTER I

INTRODUCTION

1.1 Background

In most of the Western United States, irrigation water availability to meet the irrigation demand\(^1\) of growing crops is decreasing. For this reason, a large acreage could be converted from irrigated farming to dry land cropping systems or abandoned unless new water supplies are developed or cropping areas are reduced (High Plains Associates, 1982).

Arizona has already intensively developed its available water resources (Arizona Water Commission, 1975). Groundwater is the major source of water, providing about 60% of the total water supply. Annual rainfall varies from 70 to 950 mm (Sellers et al., 1985). Annual withdrawal is about 2467 million cubic meters more than natural groundwater recharge. As a result, Arizona is mining of its groundwater resources. The groundwater level has already lowered 90 to 120 meters in various locations. This deep water level has not only increased energy cost for water lifting, but also caused water quality and land subsidence problems.

\(^1\)Irrigation demand is the total quantity of water needed for growing the crops. In other words, it is the quantity of water required to meet crop evapotranspiration plus losses in water applications.
Surface water is another source of water, contributing about 40% of the total water supply. The Central Arizona Project (CAP) has been developed to bring surface water from the Colorado River to the groundwater overdraft areas. Arizona has rights to about 1850 million cubic meters (MCM) of water from the Colorado River annually. The amount will vary from 500 to 2700 MCM, depending on the water storage in Lake Mead (Malloch, 1986). The average water availability for CAP will decrease with time due to the increased use of the Colorado River water in the upper basin. DWR (1980) estimated a reduction of 280 MCM of CAP water availability in the year 2005 from the base year, 1985. However, CAP water is expected to reduce dependence on groundwater in Arizona and will provide a long term, assured water supply.

In 1980, the Arizona State Legislature passed the Groundwater Management Act to reduce the consequences of groundwater mining. The main aim of this Act is to achieve "safe yield" management of most of the state's basins to eliminate the current groundwater overdraft problem. This is to be accomplished through a long term balance between withdrawals and recharge. The Act set up three levels of management depending on the extent of groundwater use. The lowest level is a general type which applies statewide. The mid-level applies to the Irrigation Non-Expansion Areas (INAs). INAs are designated for the areas where the groundwater overdraft problem is not yet severe. Three INAs were established in
the state. The goal of INAs is to prohibit further expansion of irrigated acreage using groundwater. The highest level of management applies to the Active Management Areas (AMAs) where overdraft is most severe. The Act created four AMAs in the state. They are in the Phoenix, Tucson, Pinal and Prescott areas. The management goal is to accomplish "safe yield" by the year 2025 except in the Pinal AMA. As economy of the Pinal AMA is predominantly agriculture based, the management goal is to preserve groundwater for non-irrigation uses while extending the life of the agricultural economy as long as possible. The Act also established the Department of Water Resources (DWR) as a state agency for administering the Act.

The Groundwater Management Act emphasized exploration of alternative sources to groundwater. The most important alternative is surface water, such as from CAP. Conjunctive use of surface and groundwater is needed for reliable water supply to support continued economic development in several Arizona areas. Other, limited alternative supplies could be effluent, runoff from catchments and additional moisture due to weather modification (DWR, 1991).

A rigorous water management plan has been set up for four AMAs. DWR is responsible for the development of five successive management plans for each AMA. Each plan establishes definite water conservation requirements. The management plan requires review of the achievements made during the past plan periods and also adjustment of the conservation requirements to achieve the final
goal. DWR has already published the first and second management plans for the periods 1980-1990 and 1990-2000, respectively.

The management plans prescribe the maximum annual allowable irrigation water duty\(^2\) based on historical information. This information includes irrigation requirements for crops grown during the base period of 1975-1979. The plans establish target irrigation efficiencies for future years to conserve water. Target irrigation efficiencies of different irrigation methods are used in the calculation of irrigation water duty. On average, water use must not exceed the assigned irrigation water duty. However, the rule has a provision for an operating flexibility account for inter-year irrigation water use permitting "saving" or "borrowing" of water from the assigned amount. There is no restriction on the "save" amount, but the "borrow" amount cannot exceed 50% of the annual assigned amount.

CAP began delivery of water to AMAs in 1986. The CAP has a series of canals and dams designed to distribute Colorado River water to Arizona agricultural users. As a major substitute supply for groundwater pumping, the CAP is a fundamental component of the state's water conservation and management programs. Irrigation districts, the water supply management agencies, are

\(^2\)The Groundwater Management Act defines water duty as "...shall be calculated as the quantity of water reasonably required to irrigate the crops historically grown on the farm unit and shall assume the maximum conservation consistent with prudent long-term farm management practices within areas of similar farming conditions, considering the time required to amortize conservation investments and financing costs." (Carr et al., 1990).
responsible for delivering water at the farm inlet subject to 24-hour prior request by the water users. The districts also manage water withdrawals from wells within the district. Irrigation water users are only required to abide with the maximum assigned irrigation water duty (Betcher, 1990).

1.2 Statement of the problem

Irrigation water management is an important technical, economical, political and social issue. The reason is the increase in competition for existing water and energy supplies between domestic, industrial, commercial and agricultural users for scarce water resources. As a result, most ground water basins have an overdraft problem and a reduction in available water for crop production.

Many irrigation projects are operating with low efficiencies. The reasons for such low efficiencies are often poor water management practices. A major effort has been undertaken to increase irrigation efficiencies through mandated goals set by the Groundwater Management Act. As mentioned earlier, the Act restricts the water users from using more water than an assigned amount. To meet the water use regulations, most of presently irrigated areas now need improvement in off-farm and on-farm irrigation management or must set aside some irrigated areas for dryland farming.

During the past 9 years, some improvements have been made in on-farm
management, particularly in irrigation methods and controls of water flow rates. The Irrigation Management Service (IMS), operated through the Soil Conservation Service, is directly helping Pinal County farm owners to improve on-farm operations through its evaluation procedures (Ekolt, 1990). Today, about 33% of fields under irrigation use the level basin method, which can provide good control of irrigation water application (IMS, 1989). The improvement has not only increased the operational efficiency, but also enhanced benefits from use of available water resources. However, better management of the overall irrigation system could further improve water use. Systems engineering techniques can provide additional capabilities for making appropriate, perhaps optimal, decisions for most beneficial irrigation system operation.

The task of the irrigation system manager is to distribute irrigation water to the farm in a timely and efficient manner. This task is very complex, and an advanced level of management of the distribution system is needed to meet water needs most cost effectively even if the water supply is adequate to meet the water demand. Irrigation system managers have to manage the canal system with control structures and turnouts to satisfy the on-farm demand at different locations in the irrigation project. Eisele (1988) termed canal system management as the management of flow. The flow rate and flow depth vary with time and space in actual canal operation. Mathematically, the management of flow can be expressed through the continuity and momentum equations. The numerical solution of these equations can be simplified by assuming steady flow or the solution may be
complex for unsteady and non-uniform flow conditions. The assumption of steady
or unsteady flow depends on the needed flow description precision and the
characteristics of the system.

Another task of the irrigation system manager is water allocation to the
different demand areas. Allocation decisions are made based on the experience of
one or more individuals who are in charge of the canal operation in many irrigation
projects. This method of decision making can yield non-optimal system performance. There is a need for appropriate systems analysis techniques which
can assist the manager by providing information on allocation which will optimize
the farm income (or other justified objectives). The analysis should consider the
interrelated issues of changing demand of irrigation water with time and space,
irrigation water supply, canal carrying capacity and control structure capability,
operational policy and allocation criteria, crop water response, irrigation
efficiencies, etc.

1.3 Purpose of the study

Irrigation system management typically includes irrigation scheduling, water
supply, water allocation and distribution. Crop response to water must be predicted
to estimate irrigation benefits. A research program was developed using the
following general guidelines to improve irrigation system management:

1. To develop a general irrigation water allocation management tool that is applicable to different irrigation projects,

2. To utilize benefit maximization as the objective of the management tool and

3. To consider sensitive crop growth periods to maximize crop yields.

Considering the above guidelines, objectives of this study were:

1. To develop a computer based tool for optimal management of water delivery to crops in an area served by a canal delivery system and

2. To evaluate the model as a planning and management tool for the Maricopa Agricultural Center.

1.4 Maricopa Agricultural Center

The Maricopa Agricultural Center (MAC) was selected to evaluate the irrigation planning and management tools developed in this study. Since MAC is owned and operated by the University of Arizona, information on irrigation system
operation are accessible to University researchers for applied research and demonstration. A brief introduction of the MAC is given below:

The MAC was established by the College of Agriculture, University of Arizona in 1983. It is about 4.8 kilometers east of Maricopa and 4.8 kilometers north of the Casa Grande-Maricopa Highway in the Pinal County, Arizona. It is a single farming unit of 854 hectares which is within the Pinal AMA. Out of 854 hectares, the research farm contains 182 hectares and the remaining area is allotted to the Agricultural Research Demonstration Farm (ARDF). The research farm is used for experimental plot research while the ARDF operates on a commercial basis and serves as a facility to demonstrate the commercial feasibility of research results. MAC is an essential part of teaching, research and extension of College of Agriculture.

The average elevation of the farm is 358 meters. It slopes gradually from the southeast to the northwest. The elevations of southeast and northwest are 363 and 356 meters respectively. Three soil series found at the MAC farm are Casa Grande, Trix and Shontix. Soil surface (0-30 cm. depth) textures are sandy loam, sandy clay loam and clay loam (Post et al., 1988). Groundwater depth varies from 60 to 140 meters. Average annual rainfall is 185 mm. Thirteen wells and three CAP outlets are the main sources of irrigation water. Well depths and capacities range from 116 to 374 meters and 38 to 150 liters per second, respectively. The CAP outlets have a maximum supply capacity of 566 liters per
second. MAC can use water bypassed by the Gila River Indian Reservation, but the availability of such water is very unpredictable and unreliable.

MAC has a network of main canals and flow control structures and turnouts which convey and distribute irrigation water from the water supply sources to secondary canals. Main canals release water directly to the secondary canals which allows field irrigation through siphon tubes. Water takeoff from the canal system is manually controlled. The cross-section of all canals is trapezoidal, and all canals are lined with precast concrete.
CHAPTER II

LITERATURE REVIEW

Water allocation may depend on quantification of water needs, evaluation of delivery system capabilities, estimation of potential benefits derived from water allocation and optimization of the benefits by allocation. Integration of these four elements in a water allocation program could greatly improve water management.

2.1 Irrigation scheduling model

Literature on irrigation scheduling is voluminous (ASAE, 1985), with various methods utilized or proposed for use in different climate regions with different levels of technological input. Irrigation scheduling models typically calculate soil moisture depletion due to crop water use, soil water storage, soil water movement and evapotranspiration to determine irrigation scheduling and application quantity recommendations. Scheduling programs have utilized handbooks and calculators. However, only literature on the computer based irrigation scheduling programs is discussed here.

Jensen et al. (1970) presented a practical method for using climatic, crop and soil data to schedule irrigations without a need for direct measurement of soil water status or plant stress. Kincaid and Heermann (1974) described the procedure
known as the USDA-ARS irrigation scheduling method for use with a programmable calculator. They used the water balance principle to schedule irrigation to each field.

Stegman and Coe (1984) presented an irrigation scheduling algorithm using an applied water balance method for using APPLE, IBM PC or IBM compatible microcomputers. The source code was written to accommodate locally calibrated regression coefficients for polynomial relationships fitted to crop coefficient curves.

Recently developed irrigation scheduling programs have considered a principle called "management allowed depletion" for reducing the quantity of water application without yield reduction (Shayya and Bralts, 1988 and Scherer et al., 1990). The program developed by Shayya and Bralts (1988), known as the USDA-SCS irrigation scheduling program, has been tested in different US states for the last two years. The program has not yet reached its expected capabilities. However, the program calculates ET by the Penman method using "days after emergence" based crop coefficients. The program developed by Scherer et al. (1990) calculates ET by the Penman method using "growing degree days" based crop coefficients, which helps make the program applicable to different climatic conditions.
2.2 Crop response model

Crop response models have been developed through field experiments to determine a relationship between crop yield and water application quantities. These models have been used to determine the actual yield of the crop resulting from application of various amount of water. Such information is essential for the management of the irrigation systems.

Steward and Hagan (1973) described the relationship of crop or yield response (\( Y \)) to both ET and irrigation water applications (IRR). They demonstrated that \( Y = f(ET) \) and \( Y = f(IRR) \) are linear and convex, respectively. The difference between these response functions is the "non-ET" portion (i.e. percolation, change in soil water content, runoff, etc.) of the applied water.

Hanks (1974) presented a yield to relative transpiration model, i.e. \( Y = (T/T_p)Y_p \) where \( T \) is the seasonal transpiration, \( T_p \) the maximum seasonal transpiration, and \( Y_p \) the yield at \( T_p \). A series of testing of the model indicated its ability to estimate crop yield for different crops and situations (Hanks and Hill, 1980).

Steward et al. (1977) described a generalized crop response function, \( (1-Y_s/Y_m) = \beta(1-ET_s/ET_m) \) where \( Y_s \) is the actual yield, \( ET_s \) the actual seasonal ET, \( Y_m \) the maximum yield, \( ET_m \) the seasonal ET for maximum yield, and \( \beta \) a constant.
(yield reduction ratio). Based on the results of the testing of both Hanks' and Steward's models in Arizona, California and Utah, Vaux and Pruitt (1983) concluded that there was a strong linear relationship between grain yield and ET, as well as between dry matter quantity and ET at all sites.

Doorenbos and Kassam (1979) presented the relationship between yield and water supply utilizing the concept of Steward's model. They termed "\( \beta \)" of the Steward's model as the yield response factors (\( K_y \)) which relate the relative yield decrease, \( (1-Y_a/Y_m) \) to the relative evapotranspiration deficit, \( (1-\text{ET}_a/\text{ET}_m) \). The development of this model was based on the assumption that the relationship between \( (1-Y_a/Y_m) \) and \( (1-\text{ET}_a/\text{ET}_m) \) is linear and is valid for water deficits up to 50 percent of maximum crop demands. They published extensive values of \( K_y \) for both total growing season and individual growth periods of different crops.

2.3 Water allocation model

Water allocation models are tools which can be used in the distribution management of the available water supplies to different fields/field turnouts according to the demands of the growing crops. Given the constraints of the system that influence the allocation decisions and established objectives/goals, allocation models can provide rational and effective recommendations. Loftis and Skogerboe (1984) developed a reservoir storage-delivery network model for a water supply and storage company. They used a linear programming model as the
optimization tool in managing water deliveries which satisfied irrigation demands while maintaining storage at high elevation reservoirs. Some weighting factors were chosen to rank storage preferences and also for exchange priorities. Capacity constraints for canals and reservoirs were included in the model.

Loftis and Stillwater (1986) presented a large scale water delivery system model in which linear and dynamic programming are used for daily allocation of water over space and time, respectively. The objective of this program was to minimize shortages of water over the growing season. Hydraulic flow routing was ignored in this model. Loftis and Houghtalen (1987) presented another dynamic programming model for the same project whose objective was to minimize the sum of squares of shortages over the irrigation season. Further improvement of this model was presented by Houghtalen, Loftis and Fontane (1987). The model uses objective space dynamic programming to avoid a dimensionality problem resulting from multiple reservoirs. The model is deterministic in nature. To incorporate stochastic processes in the formulation, Houghtalen and Loftis (1988) proposed an aggregate state dynamic programming model; this model also encounters the dimensionality problem. The objectives of all these models (Houghtalen, Loftis and Fontane, 1987 and Houghtalen and Loftis, 1988) were the same, i.e. minimization of the seasonal sum of squares of shortages of water. This objective tends to distribute shortages throughout the growing season.
Some other dynamic programming models have been developed for allocation of water to specific crops (Hall and Butcher, 1968, Dudley et al., 1971, Dudley and Burt, 1973, Howell et al., 1975, Yaron et al., 1980, Bras and Cordova, 1981). However, these models did not include crop response to irrigation water application.

Martin, Brocklin and Wilmes (1989) described a multi-seasonal water allocation model using dynamic programming. The program also used nonlinear programming to predict the optimal irrigated area and depth for a given amount of water available at the beginning of irrigation season. However, the model ignored physical network constraints and flow routing procedures.

Eisele (1988) developed a water allocation model for a canal network project using simulation principles. The model uses hourly time steps and allows water supply decisions for up to five day periods. The model incorporates the use of alternate allocation criterions, multiple water sources, canal physical constraints, canal internal storage and water delivery lag time. The model uses both allocation management and flow routing principles. However, the hydraulic component of the model may be less precise than hydraulic models developed by Merkley (1987) and Gichuki (1988). This model also is limited to IBM AT compatible machines (Keller et al., 1988).
2.4 Canal delivery model

Canal delivery models are being developed to improve canal network system operation, analysis, design and training. Advanced computer programs now accommodate variable canal system configurations. Model use in planning and analysis of actual system performance can improve overall irrigation system efficiency of an irrigation project. Recently, the Cornell University developed a canal and reservoir operational model for Gal Oya irrigation project in southeastern Sri Lanka using Basic programming language (Dearth, 1985). The model assumed steady state flow in the canal network. This operational model determines a weekly schedule of reservoir releases and canal flows (including gauge height) for any canal branch or the entire canal network. Such information is then used by the canal operators for regulating the canal flow and distributing water throughout the irrigation project.

Utah State University has developed a main canal hydraulic model using both Fortran and Pascal programming languages for transient, or unsteady flow (Gichuki, 1988 and Merkley, 1987). The model is based on the numerical solution of the complete hydrodynamic equations of continuity and momentum, with an aim to supply steady, reliable and equitable flows throughout a branching canal network. Recently, Utah State University has developed another canal model based on steady state flow utilizing the one dimensional flow equation (Merkley, 1991). The application of these models is to determine appropriate control structure
settings and water levels in the entire canal network for maintaining stable water deliveries from turnouts. Then, the recommended control structure settings can be manually implemented by the canal operators. These models also can be used as planning, design and training tools for analysis of canal system performance through simulation of a real canal system.
CHAPTER III

MODEL DEVELOPMENT

3.1 Irrigation scheduling model

3.1.1 Basic concepts of irrigation scheduling

Irrigation water demands depend on weather, cropping pattern, crop stage and irrigation practices. These factors directly affect the canal flow requirement and control structure settings. Irrigation water demand is the principal input to the water allocation model.

The basis for scheduling irrigation depends on maintaining water available to the crop in the effective rootzone. A soil water balance equation is used to estimate the soil water content in the effective root zone on a daily basis. The soil water balance equation relates inflow and outflow terms. Effective precipitation and irrigation are the inflows, and evapotranspiration is the outflow from the rootzone. The growth of crop roots is considered in determining the effective water storage volume. The soil water balance equation may be expressed as follows:

\[ D_t = D_{t-1} + (ET_t - P_t - IR_t) \]  

(3.1)
in which $D_i$ is soil water depletion in mm on day $i$ ($D_i = 0$ when available water content is at field capacity), $D_{i-1}$ the soil water depletion in mm in day $i-1$, $P_i$ the effective precipitation on day $i$, $IR_i$ the net irrigation depth on day $i$ and $ET_i$ the estimated ET on day $i$.

The soil water content must be initialized from the measurements of initial soil water status. Subsequent measurements are needed to verify the predicted deficits.

Daily crop water use is estimated using the reference or potential evapotranspiration ($ET_o$) and crop coefficient ($K_c$) values (Equation 3.2). Both the $ET_o$ and $K_c$ values must be based on the same reference crop to avoid a significant error in calculation of evapotranspiration (ET). Established reference crops are alfalfa and grass.

$$ET = K_cET_o$$

(3.2)

Doorenbos and Pruitt (1984) defined the $ET_o$ as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water." They provided procedures for calculating grass based $ET_o$ by four methods using the mean daily climatic data for 30 or 10-day periods. The methods are the Penman, Radiation, Blaney-Criddle and Pan Evaporation Methods. Burman
et al. (1980) presented the Penman, Jensen-Haise and Blaney-Criddle Methods for calculating alfalfa based ET. Selection of a method is dependent on available climatic data and the degree of precision required in calculating crop water requirements.

The crop coefficient \( (K_c) \) is the ratio of the actual crop evapotranspiration \( (ET) \) to the evapotranspiration of the reference crop \( (ET_0) \). The actual evapotranspiration is determined by direct field experiments, preferably using a weighing lysimeter. The reference evapotranspiration \( (ET_0) \) values can be calculated using agro-meteorological data for the same location and for the same periods. \( K_c \) values may be related to several other factors:

\[
K_c = K_{co}K_s + K_a \tag{3.3}
\]

where \( K_{co} \) is the basal crop coefficient or the coefficient determined by the crop growth stage and plant cover, \( K_s \) the soil dryness coefficient or the coefficient dependent on available soil moisture and \( K_a \) is a coefficient to allow for increased evaporation from the soil surface occurring after rain or irrigation.

The soil dryness coefficient \( (K_a) \) expresses the effect of soil water availability on the actual ET. When available water is decreasing, actual ET also decreases. Kincaid and Heerman (1974) used a logarithmic relationship to represent
the dryness coefficient:

$$K_s = \frac{\log \left[ 1 + 100 \left( 1 - \frac{D_p}{D_r} \right) \right]}{\log (101)}$$  \hspace{1cm} (3.4)

where $D_p$ is the soil water depletion and $D_r$ is the total available water within the rootzone at field capacity.

Just after rain or irrigation, water use will be near the maximum rate because of evaporation from the soil surface. Kincaid and Heerman (1974) used the following equation to estimate additional water use due to soil evaporation.

$$K_s = K_r (0.9 - K_{eo}), \text{ when } K_{eo} < 0.9$$
$$K_s = 0, \text{ when } K_{eo} \geq 0.9$$  \hspace{1cm} (3.5)

The $K_r$ coefficient takes a value of 0.8, 0.5 and 0.3 for the first day, second day and third day, respectively, following an irrigation or rainfall.

3.1.2 Irrigation water demands

Evapotranspiration of an individual crop growing in a field can be predicted using Equation 3.2. For multiple crops growing in a single large field, ET amounts are computed from individual crops and then weighted using the areas of the individual crops.
Irrigation water demand values then can be obtained for turnouts from the calculated ET, if irrigation efficiency is known, by dividing ET amounts by the irrigation efficiencies. These water demand values are used as inputs to the water allocation model.

3.1.3 Model selection

For this study, two recently developed irrigation scheduling models were evaluated by checking their capabilities in different irrigation projects. These were the USDA-SCS model (Shayya and Bralts, 1988) and a model developed at the University of Arizona (Scherer et al., 1990).

The purpose of this study was to develop a general type water allocation model that could be applied to different irrigation projects. The irrigation scheduling model developed by Scherer et al. (1990) uses a "growing degree day" based crop coefficient which can be applied in different geographical locations. The model requires little input data. Moreover, the model has been tested successfully at the Maricopa Agricultural Center. The USDA-SCS model uses "days after emergence" based crop coefficients which limit application to tested climatic locations. The model has not yet been tested in Arizona. Thus, the model of Scherer et al. (1990) was selected for use with the allocation model.
3.1.4 Data requirements

The following input data are required to run the irrigation scheduling model used in this study, i.e. Scherer et al. (1990).

1. Crop information,
2. Management allowed deficiency,
3. Irrigation efficiency and
4. Weather data.

Crop information:

The program is designed for use with up to 10 upland crops. These are the dry onion, cotton, sweet corn, wheat, barley, potato, soybean, early cabbage and sorghum. The program is currently capable of scheduling 60 fields simultaneously with any combination of the above listed crops. Additional crops could be included in the program if base and maximum temperatures needed for growing the crops, total growing days required to mature the crops and growing degree based polynomial crop coefficient functions are known.

The planting date for individual crops is needed as an input to the model. However, the model predicts the harvest date of the crop based on "accumulated growing degree days."
Management allowed deficiency:

Management allowed deficiency (MAD) values represent the acceptable minimum available soil water content. If water content declines below the specified MAD level, an unacceptable crop yield will occur. MAD values depend on the crop, stage of growth and the irrigation management objectives. MAD values must be input to the irrigation scheduling model for each crop.

Irrigation efficiency:

Irrigation efficiency is defined as the ratio of amount of irrigation water consumed by the crops to the quantity of water delivered or applied to the crops during the same period of time. Surface runoff, water spillage, on-farm water distribution system leakage and nonuniform water application affect the irrigation efficiency. Thus, irrigation efficiency values are used in computation of the gross water application depth to be applied in each field.

Irrigation efficiency varies with different crops and also with stages of crop growth (Schoneman et al., 1990 and Ayars, et al., 1990). Root growth is an important criteria for determining the efficiency values for various stages of a crop. Low efficiency often is obtained at the planting stage and a higher efficiency is attained when root growth reaches at its maximum depth. This study uses variable irrigation efficiency values to account for the change.
Weather data:

Long term historical and/or current weather data are required for use by the irrigation scheduling model. Historical data include the maximum and minimum temperatures, maximum and minimum relative humidities, 24-hour average wind speed, day to night average wind speed ratio and solar radiation. These data are used to provide ET calculations from default weather values where the actual weather data for a specific day are not available.

Local weather data, for example Arizona Meteorological Network data, obtained through a computer modem improves the accuracy of water use calculations. The evaluation reported here used actual weather data from Arizona Meteorological Network.

3.2 Crop response model

3.2.1 Introduction

Crop response to water use involves the interrelationship between the crop, climate, water and soil. Although considerable research information on these relationships is available, simplification is needed to obtain a meaningful analysis of crop response to water.
Doorenbos and Kassam (1979) presented a relationship for relative yield decrease, \( \left(1 - \frac{Y_a}{Y_m}\right) \), to relative water deficit, \( \left(1 - \frac{ET_a}{ET_m}\right) \). The relationship can be used to compute actual crop yield \( Y_a \) as a function of \( ET_a \), maximum evapotranspiration \( ET_m \) and maximum harvested yield \( Y_m \). Both \( ET_m \) and \( Y_m \) can be predicted from meteorological and crop data. The value of \( ET_a \) can be obtained from the water application quantities and irrigation efficiency. In other words, actual yield \( Y_a \) can be expressed as a function of irrigation water application. It is recommended that locally available yield-water application relationships be used, if available. The crop response model is thus expressed as:

\[
\left[1 - \frac{Y_a}{Y_m}\right] = K_y \left[1 - \frac{ET_a}{ET_m}\right]
\]

where \( Y_a \) is actual harvested yield and \( K_y \) the yield response factor. Yield response factor values are derived using the assumption that the relationship between \( \left(1 - \frac{Y_a}{Y_m}\right) \) and \( \left(1 - \frac{ET_a}{ET_m}\right) \) is linear and is valid for water deficits of up to 50 percent or \( \left(1 - \frac{ET_a}{ET_m}\right) = 0.5 \).

Maximum evapotranspiration, \( ET_m \), can be calculated using the reference or potential ET and crop coefficients for the most crops and climates. Actual ET, \( ET_a \), can be computed from the amount of applied water and irrigation efficiency. Maximum harvested yield \( Y_m \) is directly related to the effect of such components as variety, growing environment, growing time, pest and disease conditions and irrigation and nutrient quantities. The complexity of interrelationships among these
parameters makes prediction of the maximum yield complicated. However, Doorenbos and Kassam (1979) outlined the procedures for two methods for determining the maximum yields for different crops. The methods are the Wageningen and Agro-Ecological Zone Methods. The Wageningen Method predicts the maximum possible production potential of a standard crop for a given location using climatic, evapotranspiration and crop data. The Agro-Ecological Method uses climatic, leaf area index and other crop data. Both of the methods assume that water, nutrients, salinity, pests and diseases do not limit crop growth and yield.

It is very difficult to quantify the effect of a short time sudden change in climate, limited supplies of inputs or such farm operations as land preparation, weeding and harvesting on crop yield. Thus, under actual farming condition, the predicted yield can be higher than the actual yield. A preferred alternative is use of locally available yield data as the yield estimate. The study reported here used $Y_m$ values obtained from actual yield data.

3.2.2 Model selection

The crop response models developed by the Food and Agricultural Organization (FAO) for different crops are linear (Doorenbos and Kassam, 1979) and generally applicable to many irrigation projects around the world. The model requires relatively little input data. Based on these considerations, the FAO crop response models were selected for this study.
3.2.3 Data requirements

The following data are needed for use of the FAO models:

1. Maximum ET,
2. Maximum yield and

Maximum ET:

Usually, the irrigation scheduling models are used to calculate $ET_m$. Alternatively, $ET_m$ can be determined using the procedures outlined in FAO Irrigation and Drainage Paper No. 24 (Doorenbos and Pruitt, 1984) or American Society of Agricultural Engineers Monograph No. 3 (Burman et al., 1980). This study uses the irrigation scheduling model, developed by Scherer et al., 1990, to obtain $ET_m$ values.

Maximum yield:

Maximum yield can be estimated for different locations using agrometeorological and crop related data, if experimental data are not available. Data requirements vary with the methods used to calculate $Y_m$. Doorenbos and Kassam (1979) provide tables and figures relating $Y_m$ to the meteorological and crop
parameters of solar radiation, vapor pressure deficit, mean temperature, latitude, leaf area index, total growing period, altitude, mean relative humidity, etc. However, the available local yield values were assumed to be $Y_m$ values in this study.

Yield response factors:

Yield response factors ($K_r$) for both the total growing period and individual growth stages are documented by Doorenbos and Kassam (1979). They provide an extensive list of $K_r$ values for the major crops grown around the world. One limitation is the lack of growth stage-wise $K_r$ values for some crops or climates. Thus, local $K_r$ values are desirable. However, $K_r$ values provided by Doorenbos and Kassam (1979) were used in this study since local data were limited.

3.3 Water allocation model

3.3.1 Theory

Linear programming models have been widely used in allocating limited resources among competing activities. With recent advances in computer technology, linear programming now is becoming more popular. According to Hillier and Lieberman (1986), 25 percent of all scientific computations on computers is related to linear programming.
Most of the linear programming models are stationary equilibrium in nature. In fact, the physical laws which govern the natural phenomenon may not be static or may have more than a single period within a planning horizon. However, the static assumption can be relaxed with multiperiod specifications which accommodate changes in parameters among the periods. Multiperiod linear programming (MLP) techniques can be successfully used in irrigation water allocation where water demand and supply of an irrigation project vary with time and space.

The planning horizon periods can be of equal or variable lengths when using MLP. The decision variables and constraints in different periods remain almost the same although the values of the parameters including coefficients and available resources among the periods are usually different. Only the objective function maintains a linkage among the periods.

The standard multiperiod linear programming model can be expressed as follows:

Maximize:

$$Z = \sum_{j=1}^{n} \sum_{k=1}^{t} C_{jk} X_{jk}$$

(3.7)
Subject to the restrictions

\[
\sum_{j=1}^{n} \sum_{k=t}^{t} a_{jk} X_{jk} \leq b_{ik} \quad (3.8)
\]

\[i = 1 \text{ to } m, \quad k = 1 \text{ to } t\]

and

\[
X_{jk} \geq 0, \quad \forall j, k \quad (3.9)
\]

in which Z is the objective function value; i, j and k are indices for constraints, activities and periods, respectively; \(m, n\) and \(t\) are numbers of constraints, activities and periods respectively; \(X_{jk}\) are the levels of activity; \(C_{jk}\) are the rewards or net benefits for the unit activity; \(a_{jk}\) are the resource requirements, \(b_{ik}\) are the available resources and \(\forall j, k\) means for all \(j\) and \(k\).

The multiperiod linear programming model (3.7, 3.8 and 3.9) is used to select activities, \(X_{jk}\), so as to maximize the value of the objective function, Z (3.7), without violating the available resource constraints (3.8) and the non-negativity levels of the activities (3.9). This model is called the primal linear programming model.

The value of the objective function in the primal linear programming model can be increased if additional units of the fixed resources are available. Unit costs of the additional fixed resources must be known for use of additional units of the
resources. This useful information is available through another linear programming model which is called the dual. The dual linear programming model is directly associated with the primal model, and provides the shadow prices (or marginal value products) of the resources, $b_{ik}$. The shadow price represents the marginal value of a resource, i.e. the objective function increase resulting from a one unit increase in the resource. The dual of the primal equations (3.7, 3.8 and 3.9) can be expressed as:

Minimize:

$$r = \sum_{i}^{m} \sum_{k}^{t} b_{ik} \lambda_{ik}$$  \hspace{1cm} (3.10)$$

Subject to the restrictions

$$\sum_{i=1}^{m} \sum_{k=1}^{t} a_{ijk} \lambda_{ik} \geq C_{jk}$$  \hspace{1cm} (3.11)$$

all $j = 1$ to $n$, $k = 1$ to $t$

and

$$\lambda_{ik} \geq 0, \forall_{ik}$$  \hspace{1cm} (3.12)$$

in which $r$ is the objective function value of the dual problem and $\lambda_{ik}$ the shadow prices of the fixed resources, $b_{ik}$ (or dual variables).
The dual objective function (3.10) helps avoid over-valuation of the resource cost by minimizing the total implicit value of the endowment of fixed resources. To protect from the under-valuation of the resource cost, the constraint equations (3.11) assure that the marginal value of the resources used by one unit of each activity must equal or exceed the marginal net return of that activity. Just as with the non-negativity constraint in the primal model (3.9), equation (3.12) prevents use of negative shadow prices in the model (Hazell and Norton, 1986).

3.3.2 Model formulation

A multiperiod linear programming has been formulated to optimally allocate irrigation water at the Maricopa Agricultural Center demonstration farm. The MLP model can be used to determine the amount of water which should be delivered to the irrigated fields in order to maximize the demonstration farm goals for given conditions. These conditions include the irrigation water demands of each field, crop response functions, water supply quantities from the CAP outlet and wells, canal carrying capacity, water cost, marketable crop prices and water allocation priorities. Details of the formulation are discussed below.

Assumptions:

Basic assumptions for multiperiod linear programming are similar to those for linear programming. These assumptions, documented in classical texts of linear
programming (Hillier and Lieberman, 1986 and Hazell and Norton, 1986), are proportionality, additivity and linearity, divisibility and certainty of equation parameters.

Since irrigation project management involves many interrelated complex decisions, the following simplifying assumptions were made.

1. Irrigation water usage, cost and benefits are considered the only factors governing water allocation decisions. Irrigation labor cost per irrigation is considered in this study. Other cropping costs and benefits are assumed to be independent of the quantity of water use,

2. Fields are assumed to be used to grow a single crop per year. In fact, this is a common practice at the MAC demonstration farm,

3. Input costs and output prices are constant over the duration of the planning period,

4. United States Department of Agriculture (USDA) policies on production control of certain crops, such as cotton, are not considered directly in the model. However, MAC managers consider USDA policies when developing cropping pattern plans,
5. Technological changes are not allowed during a planning period.

6. Variable irrigation efficiency values used to compute irrigation water demands for the crops are based on the root growth only. The intermediate irrigation efficiency values, between the initial efficiency at planting and final efficiency when root growth reaches its maximum depth, are computed using linear interpolation.

7. The water allocation model only applies to an open channel, non-looped network and

8. Return flows and groundwater inflows are not considered.

Decision variables:

The decision variables are the quantities of water to be delivered from CAP or wells to the fields for each period of the planning period. As most large canal irrigation projects use weekly, 10-day or 15-day irrigation intervals, weekly time steps were selected for this study. Equal length periods were used, but periods could be of different lengths. Similarly, the planning period could be a portion of an irrigation season, a full irrigation season, a year, or even a multi-year period. An annual planning period for all the crops grown was selected for analysis since the demonstration farm management reports the farm’s net income annually.
Objective function:

Many objective functions could be used in water allocation models. All irrigation projects are designed to implement the general principles of improving water users economic conditions, equitable water distribution to the users and maintenance of environmental quality. Since a mathematical model accepts only equations or values, these broad allocation goals must be specified by some form of physical or monetary values. Of course, approximations may be needed to quantify physical laws and socio-economic behavior. However, possible objectives could be maximizing net benefit, minimizing input costs, minimizing water shortages, maximizing equitable water or income distribution, etc.

At MAC, research findings are tested and results demonstrated to the Arizona growers. The farm revenues provide operational monies. Moreover, an increase in net benefit is a common goal for irrigated farming around the world. Thus, the maximization of net benefit was chosen as the water allocation objective. The net benefit function includes only total revenue and irrigation water cost as variables.

The net benefit equation is:

\[ NB = TR - IC - LC \]
\[ NB = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{t} (AR_j PY_j Y_{jk} - 10PX_i AR_j X_{ijk} - FLC_j) \]  

(3.13)

in which NB is the net benefit in $; TR the total revenue in $; IC the irrigation cost in $; LC the irrigation labor cost in $; i the irrigation water source; j the irrigated field; k the week; m the number of sources; n the number of fields; t the number of weeks; ARj the area of an individual field in ha; PYj the commodity price in $/tonne\(^1\); Y\(_{jk}\) the yield of the crop growing in field j, harvested during week k in tonne/ha; PX\(_i\) the cost of irrigation water from source i in $/m\(^3\), X\(_{ijk}\) the amount of water applied from source i to field j during week k in mm; 10 is a unit conversion factor to convert from ha-mm to m\(^3\) and FLC\(_j\) the irrigation labor cost for field j in $. The crop yield, Y\(_{jk}\), is defined as:

\[ Y_{jk} = Y_m \left[ 1 - k_{vj} \left( 1 - \frac{X_{ijk}}{ET_{m}} \right) \right] \]  

(3.14)

in which Y\(_m\) is the maximum yield of field j, harvested during week k in tonne/ha; k\(_{vj}\) the FAO yield response factor in fraction for field j and ET\(_m\) the maximum evapotranspiration of field j during period k in mm and IE the irrigation efficiency in fraction for field j during period k.

---

\(^1\)tonne refers to the metric ton which is equivalent to 2205 pounds.
Constraints:

1) Water supply limitation

The irrigation water allocation in each period cannot be larger than the available water supply quantity.

\[ \sum_{j=1}^{n} AR_j X_{ijk} \leq WS_{ik} \quad (3.15) \]

for all \( i \) and \( k \)

in which \( WS \) is the water supply from source \( i \) during period \( k \) in ha-mm.

2) Canal carrying capacity

Irrigation water distribution from a canal must be less than the maximum allowable flow capacity of the canal.

\[ \sum_{i=1}^{m} \sum_{j=1}^{n} AR_j X_{ijk} \leq 360 \cdot XSEC \cdot VEL \cdot IRT \quad (3.16) \]

for all \( k \)

in which \( XSEC \) is the cross section of canal in m\(^2\); \( VEL \) the canal water velocity in m/sec, \( IRT \) the irrigation time in hours and 360 is a unit conversion factor to convert from m\(^3\).hour/sec to ha-mm. Equation 3.17, the Manning equation, was
used to calculate the canal water velocity:

\[
VEL = \frac{R^{\frac{2}{3}} \sqrt{S_o}}{n}
\]  

(3.17)

in which \( S_o \) is the dimensionless slope of the energy gradient, \( n \) the roughness coefficient and \( R \) the hydraulic radius in m. The hydraulic radius is defined as:

\[
R = \frac{A}{P}
\]  

(3.18)

in which \( A \) is the flow cross-sectional area of canal perpendicular to flow in m\(^2\) and \( P \) the wetted perimeter in m.

3) Crop irrigation water demands

Irrigation water demand is the quantity of water needed to be applied to produce maximum crop yield. Irrigation water allocation cannot exceed the water demands to prevent over-irrigation.

\[
\sum_{i=1}^{m} AR_j X_{ijk} \leq AR_j D_{jk}
\]  

(3.19)

for all \( j \) and \( k \)

in which \( D_{jk} \) is the water demand at field \( j \) during the week \( k \) in mm.
4) Non-negativity constraint

An irrigated field may require no water during a period, but never gets a "negative" allocation.

\[ x_{ljk} \geq 0, \forall ljk \] \hspace{2cm} (3.20)

Additional considerations:

1) Minimum irrigation application

The minimum irrigation for all crops is considered to be 100 mm per irrigation. This is a practical surface irrigation application limitation.

2) Under-irrigation limitations

All crops must receive at least 50 percent of the desired irrigation quantity. This consideration is due to the defined limitation of the crop response model.

3) Allowable yield reduction

Calculated yield reduction can not be more than 50 percent of maximum attainable yield. Management intervention is requested if lower yields are predicted.
4) Irrigation priority based on sensitive crop growth periods

Crop response to water deficit in different crop growth periods is an important water allocation consideration. In multiple crop farming, a crop with higher sensitivity will suffer greater yield loss than a crop with a lower sensitivity factor. Thus, different crop yield response factors are specified for different crop growth periods.

3.3.3 Solution technique

In 1947, George Dantzig (1963) introduced the simplex method to solve linear programming problems. Today the principles for solving the problem remain the same, although procedures have been updated for use in computers. A commercially available mathematical program named General Algebraic Modeling System (GAMS), which uses a linear programming algorithm BDMLP\textsuperscript{2}, was used to solve the water allocation problem (Brooke et al., 1988).

\textsuperscript{2}BDMLP stands for Brooke, David, Meeraus, Linear and Programming. Brooke, David and Meeraus are the authors of the User's Guide of GAMS.
3.4 Canal delivery model

3.4.1 Basic theory

The canal delivery model is based on steady-state hydraulics utilizing a one dimensional flow equation. The equation includes a term for lateral outflow, the desired discharge from the canal system (Henderson, 1966). The flow equation is a first order, non-linear ordinary differential equation:

\[
\frac{dy}{dx} = \frac{S_o - S_f - S_l}{1 - Fr^2}
\]  \hspace{1cm} (3.21)

in which \(y\) is the flow depth (L); \(x\) the distance along the canal bed (L); \(S_o\) the longitudinal bed slope; \(S_f\) the friction loss gradient; \(S_l\) a term which accounts for lateral flow; and \(Fr^2\) the Froude number squared. The term \(S_l\) is expressed as:

\[
S_l = \frac{Q}{A^2g} \frac{dQ}{dx}
\]  \hspace{1cm} (3.22)

in which \(Q\) is the discharge (L\(^3\)/T); \(g\) the acceleration due to gravity (L/T\(^2\)); and \(A\) the flow cross-sectional area (L\(^2\)). The Froude number squared is defined as:

\[
Fr^2 = \frac{Q^2T}{gA^3}
\]  \hspace{1cm} (3.23)

in which \(T\) is the top width of flow (L).
There is no known analytical solution to the above stated equation (3.21). However, the solution of the equation can be approximated by use of numerical techniques.

3.4.2 Model selection and solution technique

The canal delivery model (CD Model) developed by Merkley (1991) was selected for the evaluation of water flow in the canals, particularly for checking the feasibility of delivering the desired irrigation water quantities through the canal network. The CD Model thus serves as a supporting computational tool in the overall irrigation system management program. The model incorporates steady state hydraulic equations for a canal water distribution system and has been tested successfully for a large scale irrigation project in Thailand (Merkley, 1991).

The CD Model uses numerical techniques, that is, a 4th and 5th order Runga-Kutta method, to solve for flow depth from the flow equation (3.21). Then, the model uses flow depths and the stage-discharge relationships of the control structures, lateral takeoffs and turnouts to calculate discharges and gate settings.

3.4.3 Data requirements

Application of the CD Model requires site specific canal hydraulic data. Some data may be obtained from the design and construction specifications. Field
measurements may be required to obtain other data. The following categories of data are needed to run the model.

1. Reach linkages,
2. System dimensions,
3. Canal reach data,
4. Control structure parameters,
5. Turnout structure parameters,
6. Canal system inflow,
7. Canal system outflow demands and
8. Irrigation water demands by turnout.

Reach linkages:

Reach linkages specify the physical layout of a canal system in terms of reach connections. A canal reach is a portion of canal length that bounded on the upstream and downstream ends by control structures. Reaches can be connected in series or parallel depending on the actual layout of the canal network. Reaches are separated by the control structures. The first reach of the primary or main canal must be connected to the water supply source. A reach can be linked at the upstream end or downstream end of the existing reaches. An exception is the reach at the water source where an upstream linkage is not allowed. To insert a reach that branches from the existing reach, i.e. a parallel connection, a lateral
offtake structure is required. A lateral offtake, similar to a turnout, delivers water to another reach of a canal system, whereas a turnout delivers water directly to a field.

System dimensions:

The system dimension data specify the number of reaches, control structures, turnouts, and lateral offtakes. The CD Model can be used to simulate a maximum of 250 reaches, 300 control structures, 620 turnouts and 60 lateral offtakes. The maximum number of control structures, turnouts, and lateral offtakes per reach is 9, 25 and 9, respectively. Large numbers of the reaches, control structures and turnouts require many computational cells in hydraulic simulation. Model size was selected for compatibility with 640 K RAM microcomputers.

Canal reach data:

The canal reach data includes:

1. Reach length (m),
2. Canal longitudinal slope (m/m),
3. Canal side slope (m/m),
4. Canal base width (m),
5. Canal depth (m),
6. Canal hydraulic roughness coefficient,
7. Canal seepage rate (mm/day) and
8. Bottom elevation change from the downstream of the reach to the upstream end of the next reach (m).

Control structure parameters:

Control structures are in-line flow control structures used to regulate flow rate and levels in a canal reach. The model has the provision for five types of control structures. They are the circular sluice, rectangular sluice, rectangular weir, centrifugal pump and section change. Depending on the types of control structures, the following data are required:

1. Discharge coefficient,
2. Width or diameter (m),
3. Weir sill width (m),
4. Sill or culvert height (m),
5. Upstream elevation drop (m),
6. Downstream elevation drop (m),
7. The difference in elevation between the canal bottom on the upstream side of the centrifugal pump and the center of pipe at the downstream pump exit (m),
8. Friction loss coefficient and
9. Polynomial coefficients to determine total dynamic head for centrifugal pumps.

Turnout and lateral offtake structure parameters:

Turnouts are used to deliver quantities of water from the canals to the fields. Six types of turnouts are used in the CD model. These are the circular orifice, rectangular orifice, round orifice, rectangular weir, wasteway weir and centrifugal pump. Depending on the type of the turnouts, the following turnout data are required:

1. Discharge coefficient,
2. Width or diameter (m),
3. Height (m),
4. Distance from the beginning of a canal reach to the location of turnout (m),
5. Elevation difference between the bottom of the canal at the turnout location and the bottom of the turnout opening (m),
6. Depth of flow on the downstream side of an orifice-type turnout when the discharge through the turnout is zero (m),
7. Slope of the linear stage-discharge relationship used to approximate flow depths at the downstream side of orifice-type turnouts,
8. The difference in elevation between the canal bottom on the upstream side of the centrifugal pump and the center of pipe at the downstream pump exit (m),

9. Friction loss coefficient and

10. Polynomial coefficients to determine total dynamic head for centrifugal pumps.

Lateral offtakes and turnouts are similar in hydraulic structure. However, the following additional data are required for lateral offtakes:

1. Distance from the upstream end of the reach to the center of the lateral offtakes (m) and

2. Elevation difference between the bottom of the canal at the upstream side of the lateral and the bottom of the canal just downstream from the lateral.

Canal system inflow:

The reservoir level is an input to the CD model used to calculate system inflow which in turn determines the headgate settings. A reservoir level is a depth of available water at the system source. A headgate is a control structure at the system source that regulates the inflow to the canal system. If data on the reservoir level is not entered, i.e. a zero value, the CD model calculates the required inflow rate at the source to satisfy the turnout water demands.
Canal outflow demands:

Canal outflow demands are the required discharge from the last reaches of the canal system. Usually, the outflow demands of the last reaches are zeroes. However, a positive number for the outflow demand may be required to satisfy the water demands outside the canal system, if any.

Turnout demands:

Turnout irrigation water demand values consist of the desired discharges through the turnouts of the canal systems. Turnout demands are to be specified before conducting the hydraulic simulation.

3.5 Interaction of the models

The linkage among the four models, i.e. irrigation scheduling, crop response, water allocation and water delivery models, is illustrated in Figure 3.1. The irrigation scheduling model is used to compute irrigation water demand and maximum ET for each field and period. The crop response model is used to estimate crop yield. Then, the water allocation model is used to determine optimal allocation of irrigation water based on the output of the irrigation scheduling and crop response models and data on crop values, irrigation water cost, canal water delivery capacity, etc. The canal distribution model then checks the feasibility of
the allocation decision and determines needed settings for the control structures.
Figure 3.1 Interaction of the irrigation scheduling, crop response, water allocation and canal delivery models.
CHAPTER IV

MODEL EVALUATION

4.1 Allocation model validation

The water allocation model, including the irrigation scheduling, crop response and canal delivery models, was evaluated as an irrigation planning tool to determine its capabilities and limitations. Results of the test using physical characteristics and cropping data from the University's MAC demonstration farm are discussed below.

4.1.1 Irrigation scheduling model data

The irrigation scheduling model was evaluated using data obtained from the Maricopa Agricultural Center (MAC) demonstration farm during the 1988-89 cropping season. Four crops, barley, cotton, grapes and wheat, were grown in several different fields. A field map of MAC is shown in Figure 4.1. Field areas and crop distribution are listed in Table 4.1. Cotton is the principal crop at MAC and occupied 47.9 percent of total crop area, Figure 4.2. Grapes are an established, perennial crop.
Figure 4.1 Field map of Maricopa Agricultural Center.
Table 4.1  Field areas and crop distribution

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Cotton</td>
<td>34.54</td>
</tr>
<tr>
<td>28</td>
<td>Cotton</td>
<td>38.47</td>
</tr>
<tr>
<td>29</td>
<td>Cotton</td>
<td>36.71</td>
</tr>
<tr>
<td>30</td>
<td>Barley</td>
<td>36.59</td>
</tr>
<tr>
<td>31</td>
<td>Cotton</td>
<td>34.89</td>
</tr>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>18.86</td>
</tr>
<tr>
<td>32W</td>
<td>Wheat</td>
<td>19.22</td>
</tr>
<tr>
<td>33</td>
<td>Barley</td>
<td>13.17</td>
</tr>
<tr>
<td>34</td>
<td>Barley</td>
<td>14.43</td>
</tr>
<tr>
<td>35</td>
<td>Barley</td>
<td>14.38</td>
</tr>
<tr>
<td>36</td>
<td>Cotton</td>
<td>13.50</td>
</tr>
<tr>
<td>37</td>
<td>Barley</td>
<td>18.69</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>18.69</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>18.22</td>
</tr>
</tbody>
</table>

Five crop growth stages, establishment, vegetative, flowering, yield formation and ripening, were considered. The approximate duration of the five crop growth stages are given in Table 4.2. The planting dates was used to determine the exact duration of a crop growth stage in this study. The planting dates of the crops are given in Table 4.3. The date of bud break was used as the planting date for the grapes field, 38. The management allowed depletion (MAD) for a crop
Figure 4.2 Crop area distribution, percent.

...varies with its stages of growth. MAD information used in this study was obtained from Doorenbos and Kassam (1979) and is presented in Table 4.4.

Post et. al (1988) reported the three soil textures at the demonstration farm are sandy loam (SL), sandy clay loam (SCL) and clay loam (CL). The total water holding capacities of SL, SCL and CL are 152, 183 and 216 mm, respectively (Roth, 1992). MAC soil data were limited, so variations in water holding capacities by depth were assumed to be similar values provided by Fox et al. (1991) for Maricopa County. The initial soil moisture content of all fields was assumed to equal field capacity.
Table 4.2  Approximate duration of each growth stage for barley, cotton, grapes and wheat

<table>
<thead>
<tr>
<th>Crop</th>
<th>Duration of the growth stages (weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Establishment</td>
</tr>
<tr>
<td>Barley</td>
<td>3</td>
</tr>
<tr>
<td>Cotton</td>
<td>3</td>
</tr>
<tr>
<td>Grapes</td>
<td>2</td>
</tr>
<tr>
<td>Wheat</td>
<td>3</td>
</tr>
</tbody>
</table>

1including winter dormancy period and 2bud break.

Table 4.3  Planting date of the crops

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Planting date</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Cotton</td>
<td>March 15</td>
</tr>
<tr>
<td>28</td>
<td>Cotton</td>
<td>April 16</td>
</tr>
<tr>
<td>29</td>
<td>Cotton</td>
<td>March 23</td>
</tr>
<tr>
<td>30</td>
<td>Barley</td>
<td>December 15</td>
</tr>
<tr>
<td>31</td>
<td>Cotton</td>
<td>February 24</td>
</tr>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>January 24</td>
</tr>
<tr>
<td>32W</td>
<td>Wheat</td>
<td>November 15</td>
</tr>
<tr>
<td>33</td>
<td>Barley</td>
<td>January 15</td>
</tr>
<tr>
<td>34</td>
<td>Barley</td>
<td>November 30</td>
</tr>
<tr>
<td>35</td>
<td>Barley</td>
<td>January 21</td>
</tr>
<tr>
<td>36</td>
<td>Cotton</td>
<td>March 2</td>
</tr>
<tr>
<td>37</td>
<td>Barley</td>
<td>January 30</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>February 21*</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>February 1</td>
</tr>
</tbody>
</table>

*Date of bud break.
Table 4.4  Management allowed depletion$^1$ (MAD) for barley, cotton, grapes and wheat, percentage of soil water depletion

<table>
<thead>
<tr>
<th>Stages of growth</th>
<th>Barely</th>
<th>Cotton</th>
<th>Grapes</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment</td>
<td>45</td>
<td>45</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Vegetative</td>
<td>50</td>
<td>60</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Flowering</td>
<td>45</td>
<td>70</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>Yield formation</td>
<td>50</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Ripening</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

$^1$After Doorenbos and Kassam (1979).

Irrigation efficiencies may change during the growing season. The irrigation efficiencies during the growing season were determined using linear interpolation and the prediction of root development provided by the irrigation scheduling model. The initial and final efficiencies for barley, cotton and wheat at planting and at the maximum root development, respectively, are summarized in Table 4.5. As grapes

Table 4.5  Irrigation efficiencies$^1$ (IE) for barley, cotton, grapes and wheat, percent

<table>
<thead>
<tr>
<th>Crop</th>
<th>Initial$^2$ IE</th>
<th>Final$^3$ IE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Cotton</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Grapes</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Wheat</td>
<td>40</td>
<td>80</td>
</tr>
</tbody>
</table>

$^1$After Roth (1992) and Scherer (1991), $^2$at planting and $^3$at the maximum root development of the crops.
is a perennial crop, the irrigation efficiency is considered to be a constant 80% value throughout the growing season.

Irrigation scheduling results:

The irrigation scheduling model was used to predict the irrigation water demand of the crops grown in different fields of the demonstration farm using the above mentioned information and weather data from Maricopa Agricultural Center. The predicted irrigation water demand values are summarized in Tables 4.6 to 4.19.

Table 4.6 Irrigation dates and water demand for cotton grown in Field 27

<table>
<thead>
<tr>
<th>Date of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 27</td>
<td>100</td>
</tr>
<tr>
<td>May 21</td>
<td>100</td>
</tr>
<tr>
<td>June 6</td>
<td>119</td>
</tr>
<tr>
<td>June 21</td>
<td>137</td>
</tr>
<tr>
<td>July 5</td>
<td>155</td>
</tr>
<tr>
<td>July 18</td>
<td>151</td>
</tr>
<tr>
<td>July 31</td>
<td>150</td>
</tr>
<tr>
<td>August 13</td>
<td>149</td>
</tr>
<tr>
<td>August 28</td>
<td>173</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>1,234</strong></td>
</tr>
</tbody>
</table>
Table 4.7 Irrigation dates and water demand for cotton grown in Field 28

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 25</td>
<td>100</td>
</tr>
<tr>
<td>June 17</td>
<td>119</td>
</tr>
<tr>
<td>July 4</td>
<td>144</td>
</tr>
<tr>
<td>July 21</td>
<td>172</td>
</tr>
<tr>
<td>August 6</td>
<td>167</td>
</tr>
<tr>
<td>August 20</td>
<td>160</td>
</tr>
<tr>
<td>September 5</td>
<td>157</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>1,019</strong></td>
</tr>
</tbody>
</table>

Table 4.8 Irrigation dates and water demand for cotton grown in Field 29

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 30</td>
<td>100</td>
</tr>
<tr>
<td>May 23</td>
<td>100</td>
</tr>
<tr>
<td>June 8</td>
<td>105</td>
</tr>
<tr>
<td>June 22</td>
<td>127</td>
</tr>
<tr>
<td>July 5</td>
<td>145</td>
</tr>
<tr>
<td>July 17</td>
<td>135</td>
</tr>
<tr>
<td>July 29</td>
<td>140</td>
</tr>
<tr>
<td>August 10</td>
<td>137</td>
</tr>
<tr>
<td>August 22</td>
<td>143</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>1,132</strong></td>
</tr>
</tbody>
</table>
Table 4.9  Irrigation dates and water demand for barley grown in Field 30

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 3</td>
<td>100</td>
</tr>
<tr>
<td>February 20</td>
<td>100</td>
</tr>
<tr>
<td>March 4</td>
<td>100</td>
</tr>
<tr>
<td>March 14</td>
<td>100</td>
</tr>
<tr>
<td>March 28</td>
<td>100</td>
</tr>
<tr>
<td>April 5</td>
<td>111</td>
</tr>
<tr>
<td>April 11</td>
<td>109</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>720</strong></td>
</tr>
</tbody>
</table>

Table 4.10  Irrigation dates and water demand for cotton grown in Field 31

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 28</td>
<td>100</td>
</tr>
<tr>
<td>May 21</td>
<td>114</td>
</tr>
<tr>
<td>June 6</td>
<td>140</td>
</tr>
<tr>
<td>June 18</td>
<td>130</td>
</tr>
<tr>
<td>June 30</td>
<td>141</td>
</tr>
<tr>
<td>July 12</td>
<td>150</td>
</tr>
<tr>
<td>July 25</td>
<td>162</td>
</tr>
<tr>
<td>August 10</td>
<td>178</td>
</tr>
<tr>
<td>August 26</td>
<td>179</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>1,294</strong></td>
</tr>
</tbody>
</table>
Table 4.11  Irrigation dates and water demand for wheat grown in Field 32E

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 4</td>
<td>100</td>
</tr>
<tr>
<td>March 27</td>
<td>100</td>
</tr>
<tr>
<td>April 6</td>
<td>100</td>
</tr>
<tr>
<td>April 15</td>
<td>127</td>
</tr>
<tr>
<td>April 23</td>
<td>143</td>
</tr>
<tr>
<td>April 30</td>
<td>120</td>
</tr>
<tr>
<td>May 9</td>
<td>143</td>
</tr>
<tr>
<td>May 23</td>
<td>139</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>972</strong></td>
</tr>
</tbody>
</table>

Table 4.12  Irrigation dates and water demand for wheat grown in Field 32W

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 19</td>
<td>100</td>
</tr>
<tr>
<td>February 11</td>
<td>100</td>
</tr>
<tr>
<td>February 26</td>
<td>100</td>
</tr>
<tr>
<td>March 12</td>
<td>100</td>
</tr>
<tr>
<td>March 29</td>
<td>128</td>
</tr>
<tr>
<td>April 7</td>
<td>136</td>
</tr>
<tr>
<td>April 16</td>
<td>128</td>
</tr>
<tr>
<td>May 3</td>
<td>148</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>940</strong></td>
</tr>
</tbody>
</table>
Table 4.13  Irrigation dates and water demand for barley grown in Field 33

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 28</td>
<td>100</td>
</tr>
<tr>
<td>March 5</td>
<td>100</td>
</tr>
<tr>
<td>March 16</td>
<td>100</td>
</tr>
<tr>
<td>April 1</td>
<td>100</td>
</tr>
<tr>
<td>April 8</td>
<td>103</td>
</tr>
<tr>
<td>April 14</td>
<td>111</td>
</tr>
<tr>
<td>April 20</td>
<td>108</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>722</strong></td>
</tr>
</tbody>
</table>

Table 4.14  Irrigation dates and water demand for barley grown in Field 34

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 29</td>
<td>100</td>
</tr>
<tr>
<td>February 18</td>
<td>100</td>
</tr>
<tr>
<td>March 4</td>
<td>100</td>
</tr>
<tr>
<td>March 15</td>
<td>100</td>
</tr>
<tr>
<td>March 29</td>
<td>113</td>
</tr>
<tr>
<td>April 5</td>
<td>114</td>
</tr>
<tr>
<td>April 12</td>
<td>120</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>747</strong></td>
</tr>
</tbody>
</table>
Table 4.15  Irrigation dates and water demand for barley grown in Field 35

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 25</td>
<td>100</td>
</tr>
<tr>
<td>March 13</td>
<td>100</td>
</tr>
<tr>
<td>April 1</td>
<td>100</td>
</tr>
<tr>
<td>April 9</td>
<td>107</td>
</tr>
<tr>
<td>April 16</td>
<td>116</td>
</tr>
<tr>
<td>April 22</td>
<td>105</td>
</tr>
<tr>
<td>April 29</td>
<td>116</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>744</strong></td>
</tr>
</tbody>
</table>

Table 4.16  Irrigation dates and water demand for cotton grown in Field 36

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2</td>
<td>100</td>
</tr>
<tr>
<td>May 25</td>
<td>122</td>
</tr>
<tr>
<td>June 11</td>
<td>149</td>
</tr>
<tr>
<td>June 24</td>
<td>144</td>
</tr>
<tr>
<td>July 9</td>
<td>180</td>
</tr>
<tr>
<td>July 22</td>
<td>153</td>
</tr>
<tr>
<td>August 7</td>
<td>183</td>
</tr>
<tr>
<td>August 23</td>
<td>180</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>1,211</strong></td>
</tr>
</tbody>
</table>
Table 4.17  Irrigation dates and water demand for barley grown in Field 37

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1</td>
<td>100</td>
</tr>
<tr>
<td>March 15</td>
<td>100</td>
</tr>
<tr>
<td>April 2</td>
<td>100</td>
</tr>
<tr>
<td>April 10</td>
<td>100</td>
</tr>
<tr>
<td>April 17</td>
<td>105</td>
</tr>
<tr>
<td>April 23</td>
<td>108</td>
</tr>
<tr>
<td>April 30</td>
<td>117</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>730</strong></td>
</tr>
</tbody>
</table>

Table 4.18  Irrigation dates and water demand for grapes grown in Field 38

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 11</td>
<td>121</td>
</tr>
<tr>
<td>April 22</td>
<td>122</td>
</tr>
<tr>
<td>May 3</td>
<td>157</td>
</tr>
<tr>
<td>May 14</td>
<td>153</td>
</tr>
<tr>
<td>June 3</td>
<td>185</td>
</tr>
<tr>
<td>June 24</td>
<td>182</td>
</tr>
<tr>
<td><strong>Total irrigation demand:</strong></td>
<td><strong>920</strong></td>
</tr>
</tbody>
</table>
Table 4.19 Irrigation dates and water demand for barley grown in Field 39

<table>
<thead>
<tr>
<th>Dates of irrigation</th>
<th>Demand (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 3</td>
<td>100</td>
</tr>
<tr>
<td>March 27</td>
<td>100</td>
</tr>
<tr>
<td>April 5</td>
<td>100</td>
</tr>
<tr>
<td>April 13</td>
<td>100</td>
</tr>
<tr>
<td>April 20</td>
<td>116</td>
</tr>
<tr>
<td>April 26</td>
<td>106</td>
</tr>
<tr>
<td>May 3</td>
<td>119</td>
</tr>
<tr>
<td>Total irrigation demand:</td>
<td>741</td>
</tr>
</tbody>
</table>

4.1.2 Crop response model data

The crop response model was used to predict actual yield of the crops based on the water application quantities. Data on maximum yields ($Y_m$) of the crops and yield response factors ($k_y$) were used to compute the actual yield. The maximum yield, $Y_m$, values for barley, cotton and wheat obtained for MAC from Roth (1992) and Murphree (1992) are shown in Table 4.20. The yield response factors, ($k_y$), presented in Table 4.21, utilized in this study were obtained from FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979).
Table 4.20  The maximum crop yield \( (Y_m) \) values, tonne/ha

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>( Y_m ) (tonne/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Cotton</td>
<td>1.799</td>
</tr>
<tr>
<td>28</td>
<td>Cotton</td>
<td>1.795</td>
</tr>
<tr>
<td>29</td>
<td>Cotton</td>
<td>1.735</td>
</tr>
<tr>
<td>30</td>
<td>Barley</td>
<td>6.72*</td>
</tr>
<tr>
<td>31</td>
<td>Cotton</td>
<td>1.858</td>
</tr>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>5.38*</td>
</tr>
<tr>
<td>32W</td>
<td>Wheat</td>
<td>6.72*</td>
</tr>
<tr>
<td>33</td>
<td>Barley</td>
<td>6.05*</td>
</tr>
<tr>
<td>34</td>
<td>Barley</td>
<td>7.17*</td>
</tr>
<tr>
<td>35</td>
<td>Barley</td>
<td>5.83*</td>
</tr>
<tr>
<td>36</td>
<td>Cotton</td>
<td>1.877</td>
</tr>
<tr>
<td>37</td>
<td>Barley</td>
<td>5.61*</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>3.34*</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>4.83*</td>
</tr>
</tbody>
</table>

*Estimated \( Y_m \) values based on historic yield data, and information on soils, crop cultivars and planting dates.

Table 4.21  Yield response factors\(^1\) (\( K_r \)) for barley, cotton, grapes and wheat

<table>
<thead>
<tr>
<th>Stages of crop</th>
<th>Barley</th>
<th>Cotton</th>
<th>Grapes</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetative</td>
<td>0.20</td>
<td>0.20</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>Flowering</td>
<td>0.55</td>
<td>0.50</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>Yield formation</td>
<td>0.45</td>
<td>0.45</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>Ripening</td>
<td>0.20</td>
<td>0.25</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>Total growing</td>
<td>0.90</td>
<td>0.85</td>
<td>0.85</td>
<td>1.00</td>
</tr>
<tr>
<td>period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)After Doorenbos and Kassam (1979).
4.1.3 Allocation model input information

The irrigated area consists of fourteen fields, 27 through 39, supplied irrigation water from CAP outlet E13-8 at MAC. Field areas are given in Table 4.1. The allocation decisions were made for fifty two, one-week-long time periods beginning with November 15, approximately the beginning of the irrigation season.

The irrigation water cost utilized was $418 dollars per hectare meter. The irrigation water cost is set by the Maricopa-Stanfield Irrigation and Drainage District. The irrigation labor cost used was $7.41 per hectare per irrigation.

The irrigation period was considered to be 24 hours or three 8-hour shifts per day, 7 days per week, for a maximum total of 168 hours per week. The maximum CAP outlet capacity is 0.5667 m$^3$/s. The flow cross-sectional areas of the main and secondary canals are 0.74 and 0.39 square meters, respectively.

Variable irrigation efficiencies used to compute irrigation allocation quantities for barley, cotton and wheat were calculated using the method described in section, 4.1.1. Since grapes is a perennial crop, an irrigation efficiency of 80 percent was used throughout the growing season.

The irrigation scheduling model estimated the maximum crop evapotranspiration ($\text{ET}_m$) quantities, determined irrigation dates and provided
irrigation water demand values. The maximum crop yield \( Y_m \) and yield response factors \( K_y \) that were used are listed in Tables 4.20 and 4.21, respectively. The crop prices \( p_y \) are shown in Table 4.22.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Crop price in $ per tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>121</td>
</tr>
<tr>
<td>Cotton</td>
<td>1577</td>
</tr>
<tr>
<td>Grapes (raisins)</td>
<td>772</td>
</tr>
<tr>
<td>Wheat</td>
<td>143</td>
</tr>
</tbody>
</table>

\(^1\)After Roth (1992) and Murphree (1992).

The water allocation model, discussed in Chapter III, was written in GAMS and is presented in Appendix Table A.1. The CAP outlet was the water source in the allocation model. There is no restriction to water supply from the Irrigation District up to the maximum capacity of the canal system, i.e. 0.5667 m\(^3\)/s. Irrigation water cost is the same irrespective of water quantity or source. Thus, inclusion of wells in the model would not have influenced the allocation decisions. Moreover, water sources are controlled by the Irrigation District, not by MAC.

As mentioned earlier, 52 time steps, i.e. weeks, were considered in this study. Of these, 33 weeks needed irrigation water based on the results of the irrigation scheduling model. During the mid-irrigation season, irrigation water
demand quantities varied significantly from week to week. The irrigation water
demand quantities obtained from the irrigation scheduling model were adjusted
among the consecutive weeks to reduce the irrigation demand fluctuations and
permit better operation of the canals.

The lower and upper bounds of the decision variables, i.e. $X_{ijk}$ (irrigation
water allocation quantities), for the weeks that did not have irrigation water
demand were set to zeros as to reduce the computational time. The lower bounds
of the decision variables, irrigation allocation quantities, were set to 50 percent of
irrigation water demands to meet the requirements of FAO crop response models.
The minimum irrigation application quantity was set to 100 mm for practical
surface irrigation application requirements (Appendix Table A.1).

4.1.4 Validation test results

The water allocation model was run without any resource constraint to
compare the simulated irrigation demand and crop yield values with actual MAC
data for 1988-89.

The General Algebraic Modeling System (GAMS), an optimization software,
was used to compile, execute and solve the allocation model. An optimal solution
of the model was found at the 233rd iteration using GAMS linear programming
algorithm, BDMLP. The estimated net benefit was $442,000 (considering water
costs only). The solution to the model provided the irrigation allocation quantities by field for each period of the entire planning period. All crops received full irrigation quantities for all periods. The irrigation water allocation results are summarized in Figure 4.3. The model also provided the simulated crop yields. The irrigation allocation quantities and crop yields obtained by GAMS are summarized in Tables 4.23 and 4.24, respectively.

![Figure 4.3 Irrigation allocation quantities, ha-mm](image)

The simulated irrigation demands and crop yields are similar to the actual field data for MAC in 1988-89 (Tables 4.23 and 4.24). The small differences are due to the procedures used in this study to compute irrigation water demands and
yields. Note that the actual irrigation water application quantities and yields for barley, wheat and grapes were estimated due to unavailability of the actual field data. However, the results obtained in this study were considered to be acceptably close to values available for MAC.

Table 4.23  Comparison of the simulated irrigation demand with actual field data of 1988-89

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Actual irrigation applied (mm)</th>
<th>Simulated irrigation demand (mm)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Cotton</td>
<td>1289</td>
<td>1234</td>
<td>4.3</td>
</tr>
<tr>
<td>28</td>
<td>Cotton</td>
<td>1100</td>
<td>1019</td>
<td>7.4</td>
</tr>
<tr>
<td>29</td>
<td>Cotton</td>
<td>1031</td>
<td>1132</td>
<td>8.9</td>
</tr>
<tr>
<td>30</td>
<td>Barley</td>
<td>790*</td>
<td>720</td>
<td>8.8</td>
</tr>
<tr>
<td>31</td>
<td>Cotton</td>
<td>1285</td>
<td>1294</td>
<td>0.7</td>
</tr>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>990*</td>
<td>972</td>
<td>1.8</td>
</tr>
<tr>
<td>32W</td>
<td>Wheat</td>
<td>965*</td>
<td>940</td>
<td>2.6</td>
</tr>
<tr>
<td>33</td>
<td>Barley</td>
<td>785*</td>
<td>722</td>
<td>8.0</td>
</tr>
<tr>
<td>34</td>
<td>Barley</td>
<td>737*</td>
<td>747</td>
<td>1.3</td>
</tr>
<tr>
<td>35</td>
<td>Barley</td>
<td>724*</td>
<td>744</td>
<td>2.7</td>
</tr>
<tr>
<td>36</td>
<td>Cotton</td>
<td>1252</td>
<td>1211</td>
<td>3.3</td>
</tr>
<tr>
<td>37</td>
<td>Barley</td>
<td>762*</td>
<td>730</td>
<td>4.2</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>915*</td>
<td>920</td>
<td>0.5</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>760*</td>
<td>741</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* Estimated irrigation demand based on historical irrigation water use data, and information on soils, crop cultivars and planting dates.
Table 4.24 Comparison of the simulated and actual crop yields of 1988-89

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Actual yield (tonne/ha)</th>
<th>Simulated yield (tonne/ha)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>Cotton</td>
<td>1.799</td>
<td>1.721</td>
<td>4.3</td>
</tr>
<tr>
<td>28</td>
<td>Cotton</td>
<td>1.795</td>
<td>1.718</td>
<td>4.3</td>
</tr>
<tr>
<td>29</td>
<td>Cotton</td>
<td>1.735</td>
<td>1.706</td>
<td>1.7</td>
</tr>
<tr>
<td>30</td>
<td>Barley</td>
<td>6.72*</td>
<td>6.687</td>
<td>0.5</td>
</tr>
<tr>
<td>31</td>
<td>Cotton</td>
<td>1.958</td>
<td>1.862</td>
<td>4.9</td>
</tr>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>5.38*</td>
<td>5.144</td>
<td>4.4</td>
</tr>
<tr>
<td>32W</td>
<td>Wheat</td>
<td>6.72*</td>
<td>6.209</td>
<td>7.6</td>
</tr>
<tr>
<td>33</td>
<td>Barley</td>
<td>6.05*</td>
<td>6.032</td>
<td>0.3</td>
</tr>
<tr>
<td>34</td>
<td>Barley</td>
<td>7.17*</td>
<td>6.898</td>
<td>3.8</td>
</tr>
<tr>
<td>35</td>
<td>Barley</td>
<td>5.83*</td>
<td>5.571</td>
<td>3.1</td>
</tr>
<tr>
<td>36</td>
<td>Cotton</td>
<td>1.877</td>
<td>1.782</td>
<td>5.1</td>
</tr>
<tr>
<td>37</td>
<td>Barley</td>
<td>5.61*</td>
<td>5.577</td>
<td>0.4</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>3.34*</td>
<td>3.049</td>
<td>8.7</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>4.93*</td>
<td>4.685</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Estimated yield values based on historic yield data, and information on soils, crop cultivars and planting dates.
4.2 Canal model test

The canal delivery model was evaluated using canal description and operational data for the canals of the Maricopa Agricultural Center. The schematic plan view of the main and three of the fourteen secondary canals used in this evaluation is presented in Figure 4.4.

Figure 4.4 Schematic plan view of the canal system.
4.2.1 Canal description

The main canal runs from the CAP outlet to Field 39. The length of the main canal is 3810 meters. The main canal profile was surveyed and is presented in Appendix Table B.1 and Figure 4.5. The main canal discharges water directly to the secondary canals. Trapezoidal jack gates (also called check gates) are used to regulate water flows both in main and secondary canals. The gate consists of a trapezoidal slide gate with a notched stem mounted on top of the gate frame. The slide gate is raised or lowered by operation of the jack along the notched stem. Dimensions vary with canal size and shape. However, jack gates of 30.5 and 61.0
centimeters (cm) bottom width are used at the MAC demonstration farm for secondary and main canals, respectively.

There are fourteen secondary canals, one for each field. The canal dimensions are identical for all the secondary canals. The secondary canals have different lengths depending on the length of the fields. The canal profiles for two fields, 34 and 38, were surveyed and are presented in Appendix Table B.2 and Figures 4.6 and 4.7. The other canals are of similar construction and shape, as these data were assumed applicable to the other twelve canals. Secondary canals discharge water into the fields through siphons. Siphons are 5.08 and 7.62 cm plastic tubes.

Figure 4.6 Secondary canal profile (Field 34).
Trapezoidal ditch checks are used to maintain a constant head within a reach of the secondary canals, permitting delivery of a constant flow rate through the siphons. Usually, these ditch checks can withstand the strain of a 101.6 cm head. Rubber gaskets are usually used in bottom and side edges of ditch checks to prevent water leakage. The bottom width of the ditch checks is 30.5 cm, to fit the size of the canal base. Circular culverts, located in the junction between the main canals and secondary canals, are used as the lateral takeoff structures. The diameter of the circular culverts is 71.1 cm.

Figure 4.7 Secondary canal profile (Field 38).
Jack gates and ditch checks are not included among the control structures available in the canal delivery model (Merkley, 1991). Thus, jack gates and ditch checks were considered to be rectangular sluice gates and a rectangular weirs, respectively. Because of a similar model limitation, the siphons and circular culvert were considered to be circular orifices.

The following adjustments were made to apply the canal model to the canal system of MAC. These adjustments are considered reasonable as the primary use of the canal model in this study is to check the ability of the canal system to deliver the allocated quantities of irrigation water.

1. A control structure, a flow inlet structure at the CAP outlet, was added upstream of the first reach of the main canal. The control structure was considered to be a rectangular sluice gate.

2. The current irrigation practice of MAC is to simultaneously use sixty to eighty-two 5.08 cm diameter siphons (or thirty to forty 7.62 cm siphons for grains) in each secondary canal to irrigate cotton (Murphree, 1992). The discharge of eighty-two 5.08 cm siphons are about equal to the discharge of forty 7.62 cm siphons for same water head. The maximum possible number of siphons for each secondary canal, i.e. eighty-two 5.08 cm siphons, were considered in this test. These 82 siphons were replaced by one adjustable
turnout, a circular orifice 45.7 cm in diameter. This turnout was
added at the inlet of the first reach of each secondary canal. The
theoretical discharge of the 82 siphons, 0.19 m³/s, is approximately
equal to the discharge of the circular orifice for a water head of
15.00 cm. These adjustments were made to simplify the descriptions
of secondary canal turnouts and control structures. The total desired
flow of eighty-two 5.08 cm siphons was entered as the desired flow
from one circular orifice 45.7 cm in diameter.

Data on the canal reaches, control structures, turnouts and lateral offtakes
are presented in Tables 4.25 to 4.28. Standard or recommended data on the
coefficient of discharges for the control structures, turnouts and offtakes were
used since calibration data were not available.

Table 4.25  Data on the canal reaches

<table>
<thead>
<tr>
<th>Item</th>
<th>Main canal</th>
<th>Secondary canal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base width, cm</td>
<td>61.00</td>
<td>30.50</td>
</tr>
<tr>
<td>Maximum depth, cm</td>
<td>76.20</td>
<td>61.00</td>
</tr>
<tr>
<td>Top width, cm</td>
<td>237.74</td>
<td>152.40</td>
</tr>
<tr>
<td>Side slope, cm/cm</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Manning's roughness coefficient</td>
<td>0.013¹</td>
<td>0.013¹</td>
</tr>
<tr>
<td>Longitudinal slope, m/m</td>
<td>0.0007</td>
<td>0.0009</td>
</tr>
<tr>
<td>Seepage rate, (mm/day)</td>
<td>0.00²</td>
<td>0.00²</td>
</tr>
</tbody>
</table>

¹After Walker and Skogerboe (1987) and ²canals are lined with concrete.
Table 4.26  Data on the control structures

<table>
<thead>
<tr>
<th>Item</th>
<th>Main canal</th>
<th>Secondary canal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, cm</td>
<td>61.00</td>
<td>30.50</td>
</tr>
<tr>
<td>Height, cm</td>
<td>76.20</td>
<td>61.00</td>
</tr>
<tr>
<td>Free-flow coefficient (^1) ((a_f))</td>
<td>0.60(^2)</td>
<td>0.60(^2)</td>
</tr>
<tr>
<td>Free-flow exponent ((\beta_f))</td>
<td>1.00(^3)</td>
<td>1.00(^3)</td>
</tr>
<tr>
<td>Submerged-flow coefficient ((a_s))</td>
<td>0.70(^2)</td>
<td>0.70(^2)</td>
</tr>
<tr>
<td>Submerged-flow exponent ((\beta_s))</td>
<td>1.00(^3)</td>
<td>1.00(^3)</td>
</tr>
</tbody>
</table>

\(^2\)After Merkley (1992) and \(^3\)Merkley (1991).

The discharge coefficients, \(C_{df}\), for the rectangular sluice gate are defined as:

a. For free flow condition:

\[
C_{df} = a_f \left[ \frac{G_g G_w}{h_u - E_1} \right]^\beta_f
\]

in which \(a_f\) is the free-flow coefficient, \(G_g\) the gate opening \((L)\), \(G_w\) the gate opening width \((L)\), \(h_u\) the upstream depth \((L)\), \(E_1\) the elevation change \((L)\) and \(\beta_f\) the free flow exponent.

b. For submerged flow condition:

\[
C_{df} = a_s \left[ \frac{G_g G_w}{h_d - E_1 + Z_1} \right]^\beta_f
\]

in which \(a_s\) is the submerged flow coefficient, \(Z_1\) the bed elevation change and \(\beta_s\) the submerged flow exponent.
Table 4.27  Data on the turnouts

<table>
<thead>
<tr>
<th>Item</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, cm</td>
<td>45.7\textsuperscript{1}</td>
</tr>
<tr>
<td>Free-flow discharge coefficient (C_{df})</td>
<td>0.60\textsuperscript{2}</td>
</tr>
<tr>
<td>Submerged-flow discharge coefficient (C_{ds})</td>
<td>0.60\textsuperscript{2}</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Eighty two siphons were replaced by one turnout, a circular orifice 45.7 cm in diameter and \textsuperscript{2}after Walker and Skogerboe (1987).

Table 4.28  Data on the lateral offtake

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Diameter, cm</td>
<td>71.00</td>
</tr>
<tr>
<td>Free-flow discharge coefficient (C_{df})</td>
<td>0.60\textsuperscript{1}</td>
</tr>
<tr>
<td>Submerged-flow discharge coefficient (C_{ds})</td>
<td>0.60\textsuperscript{1}</td>
</tr>
</tbody>
</table>

\textsuperscript{1}After Walker and Skogerboe (1987).

4.2.2 Canal operational data

The maximum and minimum flow rates of eighty-two 5.08 cm siphons are 0.244 to 0.154 m\textsuperscript{3}/s for water heads of 25.4 and 10.2 cm, respectively. In field conditions, water head may vary from field to field and even among the siphons within a field. An average flow rate of 0.19 m\textsuperscript{3}/s was specified as the siphon demand. The outflow demands at the terminal points of the last reaches of the main and secondary canals were considered to be zero. The outflow demands are
the expected discharges from the terminal points (or last reach) of a canal system.

The reservoir level, i.e. water level at the upstream headgate, was set to be zero as the CAP delivers water to the canal system through a flow rate metering device. The CAP outlet has a gate flow rate monitoring device, but does not have any control structure to regulate flow rate. As mentioned above, a rectangular sluice gate at the CAP outlet was used to satisfy modeling requirements.

4.2.3 Canal model test results

The canal model was used to analyze canal system operating conditions using the canal description and operational data. The canal model also determined the inflow requirement at the CAP outlet. This inflow rate could be used as the desired flow rate of the CAP outlet when placing orders to the Irrigation District. The canal model also provided the settings required of the adjustable control structures, turnouts and lateral offtakes. The canal model results, presented in Appendix Table B.3, are divided into four categories, canal reaches, control structures, farm turnouts, and lateral offtakes.

The canal model results show the canal system at MAC can supply the irrigation water needed to satisfy the desired flow of the turnouts of the secondary canals. In fact, the "ok" flow status in the printed output of the model indicates the supply is equal to the demand. When a turnout cannot deliver the
desired discharge, it can be due to a combination of a low upstream flow depth, high downstream flow depth, and/or physical limitations of the turnout. The canal model can be used to trigger the adjustment of upstream and downstream flow depths. When the supply does not equal the demand, the model prints other flow status messages. Possible flow status messages are \textit{ok, closed, surfac, maxcap, spills, pump, wasted, inflow and hilight}. The interpretations of each message are stated in the manual of the canal delivery model (Merkley, 1991).

In the printed results (Appendix Table B.3), the outflows and demands from the first reaches of secondary canals for fields 37, 38 and 39, and third reach of main canal are zeros since the outflow demands of the downstream reaches of the canals were set to zero. Settings and flows of the control structures are similarly zero.

Irrigation water allocation decisions for week 23 were chosen to demonstrate the results obtained from the canal delivery model. Fields 37, 38 and 39 required irrigation during the week 23, one of the peak irrigation requirement periods, Figure 4.3. The times required to irrigate the fields 37, 38 and 39 are about 29.6, 33.7 and 31.1 hours, respectively. However, the total allocated irrigation water quantity for week 23 is 160,340 cubic meters. The time required to apply the allocated quantities of water is about 80 hours based on the ability of the turnouts of each secondary canal to deliver 0.19 m$^3$/s flow rate without exceeding the maximum capacity of CAP outlet (0.5667 m$^3$/s). Thus, all fields can
be fully irrigated as desired.

### 4.3 Application of water allocation model with limited water supply

The water allocation model was rerun with 50 and 55\(^2\) percent reduction in CAP capacity to analyze the results of the model for limited water supply. The results are discussed below:

With 50 percent reduction in CAP capacity, an optimal solution was found at the 232nd iteration. The estimated net benefit was found to be $441,730 only $270 less than with the previous full irrigation example. The allocation results obtained by GAMS are summarized in Table 4.29. The recommended allocation quantity could not fully meet the irrigation demands for the week 22 since there was insufficient available water supply to meet the irrigation demands. The minimum irrigation limitation, however, dictated all fields be supplied at least 100 mm of irrigation.

\(^2\)The maximum irrigation demand quantity for a week was 17,930 ha-mm (Figure 4.3). Thus, about 52 percent of CAP capacity could fully meet the irrigation demands. Moreover, the minimum irrigation limitation fixed the lower bounds of water supply, i.e. 15,420 ha-mm which could be supplied by the canals using about 45 percent of CAP capacity. Thus, 50 and 55 percent reductions in CAP capacity were used in this analysis.
Table 4.29 Water allocation quantities for 50 percent reduction in CAP capacity, mm

<table>
<thead>
<tr>
<th>Field/Period</th>
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<th>Period13</th>
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<td></td>
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<td>106</td>
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</tbody>
</table>

1The number followed by field and period represents the field number of the Maricopa Agricultural Center and the week number beginning from November 15, respectively.
Table 4.29  Water allocation quantities for 50 percent reduction in CAP capacity, mm (Continued)

<table>
<thead>
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<th>Field/Period</th>
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<table>
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<table>
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</tr>
<tr>
<td>Field36</td>
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<td>180</td>
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</tbody>
</table>
The allocation model recommended full irrigation throughout the growing season for all crops except one wheat and two barley fields. The wheat field, 32E, received full irrigation throughout the growing season, except in period 22, when it was allocated the minimum irrigation quantity. One barley field, 35, received the minimum irrigation. The other barley field, 37, was allocated less than the desired irrigation quantity. Seasonal allocation and yield results for these three fields are summarized in Table 4.30.

Table 4.30  Seasonal water allocation quantities and yield reduction for 50 percent reduction in CAP capacity

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Irrigation demand (mm)</th>
<th>Irrigation allocation (mm)</th>
<th>Yield reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32E</td>
<td>Wheat</td>
<td>972</td>
<td>945</td>
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<tr>
<td>35</td>
<td>Barley</td>
<td>744</td>
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<td>37</td>
<td>Barley</td>
<td>730</td>
<td>727</td>
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</table>

The model was then rerun to examine the irrigation allocation decisions with a 55 percent reduction in CAP capacity. An optimal solution was found at the 219th iteration. The estimated net benefit was found to be $438,340, an additional $3390 reduction in net benefit. The allocation results obtained by GAMS are summarized in Table 4.31. The allocation quantities now could not fully meet irrigation demand for the weeks 21, 22, 23 and 37.
Four barley, 30, 33, 34 and 35, and one wheat fields, 32W, experienced deficit irrigation since net benefits of these crop fields were lower than the other fields that needed irrigation during the week 21. The remaining one wheat, 32E, and two barley fields, 37 and 39, requiring irrigation during week 21 received full irrigation due their higher irrigation benefits. During week 22, five barley fields, 30, 33, 34, 35, and 37, two wheat fields, 32E and 32W, and the grape field, 38, were allocated less than full irrigation. All barley fields received the minimum irrigation whereas the grape field received more than the minimum irrigation quantity due to its higher benefit.

One cotton field, 27, one wheat field, 32W, four barley fields, 33, 35, 37, and 39, and the grapes field, 38, needed irrigation in week 23. All of these fields received full irrigation except the barley field, 39. During week 37, three cotton fields, 27, 29 and 31, needed irrigation. The model recommended Field 27 receive deficit irrigation among these cotton fields because Field 27 yield less potential benefit. Possible reasons for selection of Field 27 are field parameters and planting dates effects on benefit. Seasonal allocation and yield results for these ten fields are summarized in Table 4.32.
Table 4.31 Water allocation quantities for 55 percent reduction in CAP capacity, mm

<table>
<thead>
<tr>
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'1The number followed by field and period represents the field number of the Maricopa Agricultural Center and the week number beginning from November 15, respectively.
Table 4.31 Water allocation quantities for 55 percent reduction in CAP capacity, mm (Continued)

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Table 4.32  Seasonal irrigation allocation quantities and yield reduction for 55 percent reduction in CAP capacity

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<th>Demand (mm)</th>
<th>Allocation (mm)</th>
<th>Yield reduction (%)</th>
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<td>Barley</td>
<td>720</td>
<td>701</td>
<td>3</td>
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<tr>
<td>32E</td>
<td>Wheat</td>
<td>972</td>
<td>945</td>
<td>3</td>
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<tr>
<td>32W</td>
<td>Wheat</td>
<td>940</td>
<td>876</td>
<td>8</td>
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<td>Barley</td>
<td>744</td>
<td>721</td>
<td>4</td>
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<td>Barley</td>
<td>730</td>
<td>725</td>
<td>1</td>
</tr>
<tr>
<td>38</td>
<td>Grapes</td>
<td>920</td>
<td>900</td>
<td>2</td>
</tr>
<tr>
<td>39</td>
<td>Barley</td>
<td>741</td>
<td>736</td>
<td>1</td>
</tr>
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4.4  Relaxation of the FAO crop response model assumption

The water allocation model evaluated above was developed using FAO crop response models to compute the actual yield of the crops. FAO crop response models are valid for water deficits of up to about 50 percent. However, Howell et al. (1990) reported a linear relationship between relative yield, \( \frac{Y_u}{Y_m} \), and relative evapotranspiration, \( \frac{ET_u}{ET_m} \), for dry matter and grain production of wheat for greater water deficits. The actual field data showed a linear relationship up to about 55 percent water deficit for wheat. Bhuiyan and Undan (1990) reported a linear relationship between the amount of irrigation water applied at or before
flowering and yield of mungbeans for a wide range of irrigation application quantities. They reported similar results for cowpeas, peanuts and soybeans when crop dry matter quantities were related to the amounts of applied water. Relaxation of the FAO crop response model limitation assumption is considered reasonable for small grains and some other crops.

The allocation model was rerun without the minimum crop irrigation limitation but with the 50 percent reduction in CAP capacity. An optimal solution was found at the 236th iteration. A new basis with different water allocation quantities was found in comparison with previous results. The estimated seasonal net benefit was found to be 441,770 dollars, 42 dollars more than previously obtained results with the minimum irrigation water limitation and 50 percent CAP capacity reduction.

Thus, relaxation of the FAO crop response model increased the estimated net benefit very slightly. In addition, there is a concern about the linearity of the crop response model when water deficits exceeds 50 percent.

4.5 Postoptimality analysis of the water allocation model

The water allocation model developed in this study, formulated in the Chapter III, consists of an objective function which was subject to constraints related to irrigation water availability, canal carrying capacity and irrigation water
demands. The objective function was the maximization of net returns to crop production.

The coefficients of the objective function depend on the crop yields, crop prices and irrigation water cost. These parameters vary from year to year due to changes in the input and product prices, weather and technological changes. The water supply from CAP outlet or wells was fixed in this analysis, but could vary due to pump breakdown or an increase in pumping capacity. Similarly, canal carrying capacity was a fixed value in the optimization model, but could be increased by constructing a new canal. The effect of some changes in operating parameters (crop prices, water supply, canal carrying capacity and irrigation water cost) on the optimal solution can be investigated through postoptimality analysis. The postoptimality analysis also determines the stability of the solution of the model.

4.5.1 Crop prices

A price range, ±10 and ±20 percent from actual crop prices of 1988-89, was used in a postoptimality analysis to determine the changes in the optimal solution. The sensitivity analysis for an individual crop was performed by entering a new price value for one crop without changing the prices for other crops. For "All crops" analysis, a ±10 and ±20 percent change in prices for all crops, i.e. barley, cotton, grapes and wheat, was used in the allocation model analysis (Figures 4.8
and 4.9). It was found that the basis of the solution did not change for any of the tests although the net benefit changed. Thus, the solution to the allocation model can be considered stable for the range of crop prices used in this analysis.

![Graph](image)

**Figure 4.8** Effect of crop prices, a ±10 percent change from the actual crop prices of 1988-89, on the net benefit.

![Graph](image)

**Figure 4.9** Effect of crop prices, a ±20 percent change from the actual crop prices of 1988-89, on the net benefit.
4.5.2 Irrigation water cost

Water cost was determined and assigned by the Irrigation District which charged a constant price per unit of water allocated throughout the irrigation season. Results of the postoptimality analysis evaluating effects of irrigation water cost are presented in Figure 4.10. The cost range used in the sensitivity analysis was similar to the crop price range, i.e. ±10 and ±20 percent from the irrigation cost in 1988-89. The basis of the solution to the allocation model remained unchanged for the above mentioned range of irrigation water costs. The result of irrigation water cost increases was simply decreased net benefits.

Figure 4.10 Effect of irrigation water cost on the net benefit.
4.5.3 Available water supply and demand functions for water

The net benefit of additional water supplies is positive for values up to 17,930 ha-mm (Figure 4.11 and Table 4.33). The needed increase in water supply capabilities could be obtained by increasing capacity of the CAP inlet. The irrigation allocation recommendations remain unchanged for water supplies greater than 17,930 ha-mm since irrigation water demands are fully met (Figure 4.11 and Table 4.33).

The changes in slope of the relationship between the water supply and net benefit resulted from changes of the solution basis (Figure 4.11). The shadow prices for additional water supply varied from 1.720 to 0.308 $/ha-mm as the water supply increase from 15,420 to 17,930 ha-mm. The shadow price decreases as water supplied increase.

The shadow price of irrigation water is its opportunity cost; this cost is equal to the marginal value product of irrigation water. Thus, the relationship between the shadow price and water supply quantity, termed the demand function of water, can be used to predict the economic value of irrigation water for different quantities of water supply.
Table 4.33  Changes in net benefit for different quantities of water supply

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<td>15420</td>
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³ Due to the violation of the minimum irrigation limitation.
Sensitivity analysis was used to derive the demand function curves for these examples irrigation periods having highest water demand (Table 4.34 and Figures 4.12 to 4.14). The location of the change in slope was approximated in the Figures 4.12 to 4.14 as the exact location can not be found by GAMS. The reason for the variation in shadow prices for water among the irrigation periods is the variation in irrigation demand quantities.
Table 4.34 Demand functions for irrigation water

<table>
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<th>Water supply (ha·mm)</th>
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<tr>
<td>17540</td>
<td>0.308</td>
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<tr>
<td>17140</td>
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<td>16930</td>
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Figure 4.12 Demand function for irrigation water in week 21
Figure 4.13 Demand function for irrigation water in week 22

Figure 4.14 Average demand function for water
4.5.4 Canal carrying capacity

MAC irrigation is constrained by water delivery capacity and irrigation period length. The MAC canals have sufficient delivery capacity to meet irrigation water demand during all irrigation periods with the existing cropping pattern. The MAC canals are capable of delivering up to 24 percent more than permitted by current CAP inlet capacity of 0.5667 m³/s.

4.5.5 Optimal area and irrigation water

The allocation model discussed above was modified to a nonlinear formulation to find the optimal irrigation area and water allocation quantity simultaneously. The nonlinear programming version of the allocation model was written in GAMS. The objective function was identical with the linear programming formulation since the FAO crop response model is linear. The constraint equations were similar to those in the linear formulation except the equations were nonlinear where area was used as a variable.

GAMS was used to compile and solve the nonlinear allocation model with 50 and 55 percent reduction in CAP capacity to compare the results with the linear version of the allocation model. The optimal solutions were found using the GAMS
nonlinear algorithm, MINOS⁴, at the 119th iteration. The estimated net benefits and shadow prices of water for linear and nonlinear formulations were identical. Thus, the linear programming formulation used in this study can be used to effectively find optimal irrigation allocation quantity.

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⁴MINOS stands for Modular In-core Nonlinear Optimization System.
5.1 Application of allocation model as a management tool

The evaluation tests described in Chapter IV, are examples of using the allocation model as a planning tool. The allocation model could also be used as a management tool. The allocation model could be run from a given date using current crop and water status data to obtain recommendations about subsequent week decisions. During the following weeks, the model then could be rerun with updated data. The updated data could include past water allocation data and revised maximum potential yield ($Y_m$) estimates. A computer program written in QuickBasic to compute revised $Y_m$ values using FAO crop response models is presented in Appendix Table C.1. When used in the described manner, the water allocation model could serve as a real time management tool for allocating irrigation water.

5.2 Application of allocation model in other irrigation projects

One of the guidelines of this research was to develop a general water allocation model that can be applied to other similar canal based irrigation systems. The allocation model was validated using the soils, crops, canal description and
management data of the Maricopa Agricultural Center. The test results demonstrated allocation model applicability at MAC. Thus, it is expected that water allocation model also can be applied to different surface irrigation projects in other geographical areas.

The water allocation model uses input data from the irrigation scheduling and crop response models. Thus, the general application of the water allocation model depends on the input requirements and results of these models.

The irrigation scheduling model uses "growing degree days" based crop coefficients. This consideration helps to make the model applicable to other geographical locations. The input data requirements often are used as a criterion to determine the general applicability of irrigation management models. The irrigation scheduling model used in this study requires limited site specific soil, crop and weather information.

FAO crop response models are based on results from different geographical locations. Thus, the FAO crop response model can be used for almost any irrigation area of the world. However, locally available crop response models may more accurately predict crop yields in response to irrigation water applications.

The canal model examines allocation feasibility and recommends settings of control and turnout structures. The canal model used in this study is not capable
of accepting some standard control structures and turnouts, such as jack gate and trapezoidal ditch check, since it was specifically formulated for a canal irrigation project of Thailand. However, the model can be applied to other canal based irrigation projects with the inclusion of needed control structures and turnouts.

The allocation model uses multiperiod linear programming to allocate irrigation water in both time and space. The objective function was net benefit maximization, which is a common goal for irrigation projects. The constraints used in the allocation model, such as canal carrying capacity and water availability, can limit full irrigation practices in many surface irrigation projects. Worldwide availability of linear programming algorithms, like BDMLP used in this study, makes the allocation model applicable to different irrigation projects where site specific considerations can be addressed.
CHAPTER VI

SUMMARY AND CONCLUSIONS

6.1 Summary

An irrigation water allocation model was developed for irrigation planning and management to provide information for optimal allocation decisions for multicrop farming. Multiperiod linear programming was used to incorporate the interrelated factors of irrigation water demands, irrigation water supply, crop response to water, canal carrying capacity and water allocation criteria with the objective of maximizing the farm income. The allocation factors varied with both time and space. Basic input data used in the model were the maximum crop yield, crop price, irrigation water cost, irrigation labor cost, yield response factor, irrigation water demands, water supply and canal carrying capacity. Irrigation water demands of the crops were obtained from the irrigation scheduling program developed by the Department of Agricultural and Biosystems Engineering, University of Arizona (Scherer et al., 1990). FAO yield response factor reported by Doorenbos and Kassam (1979) were used to compute crop yield from irrigation water applications. Crop yield values were then used by the allocation model to recommend irrigation water allocation. A canal delivery model developed by the Department of Agricultural and Irrigation Engineering, Utah State University (Merkley, 1991) was used to check the ability of the canal system to supply the
recommended allocation quantities.

The allocation model was evaluated using crops, soils, canal description and irrigation management data of the Maricopa Agricultural Center, University of Arizona. The model was solved with the BDMLP linear programming algorithm of GAMS, a computer optimization package (Brooke, 1988). The allocation model was validated with the actual field data from MAC. The estimated annual benefit was found to be 442,000 dollars without water supply limitations. Cotton and grape fields received full irrigation throughout the growing season when CAP inlet capacity was reduced by 50 percent from its existing capacity. However, one wheat and two barley fields were stressed at the flowering stages resulting in reduced crop yields for the wheat and barley fields. The estimated yield reduction varied 1 to 3 percent. When CAP inlet capacity was reduced by 55 percent, five barley, one cotton, the grape and two wheat fields were allocated less than full irrigation quantities during different weeks of the growing season. The estimated yield reduction varied from 1 to 8 percent. The canals were found to be capable of distribution of irrigation water as recommended by the allocation model in the subsequent canal model tests.

The allocation model was used to examine the effects of the parameters, i.e. crop price, irrigation water cost and water supply, on the solution of the allocation model. Solutions obtained using the possible variations of these parameters in postoptimality analysis indicated the allocation model solution was
stable.

6.2 Conclusions

1. A multiperiod linear programming model can provide worthwhile irrigation allocation recommendations for use in irrigation system planning. The model also can be used in systematic analysis of parameters that influence the allocation decisions.

2. A water allocation model can be used to provide real time management recommendations for maximizing irrigation water benefits.

3. The FAO crop response model can provide a satisfactory estimate of crop yield resulting from irrigation water allocation decisions, but site specific data are preferred when available.

4. Available water supply is a limiting resource that affects water allocation decisions and net revenue. Where canal carrying capacity limits allocation quantities, analysis could determine the benefits of increased capacity.

5. The available FAO yield response factors predict crop yield assuming all growth periods except the period under consideration receive full irrigation. Yield response factors that predict the cumulative effect of individual
growth period allocations on final yield could improve benefit estimation capabilities.

6. The interaction of the irrigation scheduling, crop response, water allocation and canal delivery elements is very important to irrigation system management. A careful selection of irrigation scheduling and crop response models is essential to providing an accurate physical basis for making appropriate irrigation allocation decisions. An accurate evaluation of canal delivery capability is essential to the evaluation of allocation feasibility.

7. The allocation model developed in this study is judged applicable to other similar canal based irrigation projects. However, appropriate submodel constraints will be needed to match physical characteristics and data availability of those projects.

In addition to the above conclusions, the following observations were made relative to the use of a water allocation model:

1. The use of constant irrigation efficiency values throughout the crop growing season can underestimate the irrigation water demands during the initial growth stages. Thus, irrigation efficiency values that vary with the crop growing periods should be utilized if available.
2. The cropping pattern and schedule are key elements in determining the irrigation requirements. Cropping patterns could be evaluated to estimate relative benefits using the optimization model.

3. Postoptimality analysis is necessary to check the stability of allocation model solutions and also to determine the parameters most influencing allocation recommendations.
APPENDIX A

WATER ALLOCATION MODEL CODE IN GAMS
Table A.1  Water allocation model code in GAMS

$TITLE Water Allocation Model for MAC
$OFFUPPER

SETS

I  water sources
   / CAP /
J  field numbers
   / FIELD27 * FIELD31,
     FIELD32E, FIELD32W
     FIELD33 * FIELD39/
K  time steps
   / PERIOD1 * PERIOD52 /;

SCALARS

PX cost of water in dollar per cubic meter / 0.0418 /
SCOST irrigation labor cost in dollar per ha per irriga
CDEPTH canal depth in meter / 0.762 /
CBED canal bed in meter / 0.61 /
SSLOPE canal side slope / 1.00 /
ROUGH Manning's roughness coefficient / 0.013 /
FREBOARD freeboard in the main canal in fraction / 0.20 /
CAPC  Max CAP outlet capacity in cubic meter per sec / 0.56667 /
SLOPE main canal slope in fraction / 0.0007 /
MINIRRI minimum irrigation requirement / 100 /
IRTIME total irrigation time in hour / 168 /;

PARAMETER

FSIZE(J) field FSIZE in hectare

/FIELD27 34.54,
FIELD28 38.47,
FIELD29 36.71,
FIELD30 36.59,
FIELD31 34.89,
FIELD32E 18.86,
FIELD32W 19.22,
FIELD33 13.17,
FIELD34 14.43,
FIELD35 14.38,
FIELD36 13.50,
FIELD37 18.69,
FIELD38 18.69,
FIELD39 18.22/;
### Table A.1 Water allocation model code in GAMS (Continued)

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#### TABLE D(J,K) water demand by fields and periods in millimeter

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TABLE YH(J,K) maximum crop yield in tonne per hectare

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TABLE YH(J,K) maximum crop yield in tonne per hectare

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TABLE YH(J,K) maximum crop yield in tonne per hectare

```

Table A.1  Water allocation model code in GAMS (Continued)

PARAMETER MY(J) maximum yield used for imposing restriction

/FIELD27 1.799,
FIELD28 1.795,
FIELD29 1.735,
FIELD30 6.72,
FIELD31 1.958,
FIELD32E 5.38,
FIELD32W 6.72,
FIELD33 6.05,
FIELD34 7.17,
FIELD35 5.83,
FIELD36 1.877,
FIELD37 5.6,
FIELD38 3.34,
FIELD39 4.93/;

PARAMETER NIRRGATN(J) number of irrigation

/FIELD27 9,
FIELD28 7,
FIELD29 9,
FIELD30 7,
FIELD31 9,
FIELD32E 8,
FIELD32W 8,
FIELD33 7,
FIELD34 7,
FIELD35 7,
FIELD36 8,
FIELD37 7,
FIELD38 6,
FIELD39 7/;

PARAMETER LCOST irrigation labor cost in dollar;

LCOST = SUM(J, FSIZE(J) * NIRRGATN(J) * SCOST);  

PARAMETER DEPTH flow canal depth in meter;

DEPTH = CDEPTH * (1 - FREBOARD);

PARAMETER PERIM canal perimeter in meter;

PERIM = CBED + (((DEPTH)**2) + (DEPTH * SSLOPE)**2) ** 0.5) * 2);

PARAMETER WS(I) water supply in hectare-millimeter;

WS(I) = (360 * IRTIME * CAPC);

PARAMETER XSECTION flow cross sectional FSIZE of canal in square meter;

XSECTION = (((((DEPTH * SSLOPE) * 2) + CBED + CBED) * DEPTH) / 2);
Table A.1 Water allocation model in GAMS (Continued)

PARAMETER VELOCITY water flow rate using Manning's equation in the canal in meter per second;
VELOCITY = (((XSECTION / PERIM)** (2/3) ) * (SLOPE ** 0.5)) / ROUGH;

VARIABLES
X(I,J,K) water allocated amount in millimeter
Z total profit in dollar
CTAA(I,J) field wise total eta in millimeter
YIELD(J) field wise crop yield
SELL(J) field wise sell in tonne
WUSE(J) field wise water in cubic meter;

POSITIVE VARIABLE X, CTAA, YIELD, SELL, WUSE;

PARAMETER CTETH(I,J) field wise total etm in millimeter;
CTETH(I,J) = SUM(K, MET(J,K));

EQUATIONS
BENEFIT objective function in dollar
DEMAND(J,K) observe water demand in millimeter
SUPPLY(I,K) observe water supply in hectare·millimeter
CANAL(K) observe canal carrying capacity in hectare·millimeter
TOTAL(I,J) observe field wise total eta in millimeter
AYIELD(J) observe actual yield of the crops in tonne
CROPRES(J) observe crop response to irrigation water in tonne per hectare
RYIELD(J) observe restriction on minimum level of yield
WATERUSE(J) observe water use by fields in cubic meter;

BENEFIT.. Z =E= SUM(J, PY(J) * SELL(J) - PX * WUSE(J)) - LCOST;
DEMAND(J,K).. SUM(I, FSIZE(J) * X(I,J,K)) =L= FSIZE(J) * D(J,K);
SUPPLY(I,K).. SUM(J, FSIZE(J) * X(I,J,K)) =L= WS(I);
CANAL(K).. SUM(I, SUM(J, FSIZE(J) * X(I,J,K))) =L= 360 * XSECTION * VELOCITY * IRTIME;
RYIELD(J).. YIELD(J) =G= 0.5 * MY(J);
TOTAL(I,J).. SUM(K, (IE(J,K)/100)*X(I,J,K)) =E= CTAA(I,J);
AYIELD(J).. YIELD(J) * FSIZE(J) =E= SELL(J);
Table A.1  Water allocation model code in GAMS (Continued)

\[
\text{CROPRES}(J) \cdot \text{SUM}(I,K) \cdot Y(J,K) \cdot (1 - KY(J) \cdot (1 - \text{CTAA}(I,J) \\
/ \text{CTETM}(I,J))) = \text{YIELD}(J);
\]

\[
\text{WATERUSE}(J) \cdot \text{SUM}(I,K) \cdot 10 \cdot \text{FSIZE}(J) \cdot X(I,J,K) = \text{WUSE}(J);
\]

MODEL ALLOCATN / BENEFIT, DEMAND, SUPPLY, CANAL, TOTAL, AYIELD, RYIELD, CROPRES, 
WATERUSE/;

X.LO(I,J,K) = MINIRRI;

X.LO(I,J,K) $(D(J,K) GT (MINIRRI * 2)) = 0.5 \cdot D(J,K);

X.FX(I,J,K) $(D(J,K) EQ 0) = 0;

SOLVE ALLOCATN USING LP MAXIMIZING Z;

DISPLAY X.L, X.M,
APPENDIX B

MAIN AND SECONDARY CANAL PROFILES

AND

RESULTS OF THE CANAL DELIVERY MODEL
Table B.1  Main canal profile from CAP outlet E18-3 to Field 39

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Elevation of CAP outlet is 362.71 meter (Assumed)
Table B.1  Main canal profile from CAP outlet E13-8 to Field 39 (Continued)

<table>
<thead>
<tr>
<th>Distance in meter</th>
<th>Elevation in meter</th>
<th>Distance in meter</th>
<th>Elevation in meter</th>
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<td>2013</td>
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<td>2044</td>
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<td>2074</td>
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<td>3062</td>
<td>358.73</td>
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<td>2149</td>
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<td>3702</td>
<td>357.56</td>
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<td>358.87</td>
<td>3733</td>
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<td>3810</td>
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Table B.2  Secondary canal profiles (Fields 34 and 38)

<table>
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<th>Distance in meter</th>
<th>Elevation in meter</th>
<th>Remarks</th>
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<td></td>
<td>Canal 34</td>
<td>Canal 38</td>
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<td>360.05</td>
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<td>360.02</td>
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<td>61</td>
<td>360.02</td>
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</tr>
<tr>
<td>91</td>
<td>360.02</td>
<td>357.23</td>
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<td>122</td>
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<td>152</td>
<td>360.01</td>
<td>357.22</td>
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<td>183</td>
<td>359.95</td>
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<td>357.20</td>
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<td>244</td>
<td>359.90</td>
<td>357.20</td>
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<tr>
<td>274</td>
<td>359.90</td>
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<td>305</td>
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<td>357.16</td>
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<td>366</td>
<td>359.81</td>
<td>357.13</td>
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<td>357.16</td>
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<td>357.08</td>
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<td>579</td>
<td>359.56</td>
<td>357.08</td>
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<td>610</td>
<td>359.49</td>
<td>357.07</td>
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<td>640</td>
<td>359.47</td>
<td>357.07</td>
</tr>
<tr>
<td>671</td>
<td>359.44</td>
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<tr>
<td>732</td>
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<td>-</td>
</tr>
<tr>
<td>744</td>
<td>359.28</td>
<td>357.11</td>
</tr>
</tbody>
</table>
Table B.3  Results of the canal delivery model

:::steady-state canal hydraulic model:::
:::version 2.20:::
:::maricopa agricultural center:::
:::cap outlet e13-8:::

<table>
<thead>
<tr>
<th>Reach Name</th>
<th>Reach Order</th>
<th>Inflow (m³/s)</th>
<th>Outflow (m³/s)</th>
<th>Demand (m³/s)</th>
<th>Turnout (m³/s)</th>
<th>Lateral (m³/s)</th>
<th>Seepage (m³/s)</th>
<th>US_Depth (m)</th>
<th>DS_Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Reach1</td>
<td>001</td>
<td>0.570</td>
<td>0.380</td>
<td>---</td>
<td>---</td>
<td>0.190</td>
<td>0.000</td>
<td>0.539</td>
<td>0.686</td>
</tr>
<tr>
<td>Main Reach2</td>
<td>002</td>
<td>0.380</td>
<td>0.190</td>
<td>---</td>
<td>---</td>
<td>0.190</td>
<td>0.000</td>
<td>0.424</td>
<td>0.686</td>
</tr>
<tr>
<td>Main Reach3</td>
<td>003</td>
<td>0.190</td>
<td>0.000</td>
<td>0.000</td>
<td>0.190</td>
<td>0.190</td>
<td>0.000</td>
<td>0.290</td>
<td>0.686</td>
</tr>
<tr>
<td>Field37 Reach1</td>
<td>004</td>
<td>0.190</td>
<td>0.000</td>
<td>0.000</td>
<td>0.190</td>
<td>0.190</td>
<td>0.000</td>
<td>0.190</td>
<td>0.686</td>
</tr>
<tr>
<td>Field38 Reach1</td>
<td>005</td>
<td>0.190</td>
<td>0.000</td>
<td>0.000</td>
<td>0.190</td>
<td>0.190</td>
<td>0.000</td>
<td>0.468</td>
<td>0.549</td>
</tr>
<tr>
<td>Field39 Reach1</td>
<td>006</td>
<td>0.190</td>
<td>0.000</td>
<td>0.000</td>
<td>0.190</td>
<td>0.190</td>
<td>0.000</td>
<td>0.468</td>
<td>0.549</td>
</tr>
</tbody>
</table>

Reach Name is the given name of a reach in the data file; Reach Order shows the position of a reach within the canal system, numbering from upstream to downstream; Inflow is the flow rate entering the upstream end of a reach; Outflow is the flow rate exiting from the control structure at the downstream end of the reach; Demand is the outflow demand at the terminal points; Turnout is the farm turnout discharge; Lateral is the discharge of lateral off takes; Seepage is the seepage loss rate; US_Depth is the upstream flow depth; and DS_Depth is the downstream flow depth.

<table>
<thead>
<tr>
<th>Reach Name</th>
<th>Control Name</th>
<th>Control Type</th>
<th>Rank Number</th>
<th>Setting (m)</th>
<th>Flow (m³/s)</th>
<th>Total Flow (m³/s)</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>HeadGate</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.000</td>
<td>0.570</td>
<td>0.570</td>
<td>Zero Flow</td>
</tr>
<tr>
<td>Main Reach1</td>
<td>Main R1 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.339</td>
<td>0.380</td>
<td>0.380</td>
<td>Free Flow</td>
</tr>
<tr>
<td>Main Reach2</td>
<td>Main R2 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.152</td>
<td>0.190</td>
<td>0.190</td>
<td>Free Flow</td>
</tr>
<tr>
<td>Main Reach3</td>
<td>Main R3 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Zero Flow</td>
</tr>
<tr>
<td>Field37 Reach1</td>
<td>Field37 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Zero Flow</td>
</tr>
<tr>
<td>Field38 Reach1</td>
<td>Field38 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Zero Flow</td>
</tr>
<tr>
<td>Field39 Reach1</td>
<td>Field39 C1</td>
<td>Rectangular Sluice</td>
<td>1</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>Zero Flow</td>
</tr>
</tbody>
</table>

Control Name is the given name in the data file; Rank Number 1 indicates the control structures is adjustable type; Setting is the vertical opening of the gate; Flow is the discharge through the structure; Total flow is the sum of discharges through all control structure at the downstream end of each reach; and Flow Regime shows the flow regime, which may be either free flow, submerged flow, or zero flow (no flow).
### Table B.3 Results of the canal delivery model (Continued)

#### Farm Turnouts

<table>
<thead>
<tr>
<th>Reach Name</th>
<th>Turnout Name</th>
<th>Turnout Type</th>
<th>Location</th>
<th>US_Depth</th>
<th>DS_Depth</th>
<th>Setting</th>
<th>Supply</th>
<th>Demand</th>
<th>Flow</th>
<th>Flow Status</th>
<th>Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Reach1</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Reach2</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Reach3</td>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field37 Reach1</td>
<td>Field37 T1 Circ_Drifc</td>
<td>0.468</td>
<td>0.19</td>
<td>0.389</td>
<td>0.190</td>
<td>OK</td>
<td>Free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field38 Reach1</td>
<td>Field38 T1 Circ_Drifc</td>
<td>0.468</td>
<td>0.19</td>
<td>0.389</td>
<td>0.190</td>
<td>OK</td>
<td>Free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field39 Reach1</td>
<td>Field39 T1 Circ_Drifc</td>
<td>0.468</td>
<td>0.19</td>
<td>0.389</td>
<td>0.190</td>
<td>OK</td>
<td>Free</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Turnout Name is the given name in the data file; Turnout Type is the type of the turnout in the canal reach; Location is the distance measured from the upstream end of each canal reach; US_Depth is the upstream depth of each turnout; DS_Depth is the downstream depth measured from the bed of the upstream canal; Setting is the turnout structure opening; Supply is the discharge through the turnouts as calculated by the model; Demand is the desired demand entered in the operational data file; Flow Status indicates whether the supply is equal to demand or not; and Flow Regime shows the flow regime, which may be either Subm (submerged flow), Free (free flow), or None (no flow).

#### Lateral Offtakes

<table>
<thead>
<tr>
<th>Reach Name</th>
<th>Lateral Name</th>
<th>Location</th>
<th>US_Depth</th>
<th>DS_Depth</th>
<th>Turnout Type</th>
<th>Turnout Rank</th>
<th>Setting</th>
<th>Flow</th>
<th>Flow Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Reach1</td>
<td>Field 37</td>
<td>2322</td>
<td>0.673</td>
<td>0.468</td>
<td>Field37 L1 Circ_Drifc</td>
<td>1</td>
<td>0.213</td>
<td>0.190</td>
<td>Subm</td>
</tr>
<tr>
<td>Main Reach2</td>
<td>Field 38</td>
<td>744</td>
<td>0.682</td>
<td>0.468</td>
<td>Field38 L1 Circ_Drifc</td>
<td>1</td>
<td>0.212</td>
<td>0.190</td>
<td>Subm</td>
</tr>
<tr>
<td>Main Reach3</td>
<td>Field 39</td>
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<td>0.681</td>
<td>0.468</td>
<td>Field39 L1 Circ_Drifc</td>
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<td>0.212</td>
<td>0.190</td>
<td>Subm</td>
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<tr>
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<td></td>
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<td></td>
</tr>
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<td>Field39 Reach1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lateral Name is the given name as in the data file; Location is measured from the upstream end of the respective reaches; US_Depth is the upstream depth of each turnout; DS_Depth is downstream depth of the turnout; Turnout Type is the type of lateral offtake turnout in the reach; Rank number 1 indicates the turnout is adjustable type; Setting is the turnout structure opening; Flow is the discharge through the turnout; and Flow Regime shows the flow regime, which may be either Subm (submerged flow), Free (free flow), or None (no flow).
APPENDIX C

QUICKBASIC CODE FOR ACTUAL YIELD CALCULATIONS
Table C.1 QuickBasic code for actual yield calculations

'This program computes the actual yield of the selected crops using
'the FAO crop response models (Irrigation and Drainage Paper No. 33).
'This program has been written for the partial requirements of the
'dissertation research.
10 REM Programer Hurul Alam Akhand
20 REM This print the menu
30 CLS
40 PRINT "Calculation of Actual or Potential Yield"
50 PRINT "Using FAO Irrigation and Drainage Paper #33"
60 PRINT
70 PRINT "------------------------
80 PRINT "| 1 Vegetative Period |
90 PRINT "| 2 Flowering Period |
100 PRINT "| 3 Yield Formation Period |
110 PRINT "| 4 Ripening Period |
120 PRINT "------------------------
130 INPUT "Select One => "; MN
140 IF MN = 1 THEN
150 YA = YM * (1 - .2 * (1 - (X * IE) / MET)); PRINT
160 PRINT "The new potential yield of Barley, tonne/ha =>";
170 PRINT USING "##.##"; YA
180 END SELECT
190 CASE 2
200 YA = YM * (1 - .6 * (1 - (X * IE) / MET)); PRINT
210 PRINT "The new potential yield of Barley, tonne/ha =>";
220 PRINT USING "##.##"; YA
230 CASE 3
240 YA = YM * (1 - .5 * (1 - (X * IE) / MET)); PRINT
250 PRINT "The new potential yield of Barley, tonne/ha =>";
260 PRINT USING "##.##"; YA
270 CASE 4
280 YA = YM * (1 - .1 * (1 - (X * IE) / MET)); PRINT
290 PRINT "The new potential yield of Barley, tonne/ha =>";
300 PRINT USING "##.##"; YA
310 END SELECT
Table C.1  QuickBasic code for actual yield calculations (Continued)

380 RETURN
390 INPUT "Enter the potential maximum yield of Cotton, tonne/ha"; YM
400 PRINT
410 INPUT "Enter the amount of irrigation applied in this week, mm"; X
420 PRINT
430 INPUT "Enter the irrigation efficiency of this week, fraction"; IE
440 PRINT
450 INPUT "Enter the maximum ET of this week, mm"; MET
460 REM This print the menu
470 CLS
480 PRINT " 1 Vegetative Period "
490 PRINT " 2 Flowering Period "
500 PRINT " 3 Yield Formation Period "
510 PRINT " 4 Ripening Period "
520 PRINT " "
530 PRINT " "
540 PRINT " "
550 INPUT " SELECT ONE ="; MS
560 IF MS < 1 OR MS > 4 THEN 460
570 CLS
580 SELECT CASE MS
590 CASE 1
600 YA = YM * (1 - .2 * (1 - (X * IE) / MET))
610 PRINT "The new potential yield of Cotton, tonne/ha ="; YA
620 CASE 2
630 YA = YM * (1 - .5 * (1 - (X * IE) / MET))
640 PRINT "The new potential yield of Cotton, tonne/ha ="; YA
650 CASE 3
660 YA = YM * (1 - .45 * (1 - (X * IE) / MET))
670 PRINT "The new potential yield of Cotton, tonne/ha ="; YA
680 CASE 4
690 YA = YM * (1 - .25 * (1 - (X * IE) / MET))
700 PRINT "The new potential yield of Cotton, tonne/ha ="; YA
710 END SELECT
720 RETURN
730 INPUT "Enter the potential maximum yield of Grapes, tonne/ha"; YM
740 PRINT
750 INPUT "Enter the amount of irrigation applied in this week, mm"; X
760 PRINT
770 INPUT "Enter the irrigation efficiency of this week, fraction"; IE
780 PRINT
790 INPUT "Enter the maximum ET of this week, mm"; MET
800 REM This print the menu
810 CLS
820 PRINT " 1 Vegetative Period "
830 PRINT " 2 Flowering Period "
840 PRINT " 3 Yield Formation Period "
850 PRINT " 4 Ripening Period "
860 PRINT " "
870 PRINT " "
880 PRINT " "
890 PRINT " "
900 INPUT " SELECT ONE ="; MS
910 IF MS < 1 OR MS > 4 THEN 810
920 SELECT CASE MS
930 CASE 1
940 YA = YM * (1 - .3 * (1 - (X * IE) / MET))
950 PRINT "The new potential yield of Grapes, tonne/ha ="; YA
960 PRINT USING "##.###"; YA
970 END SELECT
980 RETURN
Table C.1  QuickBasic code for actual yield calculations (Continued)

```
CASE 2
  YA = YM * (1 - .5 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Grapes, tonne/ha =>";
  PRINT USING "##.##"; YA
CASE 3
  YA = YM * (1 - .25 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Grapes, tonne/ha =>";
  PRINT USING "##.##"; YA
CASE 4
  YA = YM * (1 - .25 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Grapes, tonne/ha =>";
  PRINT USING "##.##"; YA
END SELECT
780 RETURN
790 INPUT "Enter the potential maximum yield of Wheat, tonne/ha"; YM
800 PRINT
810 INPUT "Enter the amount of irrigation applied in this week, mm"; X
820 PRINT
830 INPUT "Enter the irrigation efficiency of this week, fraction"; IE
840 PRINT
850 INPUT "Enter the maximum ET of this week, mm"; MET
860 REM This Print the menu
870 CLS
880 PRINT ; PRINT
890 PRINT "-----------
900 PRINT " 1 1 Vegetative Period !"
910 PRINT " 1 2 Flowering Period !"
920 PRINT " 1 3 Yield Formation Period !"
930 PRINT " 1 4 Ripening Period !"
940 PRINT "-------------
950 PRINT ; PRINT
960 IF MS < 1 OR MS > 4 THEN 860
965 CLS
970 SELECT CASE MS
CASE 1
  YA = YM * (1 - .2 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Wheat, tonne/ha =>";
  PRINT USING "##.##"; YA
CASE 2
  YA = YM * (1 - .6 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Wheat, tonne/ha =>";
  PRINT USING "##.##"; YA
CASE 3
  YA = YM * (1 - .5 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Wheat, tonne/ha =>";
  PRINT USING "##.##"; YA
CASE 4
  YA = YM * (1 - .1 * (1 - (X * IE) / MET)): PRINT
  PRINT ; "The new potential yield of Wheat, tonne/ha =>";
  PRINT USING "##.##"; YA
END SELECT
980 RETURN
```
REFERENCES


Merkley, G. P. 1992. Personal communication. Department of Agricultural and Irrigation Engineering, Utah State University. Logan, UT.


