SHALLOW STORAGE IRRIGATION

FOR SORGHUM PRODUCTION IN NORTH-WEST QUEENSLAND

J.F. CLEWETT

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FOREWORD

Australia has extensive areas of semi-arid grazing lands which are economically important, but subject to wide variations in rainfall so typical of semi-arid climates. The often severe disruption caused by this variability to the productivity of animals grazing native pasture is not unique to Australia. However, Australia is uncommon in possessing both this significant problem, and the appropriate scientific resources to develop methodologies that can usefully assist land management in the semi-arid zone.

Whilst control of a region's climate may well be outside the feasible economic reach of mankind, there are many land management options which need to be investigated. This book describes and evaluates one such option:– the use of shallow farm dams to temporarily store water for strategic irrigation of animal fodders such as sorghum crops which may be harvested and subsequently used to feed animals that are grazing parched pastures.

The benefits of irrigation, even limited supplementary irrigation, are well known. But, how feasible is this in a context of a surface water supply dominated by the climate, in a topographic and economic context which allows only shallow storage of water that is then so vulnerable to evaporative loss? Occasional success in such an enterprise has been experienced. But what is the productive and economic future of this practice in the longer term?

Indeed is it at all possible to escape from the tyranny of specificity in the place and time of field experiments? What if our expensive field experiments were all carried out in the proverbial "seven good years" or the "seven lean years"? Are they almost valueless, or can we use the wit of man to overcome these apparently cruel limitations?

It is in the face of such very real and demanding questions that Australian scientists have provided prominent international leadership in the development of modelling methodologies. Griffith University in collaboration with the Queensland Department of Primary Industries have been involved also in the development, application and testing of this approach. In this approach, experimental work is seen as interactive with and complementary to analysis of our current understanding of the physical, biologic and economic systems involved.

The School of Australian Evironmental Studies of Griffith University has shared with the Queensland Department of Primary Industries a deep interest in not only understanding the components of environmental and productive systems, but also putting knowledge of these components together to provide a quantitative representation of the systems with which we are concerned. This synthesis transforms knowledge of components into a form more relevant to management decisions.

The following considerations show that the problem considered in this book is a very clear example of the need for an approach which integrates the behaviour of component sub–systems so that the behaviour of the whole system can be understood: The biological and economic output of a shallow storage irrigation system involves the generation and collection of occasional runoff, and competition between its use in supplementary irrigation and loss by evaporation if stored for irrigation over time.. Also crop growth in response to weather and alternative irrigation strategies requires recognition that the effects of water stress on yield depend strongly on the stage of phasic development of the crop at which such stress occurs. Economic evaluation must consider alternative scales of operation and the relative frequency of possible outcomes in the face of long–term climatic variability.

What might be optimum strategies for such a complex system? Answers are certainly not intuitively obvious. However, when all the component sub-systems are brought together, much as a conductor produces a symphony from the varied output of component instruments, then the overall message emerges.

The examiners of the Ph.D. thesis on which this book is based expressed considerable approval of the manner in which this analysis of components and their integration to provide practical answers was achieved.

To emphasise the significance of synthesis and the importance of the integration of knowledge it was decided to publish the work as a single book rather than as fragmented articles distributed possibly in more than one journal. This book form also provides a vista of how the complex problems of agricultural systems can be clarified by the powerful methodology of interacting systems modelling with field experimentation.

This book provides answers to the specific questions outlined earlier for a broad production region of Australia. We are bold enough to hope that this significant case study in the use of systems methodology will provide stimulation and encouragement to others dealing with complex systems, even if these systems and their problems are quite different in character from those addressed in this book.

I thank the author for his invitation to introduce this volume, and record my pleasure at the interaction which led to its present form.

Prof. Calvin Rose

Calvin Rose

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Many have shared with me in the development of views and information given in this monograph. It is with great pleasure that I thank:

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Jeff Clewett

Jeff Clewett

SUMMARY

The Mitchell grass plains of North West Queensland are used almost exclusively for extensive grazing by sheep and cattle. However, the nutritive value of pastures is frequently poor and thus strategic use of grain and forage supplements to boost wool and beef production has been considered by many graziers in the region. Therefore, opportunities for crop production in this tropical, semi-arid area need to be evaluated.

The gently undulating topography and fertile, cracking clay soils of the Mitchell grass plains are well suited to agriculture but rainfall, which is highly variable and strongly seasonal (summer dominant), is only sufficient for dryland forage cropping in about twenty percent of years. The region's mean annual rainfall is 400 mm. The land system is also well suited to storage of ephemeral run-off in shallow but expansive farm dams, and use of such dams for irrigation of crops is termed 'shallow storage irrigation'. Distinctive features of shallow storage irrigation are: rapid use of water for irrigation before evaporation losses become too great, and agricultural use of the bed of the dam. This latter feature is termed 'ponded-area' cropping and is practised by planting successive strips of crop around the edges of the dam as irrigation and evaporation cause the dam's water line to recede.

This study evaluates the biophysical and economic potential of irrigated grain sorghum and ponded-area forage sorghum production from shallow storage irrigation systems on the Mitchell grass plains of north west Queensland.

The method of research was based on a systems analysis approach. A series of field experiments was conducted with the results being used to develop a weather driven mathematical model that would simulate the performance of a shallow storage system. This required division of the cropping system to its component parts so that the effects of major factors such as the weather and management on processes within components could be determined and understood. However, more importance was attached to the performance of the whole system and thus emphasis was given to the integration of information.

The field experiments were conducted at the Queensland Department of Primary Industries' Richmond Shallow Storage Research Project at Richmond in north west Queensland. These experiments included: (i) observations of run-off from a 160 ha native pasture catchment from September 1968 to October 1978, (ii) effects of irrigation strategy and plant density on the components of grain sorghum yield, and (iii) the effects of time of planting and nitrogen fertilizer on ponded-area forage sorghum yield.

The shallow storage systems model was composed of: (i) four physical component models to estimate: catchment run-off, water storage in the dam, irrigated grain sorghum production, and ponded-area forage sorghum production, and (ii) a financial accounting model to estimate annual costs of crop production. A water balance sub-model was included in each of the physical component models. The catchment run-off model also included a pasture biomass sub-model because of the significant influence that temporal changes in pasture biomass were observed to have on infiltration and run-off. The irrigated grain sorghum production model included sub-models for planting strategy (time and area), irrigation strategy (area, frequency and timing), phasic development and yield. The ponded-area forage sorghum model included sub-models for planting strategy (timing and area) and dry matter yield. Cumulative evapotranspiration, temperature and plant density were used as predictors of forage yield.

The systems' model and long-term (60 year) weather records of daily rainfall and mean monthly temperature from the Richmond Post Office were used in a series of computer simulation experiments. These experiments showed that large changes in crop production and costs of production resulted from: (i) climatic variability, (ii) changes in management strategy such as time of planting and irrigation, and (iii) changes in the system's design such as the shape and size of the dam and the size of the irrigation area.

Dryland grain sorghum yields were estimated to range from 160 to 3190 kg/ha with yields in excess of 2000 kg/ha (the estimated economic minimum) occurring in only 12 percent of years. Grain yields were found to increase with increasing irrigation frequency up to a maximum yield of 4387 kg/ha when three irrigations were applied. Water stress during the flowering phenophase was found to reduce yield more than stress at other growth stages. The application of one supplementary irrigation timed to occur at early flowering was estimated to give a long-term mean yield of 3154 kg/ha. The long-term mean dry matter yield of forage sorghum grown on the ponded-area during autumn and winter was estimated to be 1.6 t/ha. The range in yields was 1.3 t/ha for crops grown on stored soil moisture alone to yields exceeding 7 t/ha for crops receiving unusually high winter rainfall.

Principles of shallow storage design and management that minimized the cost per tonne of crop production were isolated from the results. Two such principles were: (i) the designed capacity of the dam and size of the irrigation-area should be matched so that the dam can potentially water the irrigation-area twice without further recharge from run-off, and (ii), a flexible irrigation strategy should be used which has three irrigations in the schedule (with irrigations timed at the floral initiation, flowering and grain filling phenophases of grain sorghum), but if water supply is limited then priority should be given to maximizing the area of irrigation at flowering.

The frequency and magnitude of catchment run-off was by far the most important factor affecting crop production. The effects of rainfall variability on catchment run-off and subsequent irrigation supplies had far more effect on the variability of crop production than other factors such as the direct effects of rainfall variability, temperature and evaporative demand on crop yields.

The catchment run-off model was found to accurately estimate daily run-off (R^2 = 0.89) during the field experimental period when the mean and median depth of annual run-off from the catchment were measured to be 76 and 50 mm respectively, and sufficient run-off for irrigated cropping occurred in eight out of ten years. However, the simulation results suggest that this data is biased when compared to long-term averages. The mean annual depth of run-off over the 60-year simulation period was only 35 mm and annual run-off was 5 mm or less in 50 percent of years. Sufficient run-off for irrigated cropping was estimated to occur in only 42 percent of years and in one eight year period there were seven years in which run-off was negligible.

It was therefore concluded that evaluation of shallow storage irrigation without reference to long-term weather records would have been misleading. Conclusions of a general nature which follow from this are:

(i) Short-term measurements of biological productivity can give misleading estimates of the mean and median in climates as variable as the climate of the Mitchell grass plains.

(ii) Where field experiments are conducted in variable climates it is important to measure the environmental conditions of the experiment and to then test the results over long periods of time. This implies that modelling and simulation are essential components of the research method.

(iii) It is important to obtain field data from a diversity of environmental conditions so that parameters in the model are not biased.

(iv) Emphasis should be attached to variation in short-term (5-10 years) production because of its relevance to the horizons of farm planning.

The main finding of this study was that crop production from shallow storage irrigation systems was not reliable and does not have the necessary low cost productivity for inclusion in animal production systems on the Mitchell grass plains of North West Queensland. Shallow storage irrigation has the biological capacity to boost animal production but it fails because of economic considerations.

Although the above conclusion is negative in terms of agricultural production, the study was successful with respect to evaluating an agricultural system. The results have been useful in countering a renewed interest by graziers in agriculture. In extending information to primary producers the author has found that information taken directly from the field experiments has been useful but of limited value. Producers have found it difficult to see the relevance of isolated pieces of information because of the problems of integrating to the whole system. In contrast, results from the simulation experiments (such as a time series of crop yields, profits and losses) have had an immediate impact on producers. Therefore, the study was successful in its objective of measuring the key variables and then integrating the field data to a form pertinent to management decision making.

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EQUATION NOTATION

The '=' sign is used in both the normal mathematical sense of equality, and, on occasions in the FORTRAN programming sense of replacement. Variables are commonly identified by character strings as in FORTRAN. The expressions 'min (Argument 1, Argument 2)' and 'max (Argument 1, Argument 2)' are used to specify the minimum and maximum respectively of terms enclosed by brackets, and 'ln (x)' and 'exp (x)' are used to specify the natural log and exponential respectively of terms enclosed by brackets.

CHAPTER 1

DEFINITION OF PROBLEM

1.1 Introduction

The Mitchell grass plains occur in Australia's semi-arid zone and are used almost exclusively for extensive sheep and cattle grazing. They sweep in a discontinuous arc from the Kimberley region of Western Australia, through the Northern Territory and Queensland to the New South Wales Border (Moore and Perry 1970). Queensland's northern Mitchell grass plains that are the focus of this study occupy some 10 M ha, form a reasonably homogeneous bio-physical unit and have an approximate geographic centre of 144 East, 22 South (see figure 1.1). Future references to the Mitchell grass plains will apply to this study region.

The gently undulating topography of the Mitchell grass plains naturally lends itself to storage of ephemeral run-off in shallow farm dams. Use of such dams for irrigation of crops has been considered in the study region as one way of producing stock feed needed to improve animal production. The term used to describe this agricultural system is shallow storage irrigation and an example of such a scheme is shown in plate I.

This monograph uses systems analysis methods to evaluate field data and assess the potential for grain and forage sorghum production from shallow storage irrigation systems on the Mitchell grass plains. The shallow storage irrigation scheme shown in Plate I is central to the study as it was the site of run-off observations and field crop experiments reported herein.

This chapter discusses the rationale for cropping on the Mitchell grass plains, gives details of the agricultural environment and gives further information about the concept of shallow storage irrigation. The details of this first chapter are important to defining the objectives of study given in chapter 2. They are also important to later chapters that give the results of field experiments and develop a mathematical model of the shallow storage irrigation system. The model and long-term weather records are used in computer simulation experiments to quantify changes in crop production that result from changes in the weather or from changes in the system's design and management.

1.2 The Rationale for Cropping on the Mitchell Grass Plains

The Mitchell grass plains are of considerable economic importance in Queensland. They carry up to 50% of the State's sheep population and a small but significant proportion of the cattle population (Australian Bureau of Statistics 1975). Typical properties in the region range in size from 5,000 to 30,000 ha, carry 3,000 to 20,000 sheep, and are normally operated by a manager plus one farm hand (Australian Bureau of Statistics, 1979).

Annual rainfall in the region averages less than 500 mm, is highly variable and strongly seasonal, with 75% normally occurring in the months of December to March, defined here as the 'wet season'. This rainfall pattern and the generally hot arid conditions of the environment leads to: frequent drought, pasture of low protein content during the dry season, a seasonal pattern of animal liveweight gains and losses, high rates of reproductive failure in sheep and high rates of animal mortality (Moule 1954, 1956; Smith 1962, 1964, 1965; Rose 1972, 1976; Lorimer 1976; McCown 1981; McCown et al. 1981). Animals are generally expected to gain weight from the onset of the wet season until May, maintain weight during winter, and lose weight during the hot arid months of spring.

Stephenson et al. (1976) and Knights et al. (1979) showed that increases in the plane of nutrition available to ewes and weaners led to substantial increases in productivity. White (1978) calculated that the sheep industry of the study region would benefit by $10 million per annum if the number of lambs reared to the number of ewes joined could be increased by ten percent above the current low level of forty-five percent.

Attempts to improve animal nutrition by introducing legumes to the native pasture, or by replacing the native pasture grasses with exotic species, have not been successful and the prospects for success in this direction are remote.

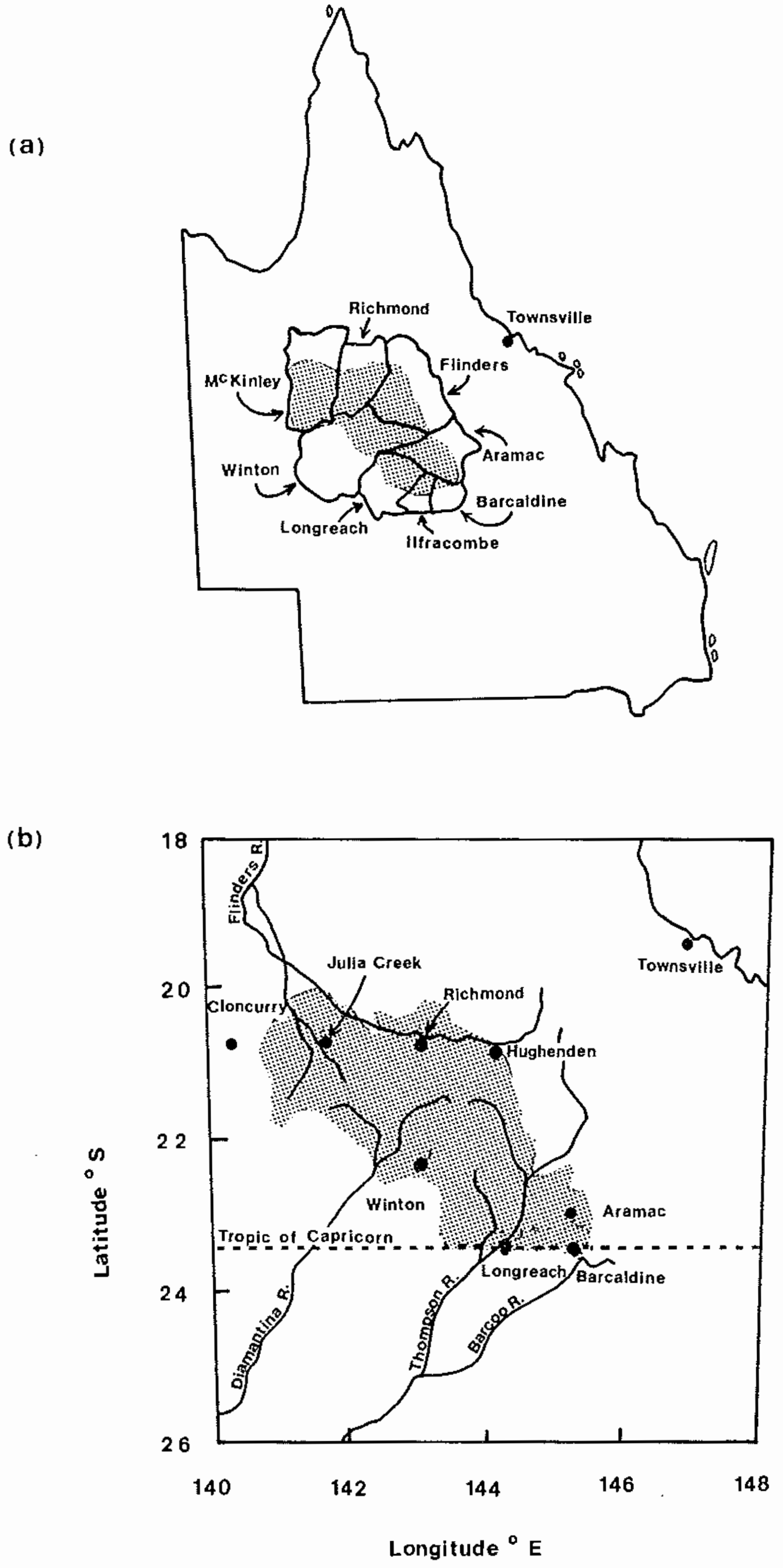


Figure 1.1 Location of Mitchell grass plains study region (shaded area) with respect to: (a) local government authority areas of Queensland and (b) townships and river systems. (Source: Queensland Resources Atlas, 1980)

Plate 1 Aerial view of the Queensland Department of Primary Industries Richmond Shallow Storage Research Project on the Mitchell grass plains at Richmond in north west Queensland (May 1970). This experimental site was set up in 1967 with field studies continuing until 1976. Ephemeral run-off from a 1660 ha native pasture catchment was temporarily stored in this scheme in a 400 ML dam before it was used to irrigate 25 ha of grain and forage crops. The irrigation-area is shown as the dark patch in the centre of the photograph. Although the dam was 600 m wide at the wall and covered 60 ha of land when it was full, the maximum depth of water stored was only 2 m with 50 percent of water stored in the top 50 cm. Thus, evaporation losses rapidly reduced the dam's surface area and volume. A plan of the experimental site is shown in figure 3.1 on page 26.

Poor animal nutrition has given impetus to cropping as a means of providing additional stock fodder. Possible stock management options using crops to improve nutrition are: feeding crop supplements such as grain, hay or ensilage to pregnant/lactating ewes during spring to increase reproductive rates; feeding crop supplements to weaner sheep to decrease mortality and possibly increase their life time wool-clip and reproductive capacity; supplementing rams and bulls; fattening bullocks by grazing forage crops; and conservation of forage for drought mitigation. Whilst this latter management alternative has fallen from economic favour (Morley and Ward 1966) it is retained here because biological gains are potentially great.

Widespread cropping with forage sorghum for silage production during the 1960's showed that the fertile, cracking clay soils and gently undulating topography of the Mitchell grass plains were well suited to cultivation (Skerman 1958). Cropping was successful in some years, but the climate was found to be too variable and too arid for sustained dryland agriculture (Commonwealth Bureau of Agricultural Economics 1964; Clewett 1969; Weston 1971; Skerman 1978; Clewett and Pritchard 1980). Clewett (1969) estimated from water balance studies that dryland forage crops could be grown in only thirty percent of years and therefore concluded that irrigation was an essential requirement for successful crop production.

In reviewing climatic limitations of dryland cropping, Weston (1965, 1972) observed that crops could be planted in a high percentage of years, but many failed to reach maturity through the lack of follow up rain. Weston contended that the heavy rains which allowed planting also produced considerable run-off. He therefore proposed that the reliability of crop production could be increased to approximately 70% of years if run-off was stored in farm dams for subsequent irrigation. The concept of storing ephemeral run-off in farm dams as an irrigation supply for cropping gained momentum during the 1960's, and is now known in the region as shallow storage irrigation (Weston 1972).

The Queensland Department of Primary Industries began a research programme to investigate the possibilities of crop production from shallow storage irrigation systems in 1967. As a consequence, the Richmond Shallow Storage Research Project (RSSRP) was established for field experiments at Richmond (20°44'S, 143°07'E) in north west Queensland (see plate I). Run-off from native pasture to the dam at the RSSRP was measured by a weir installed by the Queensland Water Resources Commission in 1968.

Crop production experiments conducted at RSSRP from 1970 to 1976 were the responsibility of the author. This monograph uses data collected from the experimental programme at RSSRP.

Previous analyses of shallow storage irrigation by Wegener and Weston (1973), Clewett (1975) and Skerman (1978) have shown that the system has merit. However, these analyses have been mainly qualitative and have excluded the interactive effects of climatic variability with system design and management. Therefore, further examination of crop production from shallow storage irrigation systems is warranted.

1.3 The Agricultural Environment of the Mitchell Grass Plains

Features of the study region's agricultural environment that are discussed below include its physiography, climate, soils, vegetation and cropping history. Surface run-off from native pasture is also considered because of its important influence on the supply of water for irrigation. Vegetation is considered because of its effect on surface run-off.

The two most outstanding features of the Mitchell grass plains are firstly, the spatial homogeneity of physiography, soils, vegetation and land use, and secondly, extreme temporal variation in rainfall, run-off, plant growth and animal production. Spatial variation in climate is not pronounced. Maps that show the Mitchell grass plains as a homogeneous unit are the soils map by Campbell et al. (1970), the vegetation map by Weston and Harbison (1980) and the land use map by Skerman (1970).

Further evidence of spatial homogeneity is provided by the land resources survey of the Gilbert-Leichardt area (28 M ha) by Perry et al. (1964) which included 4.8 M ha of the Mitchell grass plains on its southern boundary. Although the survey identified 61 land systems possessing similar topography, geology, soils and vegetation, the Mitchell grass plains were shown as one unit, the Julia land system, that was only interrupted by some narrow alluvial deposits along tributaries of the Flinders River.

Physical aspects of the regions agricultural environment and the regions history of cropping are described in the following sections.

1.3.1 Physiography

The northern portion of the study region is drained to the Gulf of Carpentaria by the Flinders River whereas the southern portion is drained to Lake Eyre by the Diamantina, Thompson and Barcoo River systems (see figure 1.1(b)).

The region's homogeneity can be traced in part to its common lithology. In early Mesozoic times an inland sea covered the entire region, and as marine sediments were deposited in depths ranging from 600 to 1,500 m the Pre-Cambrian basement of inland Queensland sagged to form the Great Artesian Basin (Prichard 1964). These Cretaceous sediments are now exposed and undergoing a phase of erosion. Elevation is 100 to 300 m, and except for some rare flat topped residuals of laterized material in the south which have resisted erosion, the local relief of the gently undulating plains is less than 30 M. The gradient of local stream channels typically ranges from 1:100 to 1:2000 and the gradient on major rivers is often less than 1:5000.

1.3.2 Climate

The restrictions that climate places on plant growth is dominated by the absence of rainfall rather than temperature or radiation (Fitzpatrick and Nix 1970). Climatic classification by Thornthwaite (1948) is semi-arid tropical, whereas Koppen (1936) classified the region as semi-arid steppe. Perry (1970) places the region within Australia's arid zone.

Three factors contribute to the regions climatic characteristics; the absence of topographic relief, continental insulation and latitudinal position. The combination of these factors produces a climate which shows some spatial trends, but more importantly a climate with extreme temporal variation in rainfall. Dick (1958) shows that the regions temporal variability in rainfall is outstanding when compared to other regions of the world with a similar mean annual rainfall.

Latitudinal position and continental insulation place the region at the limit of rain bearing weather systems, and thus rainfall is highly variable. The lack of surface relief results in only gradual climatic change. Analysis by Stewart (1973) showed that the rain bearing frontal systems which continually cross southern areas of the continent in winter, seldom penetrate to north Queensland. High temperatures and winds from the north often produce a weak trough along the region's interior border during the early summer months. These conditions produce scattered electrical thunderstorms, but their effectiveness is minimized by high levels of evaporative demand, often exceeding 10 mm/day of Class A pan evaporation.

Conditions are more favourable for deeper intrusions of maritime air associated with the southern advance of the intertropical convergence zone from December to March. Continental insulation precludes the north-west monsoon as a reliable source of rainfall. The principal source of summer rainfall is from highly variable tropical cyclones degenerating to large rain depressions as they move inland.

The long term means of temperature, evaporation and rainfall at seven locations on the Mitchell grass plains are given in table 1.1. This data illustrates a number of features. Firstly, the climate's pronounced seasonality with little spatial variation. The slightly cooler temperature, lower summer rainfall and high winter rainfall at Longreach compared to more northern towns is caused by effects of latitude on radiation and synoptic patterns. Secondly, extremely hot, dry weather conditions prevail during summer. Frosts are not common in the region, Winton having an average of four light frosts per year. Thirdly, median annual rainfall is considerably less than mean annual rainfall.

Marked seasonality in rainfall leads to the expressions 'wet season' for the summer months (November to April inclusive), and 'dry season' for the winter and spring. Annual rainfall is frequently expressed on a climatic year basis (October to September) rather than on a calendar year basis and is used throughout this study.

Three separate distributions are evident in the temporal distribution of rainfall. The first is seasonal (shown in table 1.1), the second is annual, and the third is longer with an

Table 1.1 Characteristics of climate at seven locations on the Mitchell grass plains

Location	Mean daily Temperature (°C)				Mean daily Evapn.+ (mm)		Mean Annual Evapn.+ (mm)	Rainfall (mm)			
	maximum		minimum					Mean Annual	Median Annual	Mean Wet Season*	Mean Dry Season**
	Jan.	July	Jan.	July	Jan.	July					
Northern Towns											
Hughenden	36.1	24.5	23.1	9.5	7.2	4.0	1954	497	488	401	86
Richmond	36.9	25.7	23.0	8.9	7.3	3.6	2046	471	420	406	65
Julia Creek	33.8	26.1	23.8	8.8	-	-	-	458	413	400	58
Cloncurry	37.8	25.2	25.0	10.7	8.1	3.5	2106	470	443	412	58
Southern Towns											
Barcaldine	35.8	22.8	22.8	7.4	7.4	3.0	1860	502	456	362	140
Longreach	37.3	23.2	22.6	6.9	7.7	3.0	1978	442	392	331	111
Winton	37.7	24.1	22.6	7.7	7.9	3.2	2052	407	339	319	88

Source: Bureau of Meteorology (1975).
+ Approximation of Penman evaporation (Kieg and McAlpine 1969).
* November to April inclusive.
** May to October inclusive.

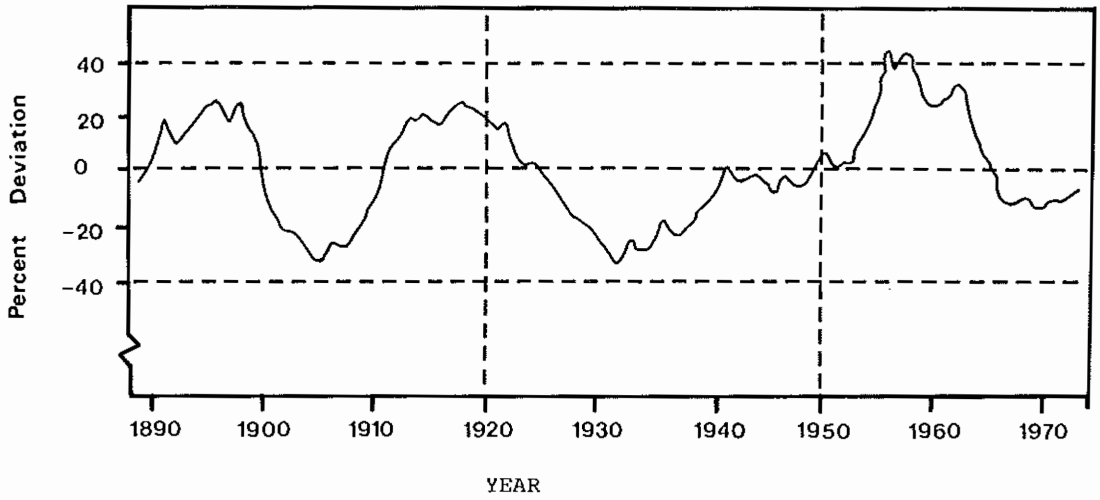


Figure 1.2 Percent deviation of ten-year mean rainfall from the long-term mean rainfall at Aramac, Queensland. (Source: White 1978)

ill-defined periodicity. These last two distributions are illustrated in figure 1.2. Analysis of annual rainfall in Queensland by Stewart (1973) showed the characteristics of long term oscillations were not predictable. Nevertheless, such oscillations have been of great importance to the viability of the pastoral industry.

Oscillations in rainfall lead to an ever-present hazard of drought. Everist and Moule (1952) showed that the probability of drought exceeding eleven months in the Richmond, Winton and Longreach districts was 0.12, 0.16 and 0.16 respectively. The probability that drought would exceed four months at these centres was 0.90, 0.85 and 0.74 respectively.

Slayter (1964) quantified the aridity and variability of the environment by using water balance methods to estimate the length of the growing season for native pastures and agricultural crops. Probabilities of pasture growth exceeding 8, 12 and 20 weeks in any year were found to be 0.74, 0.52 and 0.13 respectively at Richmond. Comparable probabilities of the growing season for agricultural crops were found to be 0.28, 0.15 and 0.03 respectively. The mean date of planting rains was mid January with a standard deviation of one month. The longer growing season for pastures was associated with their ability to grow on falls of rain that occurred before the heavy rains that were required to initiate planting. The only other climate data examined by Slayter on the Mitchell grass plains were from Hughenden where growing season lengths were found to be slightly longer than for Richmond.

1.3.3 Soils and Vegetation

Weathering of the siltstone and fine grained argillaceous greywacke sediments underlying the Mitchell grass plains has led to the formation of brown clay soils. These soils lack profile development, crack extensively when dry, and contain free gypsum at depth (Stace et al. 1968). The soil is defined as Ug 5.3 in the Northcote (1965) classification system and as 'grey-brown soils of heavy texture' in the Stephens (1962) classification.

The physical and chemical properties of the solum relate to its high clay content (approximately 64%). Below the top few centimetres of surface soil, which is typically strong fine granular and self mulching, the soil structure is classed as massive. Soil water holding capacity is high. Estimates of water storage at 'field capacity' (0.1 bar) and 'wilting point' (15 bar) are approximately 0.44 and 0.24 g/g respectively. In dry soil, cracks extend to the bottom of the solum and may be 8 cm wide at the surface. In the absence of cracking, infiltration rates are low (6 mm/hr). The C horizon of yellow impermeable clay usually occurs at a depth of approximately one metre. This clay is a good building material for the construction of water storages.

Low soil permeability prevents leaching so that bases and salts are retained in the profile. Chemical analysis data are shown in table 1.2. This table shows soil reaction to be alkaline with high base saturation and accumulation of salts at depth. The level of salt is not restrictive to plant growth and values of sodium not sufficiently high to cause dispersion. The availability of major bases is adequate for plant growth. Studies by Skerman (1958), Denning and Bell (1974), and Scanlan (1980) showed plant growth to increase with application of nitrogen, phosphorus and possibly manganese; however application of potassium, boron, magnesium, copper, zinc, iron and molybdenum did not increase yields. The supply of sulphur is generally adequate because free gypsum is usually present.

Vegetation on the Mitchell grass plains is characterized by the presence of one of the four species of Mitchell grass (Astrebla spp., mainly A. Lappacea), the absence of trees or shrubs (sometimes sparsely present) and a wide variety of annual grasses and forbes (Blake 1938; Davidson 1954; Everist 1964; Perry and Lazarides 1964). Other perennial grasses include Aristida latifolia (feathertop), Dichanthium sericeum (blue grass) and Eulalia fulva (brown top). The most important of the annual grasses is Iseilema spp. (Flinders grass).

Perry (1970) describes the plant community as one with discrete tussocks of Mitchell grass up to 100 cm high, 30 cm in diameter and 50 cm or more apart with some spatial organisation. The spaces between tussocks are bare in long dry periods but support a wide variety of annual grasses and forbes following rain. In dry weather each tussock is isolated by deep cracks in the soil. Basal cover is usually less than 4%.

Peak biomass is usually reached by April–May following cessation of summer rain. Winter rainfall promotes the growth of forbes but has little effect on Mitchell grass growth (Roe and Allen 1945; Scanlan 1980) and often accelerates the decline in pasture quality. Dry matter pasture yields range from almost zero in droughts to about 3000 kg/ha in high rainfall years (Orr 1975).

1.3.4 Surface Run–off

There are a number of qualitative conclusions that can be made from the foregoing sections about surface run–off and water supplies for shallow storage irrigation systems. Firstly, annual run–off should be low because of: the region's aridity, the gently undulating topography, the high infiltration rate of the soil when it is dry (i.e. infiltration via cracks), and the high water holding capacity of the soil. Secondly, annual run–off should be highly variable because: annual rainfall is highly variable, and the infiltration rate of the soil is low when fully wetted (soil cracks are closed). Finally, the extreme changes in surface vegetation of native pasture caused by the 'tide' of droughts and good seasons should have significant effects on run–off. This has been found in other environments where decreases in catchment vegetation due to drought, burning or increased grazing pressure have led to increased run–off (Hibbert 1967; Schreibner and Kincaid 1967; Sartz and Tolsted 1974; Hawkins and Gifford 1979; and Pressland 1982, 1983).

Measurements of stream flow have been recorded at very few sites on the Mitchell grass plains. The records that are available are summarized in table 1.3. The two most important features of this table are the high variability of annual run–off and the very short duration of records. The length of record is too short to adequately calculate statistical parameters and distributions such as the mean and the probability of exceedance of annual flows.

A number of studies have attempted to estimate the long term characteristics of run–off from the Mitchell grass plains by analysis of rainfall records. Weston (1972) examined long term, daily rainfall records for six towns from Hughenden to Cloncurry and estimated run–off to occur in 70% of years and to occur if daily rainfall exceeded 75 mm in November–December, 50 mm in January–April, and 100 mm in May–October. These criteria were based on some field observations and the experiences of graziers in the region.

Morwood (1976) assessed run–off characteristics throughout Queensland using the USDA–SCS run–off model which empirically relates run–off to rainfall, soil type and vegetation. For the Mitchell grass plains at Richmond, Moorwood estimated run–off to

Table 1.2 Soil analysis data from two sites on the Mitchell grass plains

Profile	B144*				B146**				
Depth (cm)	0–10	10–45	45–90	90–115	0–8	8–45	45–71	71–84	84–115
pH	8.0	7.4	7.7	7.8	8.4	9.0	9.2	9.1	7.8
Total sol. salts (%)	0.05	1.67	2.35	4.67	0.02	0.07	0.11	0.15	1.15
Chloride (% NaCl)	0.01	0.03	0.24	0.49	0.01	0.02	0.02	0.04	0.21
$CaCO_3$ (%)	0.02		0.07		0.02	0.14	0.36	0.42	0.27
Organic carbon (%)	0.44				0.48	0.42	0.44	0.43	
N (%)	0.051				0.046	0.041	0.042	0.038	0.020
C/N ratio	9				10	10	10	11	
Available P_2O_5 (ppm)	529				240	240	344	562	1492
Total P_2O_5 (%)	0.167	0.113	0.118	0.081	0.051		0.062		0.177
Gravel (%)	2	1	1		3	0.5			
Coarse sand (%)	1	1	1		5	5	4	3	
Fine sand (%)	16	16	14		29	28	27	27	
Silt (%)	18	18	19		16	14	16	21	
Clay (%)	63	63	64		50	50	52	48	
Exchange capacity	58.0		45.0		51.7		49.5		
Ca (m.e.%)	43.0		17.8		39.9		32.8		
Mg (m.e.%)	11.1		7.9		9.3		8.2		
K (m.e.%)	1.95		1.4		1.1		0.54		
Na (m.e.%)	0.90		17.5		1.39		7.96		
H (m.e.%)	1.1		0.37						
Saturation (%)	98		99		100		100		

* from Winton–Cloncurry road approximately 32 km south of Kynuna.
** from 35 km north of Longreach on Winton road.

Source: Hubble and Beckman (1957).

Table 1.3 Annual series of run-off from gauged catchments on the Mitchell grass plains.

Site No.	QWRC* Station Identification No.	Name	Catchment Area (km^2)	69-70	70-71	71-72	72-73	73-74	74-75	75-76	76-77	77-78	78-79	79-80	Mean
				Annual Run-off (mm, for climatic year October-September)											
1	915001	Mitchell Grass at Richmond	2.6	13	95	59	40	338	60	60	12	0	23	21	66
2	915006	Mountain Ck. near Richmond	181	–	20	27	3	127	62	71	4	0	–	3	35
3	915008	Flinders River at Richmond	16915	–	–	31	18	200	45	19	11	0	50	–	47
4	915208	Julia Ck. at at Julia Creek	1320	–	42	30	4	249	16	19	36	1	70	1	47
5	915003	Flinders River at Walkers Bend	107150	–	64	27	16	250	44	45	27	4	76	–	61
6	003205	Darr River near Longreach	2730	1	25	23	134	198	1	10	23	2	0	1	38

Source: Queensland Water Resources Commission, unpublished data.

* Queensland Water Resources Commission.

exceed 7 mm per annum in 75% of years if the catchment was in poor condition, and to exceed 2 mm per annum in 75% of years if the catchment was in good condition.

The most recent estimates of long term run-off characteristics of the study region are given by the Australian Water Resources Council (1978). This study determined run-off isopleths from the long term rainfall records of 800 weather stations throughout Australia in a multiple regression model that was established from a much smaller number of rainfall stations with run-off records. The resulting maps showed run-off from the Mitchell grass plains to have a median of less than 10 mm per annum and to exceed 25 to 50 mm per annum in ten percent of years. The study stressed that due care must be exercised in applying the results because the statistical methods of extrapolation could be misleading, particularly in regions where run-off data were not available.

1.3.5 History of Cropping

Skerman (1978), in an excellent review of North West Queensland's cropping history, traces the first crop grown in Western Queensland to one acre of potatoes at Blackall in 1874. Cropping did not develop on a regional scale on the Mitchell grass plains until the 1950's when a number of factors converged to encourage dryland production of forage sorghum (Sorghum spp. Hybrids and S. bicolor) for ensilage. The objective was drought mitigation for sheep. Skerman (1978) shows that from the first crop of 600 tonnes ensiled in 1953, the spread of dryland cropping was rapid. At its peak, silage production in western Queensland was equal to half of the State's production and 67 000 tonnes were ensiled in the period 1956–58. In 1959 there were 38 properties with underground silage reserves.

Although dryland cropping of forage sorghum for silage is no longer a part of property management in north-west Queensland, it is appropriate to discuss this practice in more detail as it sets in context the forces found to influence the viability of cropping enterprises.

Some reasons for the rapid expansion to silage production were: the determination of graziers to lessen the consequences of drought, bouyant wool prices, a sequence of years with above average rainfall, the development and increased availability of machinery for broad-acre agriculture, generous tax rebates on the purchase of agricultural machinery, active extension by the University of Queensland and the Queensland Department of Agriculture and Stock, over-estimates of cropping frequency and yield, and under-estimates of ensilage losses.

Skerman (1978) recognized nine factors as being responsible for the cessation of dryland cropping. They were: declining wool prices after 1958, rises in labour costs and reduced availability of labour, difficulties of integrating cropping with station management, low frequency of cropping due to inadequate rainfall, high cost of fallowing, difficulties of silage excavation and feeding, high ensilage losses in storage and excavation, low protein content of silage, and low dry matter yields per hectare of sorghum.

To this list can be added the value of not investing capital in an inelastic resource as it limits the options available to mitigate the effects of drought. Silage is almost non-saleable. Morley and Ward (1966) concluded that graziers would almost certainly find it more economic to invest their limited capital in avenues other than fodder conservation for drought because storage and capital investment costs make this option very expensive.

The many problems of dryland cropping led to limited development of irrigated agriculture. Irrigation schemes that are dependent upon permanent water supplies have limited application on the Mitchell grass plains because of the scarcity of such supplies. Permanent water-holes on rivers are geographically isolated, use of artesian water is restricted and national development of a large irrigation scheme is of low priority.

Effective use was made of the many artesian bores that occur on the Mitchell grass plains for irrigation of forage crops during droughts in the 1960's (Queensland Department of Primary Industries, unpublished data). Clewett and Pritchard (1980) concluded that bore water irrigation of forage crops will probably continue to play a significant part in drought mitigation because these schemes have the capacity to feed large numbers of stock and because they can be quickly brought into operation. However, bore licences are only issued for domestic use and stock watering purposes, and therefore the Water Resources Commission may be expected to rigidly enforce its regulations should attempts be made to use the water for irrigation schemes other than drought mitigation.

1.4 Concepts of Shallow Storage Irrigation Systems

There are two distinctive features of a shallow storage irrigation system:

(i) The first feature is the very shallow depth and large surface area of water that is stored in the dam. When this feature is coupled with the hot, semi-arid climate of the Mitchell grass plains, then the volume of water stored in the dam is rapidly reduced by evaporation. For example, evaporation losses from the dam at RSSRP in the first eight weeks after the dam filled were usually about 50% of storage capacity. Thus, management of shallow storage systems requires rapid and strategic use of water with no attempt being made to maintain water supply from one year to the next.

(ii) The second feature is agricultural use of the land area that is periodically flooded by the dam. Evaporation and use of water by irrigation causes the surface area of water in the dam to contract. This exposes the bed of the dam which is defined here as the 'ponded- area'. Flooding recharges the soil moisture of the ponded-area to capacity and hence the ponded-area may be planted to crops as the water line of the dam recedes. This practice is similar to the old farming system of the Nile Valley, where the river terraces were planted to crops as the flood water receded (Kamal 1971), and also to run-off farming in the Negev desert of Israel (Shanan et al. 1969).

The ponded-area does not require any seed-bed preparation before planting. However, to take advantage of surface moisture it is important that planting occurs soon after the land surface is exposed.

There is a chance that ponded-area crops will be flooded if run-off occurs in late autumn, winter or spring. However, the seasonal distribution of rainfall in table 1.1 shows that the risk of this happening is very low. Because autumn and winter rainfall is so low, the growth of ponded-area crops is almost totally reliant on the soil moisture reserves accumulated by flooding. Crops grown on the ponded-area are not irrigated.

1.4.1 Components and Design of the System

A shallow storage system may be separated into four main components:

(i) A native pasture catchment area that produces run-off (see plate II). This area is grazed by sheep or cattle and may have an area of about 400 to 4000 ha.

(ii) A shallow storage dam built across the small water-course that drains the catchment area described in (i) (see plate I). The volume of this storage may range in size from about 40 ML to 1000 ML depending on needs and circumstances. The maximum depth of water storage might vary from one to five metres.

(iii) An irrigation area (see plate III). This is best sited down-stream of the water storage so that irrigation can be by gravity flow with water applied to the land by furrow irrigation. In some circumstances it is necessary to pump water to the irrigation-area and was the case at RSSRP. The size of the irrigation-area might range from 20 ha to 400 ha.

(iv) The ponded-area of the dam (see plates IV and V). The size of the ponded-area is determined by the maximum surface area of the dam. This might range from 10 to 100 ha.

A compromise between a number of competing factors is usually involved in choosing a dam site on a property. Such factors are: catchment area, storage capacity, adequacy of bywash, location of irrigation-area, size of irrigation-area, and proximity to homestead. Construction of a large dam on a small catchment will cause a large variation in crop production, whereas, construction of a small dam on a large catchment will cause a loss in potential crop production, and may also lead to bywash erosion problems.

Another siting factor to consider is the gradient of the stream bed, as this controls the depth to volume relationship of the dam, and hence the volume of water that is likely to be lost by evaporation.

Plate II Native pasture catchment of shallow storage dam at RSSRP (August 1973) (Descrete tussocks of Mitchell grass (Astrebla lappacea) can be seen.

Plate III Furrow irrigation of grain sorghum at RSSRP. Water is being syphoned from a head-ditch to the irrigation furrows. This photograph also illustrates the variation in plant density of grain sorghum that was found to have large effects on grain yield and is discussed later.

Plate IV Ponded-area of dam at RSSRP (May 1970). This view shows the ponded-area emerging after inundation by the dam. The center left of the photograph shows crops that were planted earlier.

Plate V Ponded-area of dam at RSSRP (June 1970). This view shows a number of strips of crop of different ages. Each strip was planted around the edges of the dam as the dam dried back and thus each strip follows a contour of the dam.

1.4.2 Management of the System

The review in section 1.3.4 of surface run-off from the Mitchell grass plains showed that run-off cannot be expected in all years, and therefore conservation of crop products is essential if supplementary feeding programmes are planned on an annual basis.

High evaporation losses from shallow storages indicate that crop production will be most efficient if water is stored for only a short period of time before it is used for irrigation. Quick maturing summer crops are most suitable for this purpose.

Weston (1972) selected grain sorghum as the optimum choice of crop for the irrigation-area because it was a summer growing, high protein, high energy and saleable product that could be stored and transported easily. Grain production also minimizes labour and machinery requirements when compared to silage or hay production. However, forage rather than grain production is preferable on the ponded-area. Experiments by the author (unpublished) showed that water stress in ponded-area crops was sufficiently severe to prevent successful production of grain, but not severe enough to prevent useful growth of forage. Weston and Smith (1977) showed that cattle could be successfully fattened when grazed for 90 days on ponded-area forage sorghum crops.

Weston (1972) typified the operation of a shallow storage irrigation system as follows:

* Plough the irrigation-area in October/November each year in preparation for cropping.
* Delay planting of grain sorghum on the irrigation-area until storm rains have produced sufficient run-off from the catchment for subsequent irrigation of crops. These rains would normally be expected in January, February or March and would also provide soil moisture for planting.
* Use all stored water in one supplementary irrigation when the grain sorghum reaches the heading stage of development (about 8 weeks after planting).
* Harvest the grain sorghum five months after planting.
* Plant forage sorghum on the ponded-area every ten days or so during March/April/May as evaporation and irrigation reduce the dam's water level and expose the ponded-area.
* Harvest the forage sorghum on the ponded-area as hay or use the ponded-area to fatten cattle by grazing.
* Feed conserved grain and hay to stock as required in supplementary feeding programmes.

Time and area of planting on the irrigation-area are important management decisions. One option is to plant on storm rains which provide sufficient soil moisture for planting but do not produce run-off from the catchment for subsequent irrigation. This option exposes crops to possible failure if 'follow up' rain does not occur. A second option is to ensure crop yields by postponing planting until sufficient run-off occurs from the catchment to meet the expected requirements of subsequent irrigation. This option was proposed by Weston (1972).

Another important aspect of management concerns irrigation strategy. In arid climates the timing and frequency of irrigation have large effects on both crop yield per unit area and the area of land that a farm dam can service (Hagan et al. 1967). Losses in production and economic returns can be substantial if allocation of irrigation water is sub-optimal. The question thus arises of whether it is more efficient to frequently irrigate a small area of crop, or to irrigate a larger area only once.

Another question concerns the effects of climatic variability on irrigation scheduling because of its effects on the volume of irrigation water available and the level of soil water deficit of crops on the irrigation-area. Projections of future irrigation supplies and crop demand are important when planning irrigation schedules as is recognition of changes in the sensitivity of yield per hectare to water stress at varying stages of crop growth.

There are two important principles of irrigation strategy. Firstly, irrigation efficiency of cereal grain crops is maximized (in terms of yield increase per unit of water applied) when irrigation occurs during the flowering period (Salter and Goode 1967). Secondly, optimal management requires a flexible approach to irrigation timing, frequency and area because of dynamic and stochastic factors affecting irrigation supply, crop yield and economic returns (Flinn and Musgrave 1967; Dudley et al. 1971 (a), 1971 (b); Mapp et al. 1975; and Ahmed et al. 1976). Thus, operating rules for optimal irrigation management are often environment specific.

1.4.3 Factors Affecting Production and Costs of Production

The effects of the environment (climate, soils) on crop production from shallow storage systems are tempered by the system's design and by the effects of crop management. Design factors (such as catchment area, storage capacity, stream gradient at the dam site and size of the irrigation-area) are time invariant; however, management strategies (such as planting and irrigation) may vary from season to season depending on weather conditions.

Total crop production from a shallow storage system is the sum of production from the irrigation-area and the ponded-area. The most important factor effecting yield per unit area is the availability of water in the root zone but its effect on growth is tempered by nutrient supply and temperature conditions.

Crop production from the irrigation-area is the spatial integral of yield per unit area. If irrigation supplies are not sufficient to water the entire irrigation-area then portions of the irrigation-area may exhibit marked differences in yield. Thus in calculation of crop production it is important to recognize differences between: (i) the size of the irrigation-area (this is the area of land that is ploughed each year in preparation for cropping), (ii) the area of ploughed land that is planted, and (iii) the area of planted land that is irrigated once, twice or three times.

Differences in yield per unit area also occur on the ponded-area. This occurs because the ponded-area is planted in contour strips as the land emerges from flooding, and hence the effects of rainfall and temperature on plant growth will be different for each strip. The area of each strip depends on the depth to surface area relationship of the water storage and the rate at which evaporation and irrigation reduce the dam's water level.

Because the availability of water is the most important factor controlling production, it is useful to define the flow of water through the physical system. The flow chart in figure 1.3 shows that rainfall is the system's only source of water. Flows between the main components of the system are shown to be: run-off from the catchment area to the shallow storage dam, irrigation from the dam to the irrigation-area, and infiltration from the dam to the root zone of the ponded-area. Losses of water from the system are shown to be evapotranspiration, over-flow from the dam, run-off from the irrigation-area and deep drainage to groundwater. This latter flow is usually negligible.

The rate of infiltration on the catchment area, the irrigation-area and the ponded-area (when it is not flooded) is a function of rainfall intensity, plant cover, soil properties and antecedent soil moisture conditions. Evapotranspiration rates from the catchment, irrigation-area and ponded-area are dependent on evaporative demand, soil moisture content, soil properties and plant properties. The rate at which evaporation reduces the dam's volume is dependent on evaporative demand and the surface area of the dam.

The main effects of variation in rainfall are to alter: the timing and magnitude of run-off; the volume of water available for irrigation; the time of planting on the irrigation-area; the soil water deficit, irrigation strategy and yield of irrigated crops; and the time of planting, area and yield of ponded-area crops.

Costs of crop production may be separated into fixed and operating costs. Fixed costs relate to factors of the design such as the purchase cost of agricultural machinery, fencing and construction of the water storage and irrigation works. Operating costs include the costs of seed, labour and machinery operation, maintenance and repair.

An important factor contributing to the long-term cost per tonne of crop production is the possibility of zero crop production in some years. Zero production occurs if: (i) rainfall is not sufficient for planting on the irrigation-area, and (ii) run-off does not occur to flood the ponded-area. Fixed costs and the costs of ploughing in preparation for planting would still be incurred in this circumstance.

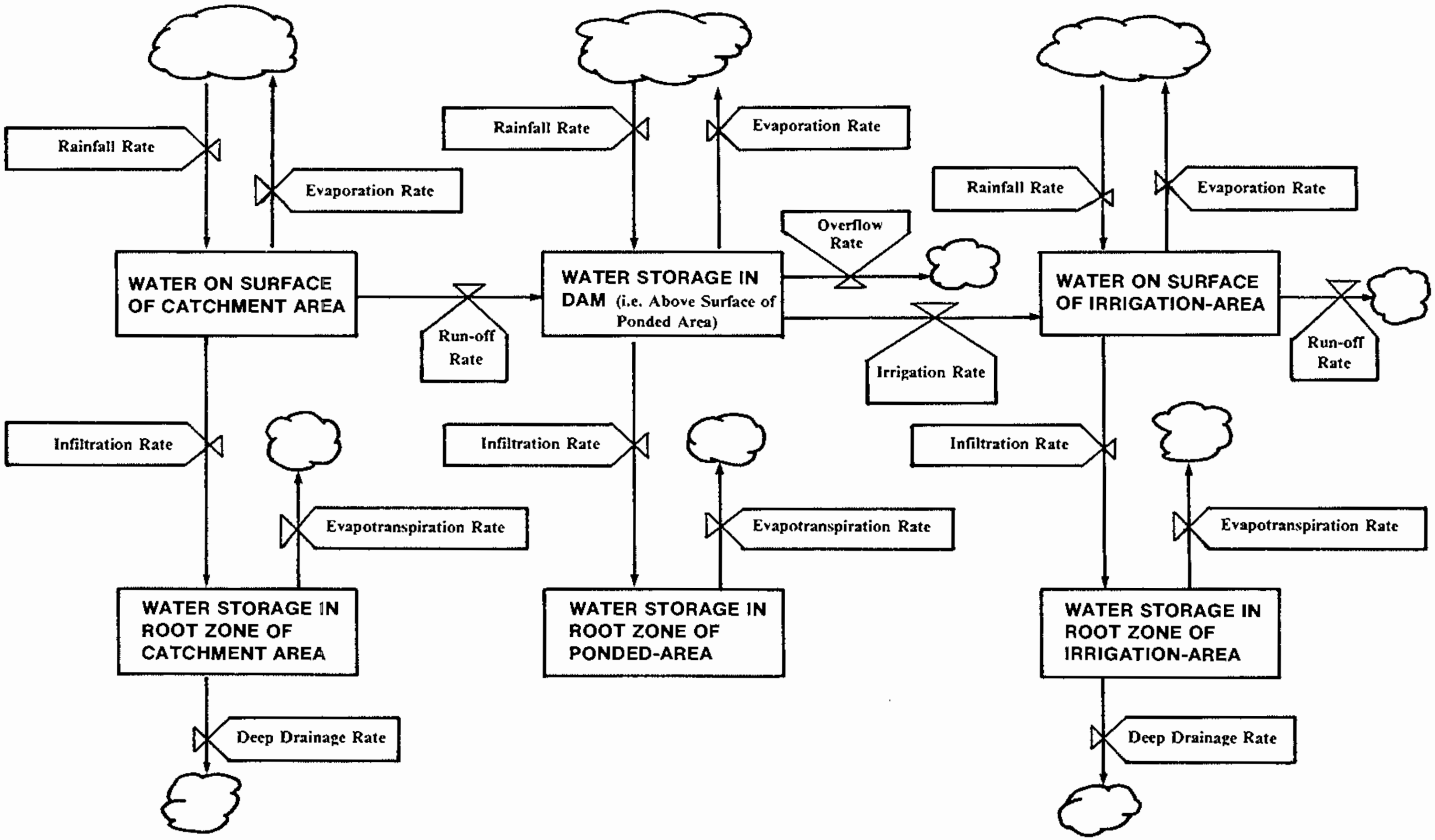


Figure 1.3 Flow chart of water movement through a shallow storage irrigation system. (Notation follows that of Forrester 1968. Level variables are shown as boxes, rate variables as valves, sources and sinks as clouds and mass flows as arrows).

1.5 Conclusions

The spatial attributes of the Mitchell grass plains were shown to be reasonably homogeneous. Therefore they may be lumped with some degree of confidence to a set of average conditions. In contrast, temporal variation in the environment is extreme and hence the use of probability and time series distributions are necessary for assessment of animal or agricultural production in the region. Assessment based on a set of average conditions has little meaning.

The failure of dry-land cropping in the region led Weston and Harbison (1979) to classify the Mitchell grass plains as being suitable only for the grazing of native pastures. However, soil characteristics offer no impediment to agriculture, and therefore removal of the climatic constraint by irrigation should allow permanent agriculture. Government legislation does not permit use of artesian water for permanent irrigation schemes and therefore irrigation supplies for cropping must come from surface run-off.

It was concluded that crop production from shallow storage irrigation systems warrants further research because:

(i) supplementary feeding programmes would benefit stock production,

(ii)information regarding run-off from native pasture was inadequate to assess the potential use of this water for irrigated cropping,

(iii) agricultural research of crop production on the Mitchell grass plains has been limited and confined to dry-land forage sorghum production, and

(iv) previous assessments of shallow storage irrigation systems have been confined to static models whereas the highly variable nature of the climate demands that such assessments be dynamic.

CHAPTER 2

OBJECTIVES AND PLAN OF STUDY

2.1 Objectives

This monograph tests the hypothesis that use of shallow storage irrigation systems on the Mitchell grass plains of North West Queensland could be an effective way for properties in the region to produce crops required for supplementary feeding programmes of sheep and cattle. To quantitatively evaluate the biophysical and economic feasibility of this hypothesis, a number of investigations were conducted with the following five objectives:

(i) To quantify the effects of environment, and in particular the effect of climatic variability on: the characteristics of run-off from native pasture; the level of water supplies available for irrigation; the frequency of crop production; the water requirement, yield and total production of grain sorghum grown on the irrigation-area; and the yield and total production of forage sorghum grown on the ponded-area.

(ii) To quantify the effects of water storage capacity on crop production for a range of dam sites defined by catchment area and stream gradient.

(iii) To quantify the effects of planting strategy (timing and area), and irrigation strategy (timing, frequency and area) on the cropping frequency, water requirement, yield and total production of irrigated grain sorghum crops.

(iv) To determine the effect of climatic variability, shallow storage design and crop management on the cost of crop production, and

(v) To isolate principles of shallow storage design and management that can be applied to maximize crop production or minimize the cost per tonne of crop production.

The effective management of a shallow storage irrigation system requires that it be an integral part of property management. For example, the need for supplementary stock feeding is dependent on seasonal pasture conditions, and therefore management objectives in crop production could alter from season to season. However, this study only considers management practices which have a direct effect on crop production. Sheep production, cattle production and supplementary feeding programmes are therefore exogenous to the system under study.

The boundary of the system under study, and the linkages between the main components of a shallow storage irrigation system, are shown by the relational diagram in figure 2.1. Property management in this figure is shown to bridge the boundary of the system to emphasize that conclusions reached can only serve as a guide to optimal management of the system.

2.2 Plan of Study

The research programme was conducted in two phases. The first phase was collection of field data on surface run-off from native pasture, and collection of crop production data from field experiments. The second phase was analysis of the data to form a mathematical model of the system, so that computer simulation experiments using long term weather data could be conducted. The reasons for adopting this approach are given in the following review.

2.2.1 Use of Mathematical Modelling and Computer Simulation

An agricultural system may be defined in a general sense as a complex set of related components which form an autonomous framework. Dent and Blackie (1979) assert that the fundamental characteristic and unifying theme of systems theory is that the whole system is more complex and comprehensive than the sum of its individual parts. Because there are a large number of related components in agricultural systems, many difficulties occur when property managers attempt interpretation of raw data which come from time and site specific field experiments. However, in making decisions a manager is required to extrapolate data through space and time, across boundaries of soil plant and animal science, and then temper the result with constraints of land, labour, capital and attitudes.

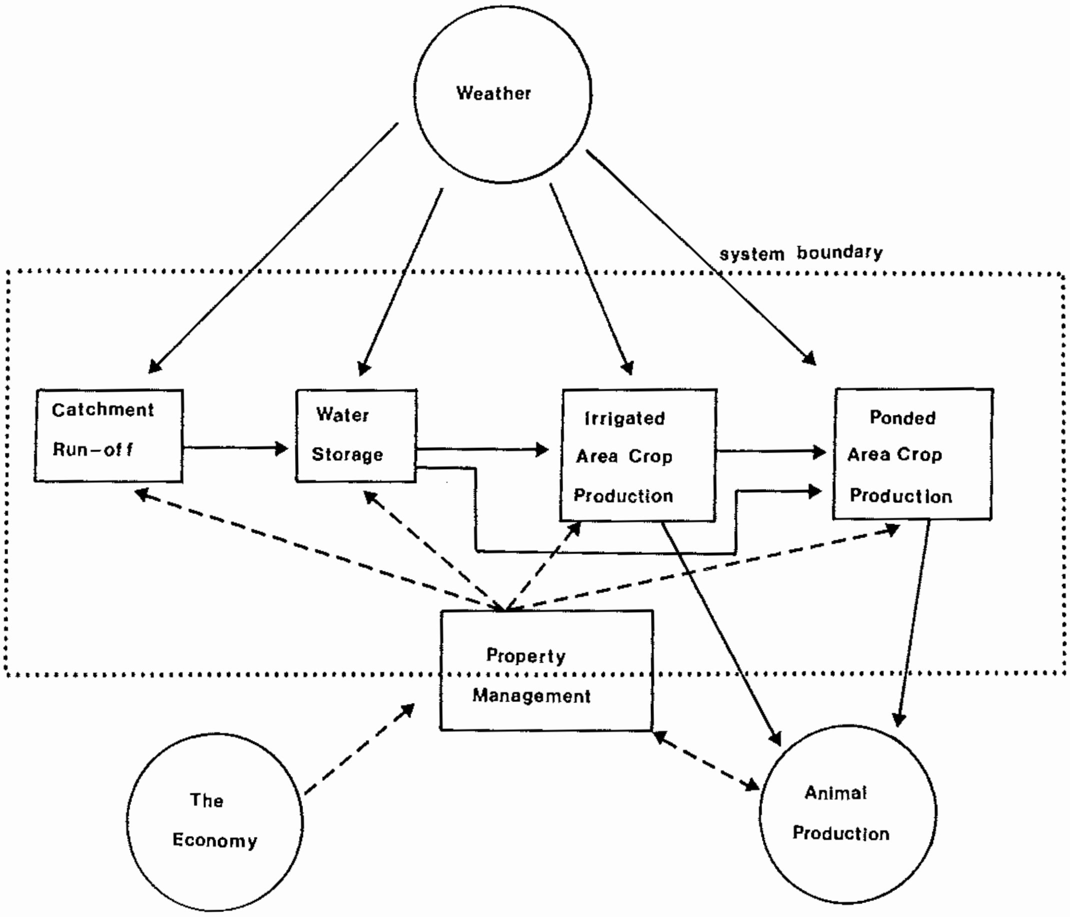


Figure 2.1 Relational diagram of the shallow storage irrigation system under study. (The dotted line shows the boundary of the system, circles are exogeneous variables, boxes are components of the system, solid arrows show direction of material flows and broken arrows show direction of information flows.)

In a review of systems studies in agriculture Ebersohn (1976) stressed that efforts committed to detailed field experimentation were not being matched by comparable efforts in synthesis of results. Thus, a major challenge to agricultural research is to establish fast and reliable methods for integrating knowledge.

Because systems display a hierarchial structure, a better understanding of their performance may be gained by decomposing the system to simpler components that are linked by flows of material or information (Goodall 1976). Autonomous components so defined can be further decomposed to the next layer of detail.

The decomposition of systems to lower levels of organization, and the definition of the inter-relationships between autonomous components in a system is the province of modelling. In contrast, the measurement of functional relationships is the province of field experimentation and observation. Whilst field experiments are often regarded as physical models of real agricultural systems their reality is constrained by the inflexible controls imposed by experimental design, and their generality is limited by the many variables that cannot be controlled (Christian et al. 1978).

Rose (1973) defined a model as 'a set of hypotheses describing the performance of a system', and simulation as 'the study of the behaviour and consequences of models'. The advantage of defining models in this way is that hypotheses may be presented conceptually and/or mathematically. The definition includes not only mathematical equations of functional relationships but also the assumptions and constraints that are frequently embedded in hypotheses. Thus, a holistic approach is used that provides a basis upon which numerical values predicted by a mathematical model may be assessed with respect to assumptions.

Process models of agricultural systems are concerned with structure and mechanisms. They attempt to numerically describe features of the system (such as soils and vegetation) and to represent physical processes (such as infiltration, evapotranspiration and plant growth) with mathematical cause-effect relationships. The principles of conservation of mass and energy are commonly central to the structure and operation of process models. The principle of mass conservation has led to the name 'soil water balance model' for description of the flux of water through the soil-plant-atmosphere system.

Mathematical models and simulation have been successfully applied to quantify the performance of complex, dynamic systems in the physical sciences (Van Dyne 1978). Following this success and the increased availability of computing facilities to handle problems that were previously intractable, the method is now receiving widespread use in biological systems (Dalton 1975; de Boer and Rose 1977; Baier 1977; Innis 1978; and McKeon and Scattini 1980).

There is a rapidly expanding literature describing the incorporation of systems research, mathematical modelling and simulation into the scientific method (Dent and Anderson 1971; Chapman and Dunin 1975; Arnold and de Wit 1976; Dillon 1976; Spedding and Brockington 1976; Dent and Blackie 1979, Baier 1979). Morley (1977) states 'modelling which is purposive, seeking to integrate knowledge, however unprecise, into a meaningful structure which may be used in the development of understanding, or the application of knowledge, is indeed a scientific activity'; and in concluding a review in hydrology, Mein (1977) states 'It is clear that use of catchment models for flood prediction and extending short term stream flow records from longer rainfall records is good engineering practice'.

Use of modelling and simulation has not been without criticism and debate in the literature (Passioura 1973). Frequently the distinction is not made between the validity of simulation as part of the scientific method and the validity of the hypotheses which form the model. The accuracy of simulation is dependent on the set of hypotheses used to define the system and if these fail to describe essential features then output errors will occur 'a priori'. Invalid hypotheses often stem from three sources. Firstly, the immense simplification of the 'real' system that is necessary when formulating the structure of mathematical models; secondly, the scarcity of data or the lumping of data may lead to ill-defined functional relationships; and thirdly, the possibility that processes have been wrongly or poorly conceived. Therefore, it is important to stress that simulation experiments do not necessarily lead to valid conclusions.

Where models are constructed for the purpose of system simulation and decision making, then the validity of individual relationships in the model should be reviewed with respect to the performance of the whole system. It is possible that use of an ill-defined relationship in the model may be of little consequence to the performance of the whole system because of strong, negative feed-back influences. White (1978) concludes that 'the proper test for a model is improvement in decision making compared to more intuitive approaches'.

The application of modelling and simulation that has received most attention in agriculture is the simulation of processes through time using weather data as input to the model. For example, the method has been used with reasonable accuracy to:

(i) estimate changes in soil moisture (Fleming 1964, Baier 1969, Fitzpatrick and Nix 1969, Carbon and Galbraith 1975, Makkink and van Heemst 1975, Rosenthal et al. 1976, Greacen 1977, Hillel 1977, and Rickert and McKeon 1982),

(ii) estimate catchment run-off (Boughton 1966, Crawford and Linsley 1966, Aston and Dunin 1980),

(iii) estimate pasture growth (Rose et al. 1972, van Keulen 1975 and Innis 1978), and

(iv) estimate crop growth and yield (Nix and Fitzpatrick 1969, Goutzamanis and Conner 1977, Maas and Arkin 1978, and Hammer and Goyne 1982).

Models of agricultural systems have been effective in evaluating the agricultural and pastoral potential of regions and determining the influence of climatic variabilty on agricultural practices (Slatyer 1964, Fitzpatrick and Nix 1970, Harrison 1976, White 1978, Leslie 1982). Simulation experiments have also been effective in studies aimed at optimizing the design and management of agricultural systems, particularly irrigation systems (Flinn and Musgrave 1967, Dudley 1972, Dudley et al. 1971a, 1971b and 1972, Mapp et al. 1975, Ahmed et al. 1976, Trava et al. 1977, Ritchie et al. 1978, English 1980, and Cull 1981).

Important differences exist in the models given above with respect to the level of resolution used to describe processes, and the time step used during simulation. Some models require a time step of minutes or less to meet the objectives of study, whereas others may satisfactorily use daily or weekly computations to meet objectives. Models in the latter group are obviously of little use for detailed investigation of processes such as photosynthesis or infiltration. However, it is also true that detailed process models have found little use in studies concerned with description or management of agricultural systems (Hammer 1981) because of the absence of input data and/or high cost. Therefore, an important aspect of modelling is keeping the objective of study, data inputs and mathematical description of processes in balance.

It is inferred from the above review that modelling and simulation should be an effective method of analysing the performance of shallow storage irrigation systems, provided the mathematical descriptions of components and processes in the system are derived satisfactorily.

The decision to use modelling and simulation in this study was based on the need to:

(i) integrate the results of many field measurements, recorded at different times and from different components of the system, to a form convenient to managerial decision making,

(ii) investigate effects of shallow storage design and management on crop production that were outside the scope of field experiments, and

(iii) quantify changes in system performance caused by the effects of climatic variability.

The ten year moving average of rainfall in the study region was shown in chapter 1 to deviate from the long-term mean for long periods of time. Therefore, it is likely that crop production characteristics observed during a short experimental period may well differ from long term expectations, and hence there is need to simulate the performance of the system using long-term climatic records.

2.2.2 Organization of Chapters

A mathematical, weather-driven model of a shallow storage irrigation system is derived in the next five chapters. This was achieved by decomposing the system model to a number of component models and sub-models. Thus, the terms system model, model and sub-model are used in a hierarchial sense. The decomposition of the system model is given in figure 2.2. This figure also shows the chapter in which the models and sub-models are derived.

Experimental data recorded at the Richmond Shallow Storage Research Project was used to derive each of the models in chapters 3 to 6. Each of these chapters contains a description of the experimental procedures, and an analysis of results that are relevant to the model derived. Each chapter also gives a literature review of the structure, processes and functional relationships of the model derived in that chapter. This sequential method of reviewing the literature was chosen to achieve clarity.

In chapter 8, a series of computer simulation experiments examine the effects of climatic variability, shallow storage design and crop management options on characteristics and costs of crop production. The simulation experiments were conducted over a period of 60 years using daily climate data from the Richmond Post Office as input to a FORTRAN computer program of the system model. The results are analysed by frequency and time series distributions.

Conclusions are presented in chapter 9 after discussing and interpreting the simulation results with respect to the objectives of study. This final chapter also gives a retrospective view of the research methods and discusses possibilities for future research.

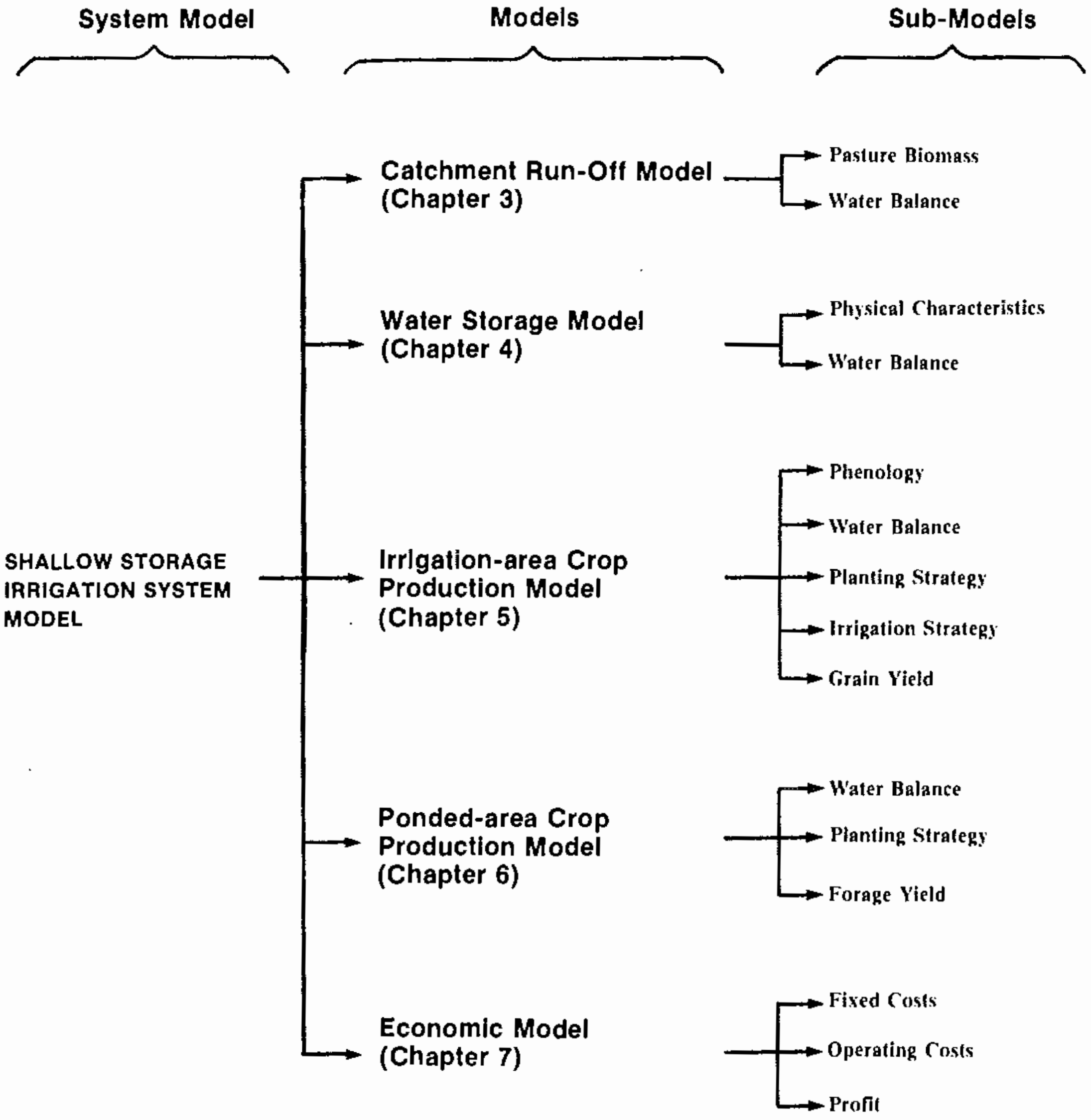


Figure 2.2 Hierarchial decomposition of shallow storage system model to models and sub-models. The chapter in which each of the models is developed is shown in brackets.

CHAPTER 3

CATCHMENT RUN-OFF MODEL

Previous chapters have shown that the timing, frequency and magnitude of catchment run-off are important factors determining the cropping potential of shallow storage irrigation systems. The purpose of this chapter is to develop a method for predicting the daily yield of run-off from Mitchell grass pasture catchments, where yield is defined as the product of catchment area by average depth of run-off.

It was shown in chapter 1 that the only set of run-off data available for the Mitchell grass plains that was directly relevant to farm dams, was the data set for the gauged catchment at the Richmond Shallow Storage Research Project (RSSRP). Therefore it is necessary to consider the validity of extrapolating the characteristics of run-off from this catchment to other catchments.

Sections of this chapter give:

(i) a review of literature with respect to the use of mathematical models for simulation of run-off,

(ii) the methods and results of field observations on the gauged catchment at the RSSRP with respect to rainfall, run-off, soil moisture and pasture conditions,

(iii) development of a mathematical model for simulating daily changes in soil moisture and the average depth of daily run-off from the gauged catchment, and

(iv) an evaluation of the model developed in (iii) for predicting run-off from long-term climatic records on the gauged catchment and other catchments on the Mitchell grass plains.

3.1 Literature Review

Digital simulation of the hydrological cycle using mathematical models began in the 1950's when the sciences of hydrology and computing were linked. Research initiated in this period led to the development of the US Army Corps Model series (Rockwood 1958) and the Stanford Watershed Model series (Crawford and Linsley 1966). Since 1960 many models have been developed for estimation of run-off such as the Boughton Model (Boughton 1966), the Australian Representative Basins Model (Chapman 1970 and Fleming 1974), the USDAL-70 Model (Holton and Lopez 1971), the Monash Model (Porter and McMahon 1971), the Sacramento Model (Burnash et al. 1973) and the WATSIM model (Aston and Dunin 1980, Aston et al. 1980).

Despite the diversity in approach and structure used in the models given above, they fall broadly into two groups: those which are only concerned with catchment yield, and those which attempt to estimate run-off hydrographs in addition to yield. The latter group contains the Stanford, Monash, Sacramento and USDAHL-70 and WATSIM models because of their reasonably detailed level of resolution. However, Boughton (1966) recognized that input data needed to operate detailed process models were not available for a large number of catchments because meteorological data were often limited to daily rainfall, and information on physiography, soils and vegetation characteristics was meagre. Consequently, Boughton developed a model which retained only the main structure and processes of the water balance.

Pattison and McMahon (1973), in reviewing the application of run-off models, recommended use of the Boughton model over more detailed models where the objective was to determine catchment yield or where the level of input data was limited. Simulation studies have shown that the Boughton model (or a derivative) can be used with reasonable confidence to simulate catchment yield from daily climatic data, provided a short period of coincident records of rainfall and run-off are available for model calibration (Boughton 1965, 1966, 1968; Jones 1970; and Moore and Mein 1977).

Simplification of a model necessarily implies some loss of realism in representing processes, and thus an important aspect of model development has been the need to calibrate models to minimize differences between model performance and observed data.

The results of Johnston and Pilgrim (1973) and Pickup (1977) clearly show that indiscriminate use of optimization procedures to calibrate parameters is meaningless.

Chapman (1975) analysed the results of the World Meteorological Organisation's model intercomparison study in which run-off predicted by nine models on many different catchments were compared with observed data. The results showed that the structure of detailed process models had no advantage over statistical methods in estimating run-off in situations where most parameter values in the model were derived by calibration rather than field measurement. This evidence shows that the complexity of model structure should be balanced to the quality of data inputs.

In this study there are a number of factors which favour use of a model similar to the Boughton model. They are:

(i) catchment yield is required rather than run-off hydrographs,

(ii) rainfall data for long-term simulation is restricted to daily records,

(iii) estimates of evaporative demand are restricted to methods based on temperature observations,

(iv) a period of run-off data is available for calibration of the model, and

(v) changes in soil moisture content were measured in conjunction with run-off to assist determination of soil water holding capacity and other parameters, such as those controlling evapotranspiration rates.

The Boughton model operates on a daily time step through three cycles: wetting, drying and drainage. Rainfall is routed through an interception store, an upper store, a drainage store and finally to a lower soil store. A cascading bucket approach is used to represent infiltration except at the lower soil store where the level of antecedent soil moisture storage is used to impede flow. Run-off is calculated as a function of daily rainfall and soil water storage. Evaporation takes place from the interception, upper and lower stores at rates depending on evaporative demand and the level of water in each store. In the drainage cycle water is routed from the drainage store to the lower store depending on the status of each. The Boughton model has not been previously applied to and calibrated for the Mitchell grass plains environment.

Direct infiltration of rainfall to sub-surface layers via cracks, and changes in infiltration characteristics due to temporal changes in catchment vegetation were considered (in chapter 1) to have important influences on infiltration. The Boughton model does not include these characteristics.

It was concluded that the water balance model most useful for estimating catchment yield in this study should be similar in structure to the Boughton model, but with modifications to: (i) allow infiltration via soil cracks, and (ii) incorporate the effects of changes in catchment vegetation on infiltration relationships. Therefore, a sub-model to predict seasonal changes in pasture biomass is required as part of the catchment run-off model.

3.2 Field Observations

3.2.1 Site Description

The soils, vegetation and topography of the experimental site at the Richmond Shallow Storage Research Project (RSSRP) were considered to be typical of the Mitchell grass plains described in chapter 1. Thus, the data reported below should be of general application to the Mitchell grass plains.

A plan of the experimental site is given in figure 3.1. This figure shows a weir within the catchment of the shallow storage dam. This weir was constructed by the Queensland Water Resources Commission for the purpose of measuring run-off from a catchment of 260 ha. The vegetation on both this gauged catchment and more than 90% of the catchment for the shallow storage dams was native pasture. The pasture was periodically grazed by sheep and cattle at normal stocking rates.

3.2.2 Methods of Field Observations

Run-off from the gauged catchment at RSSRP was measured during the period 1st October 1968 to 30th September 1978. A continuous chart of water height over the weir was used to estimate hydrographs of daily mass flow and the average depth of daily run-off. Daily rainfall was measured at 9 a.m. at the weir and at four other sites on the project as shown in figure 3.1. A tipping bucket pluviometer was also located near the weir.

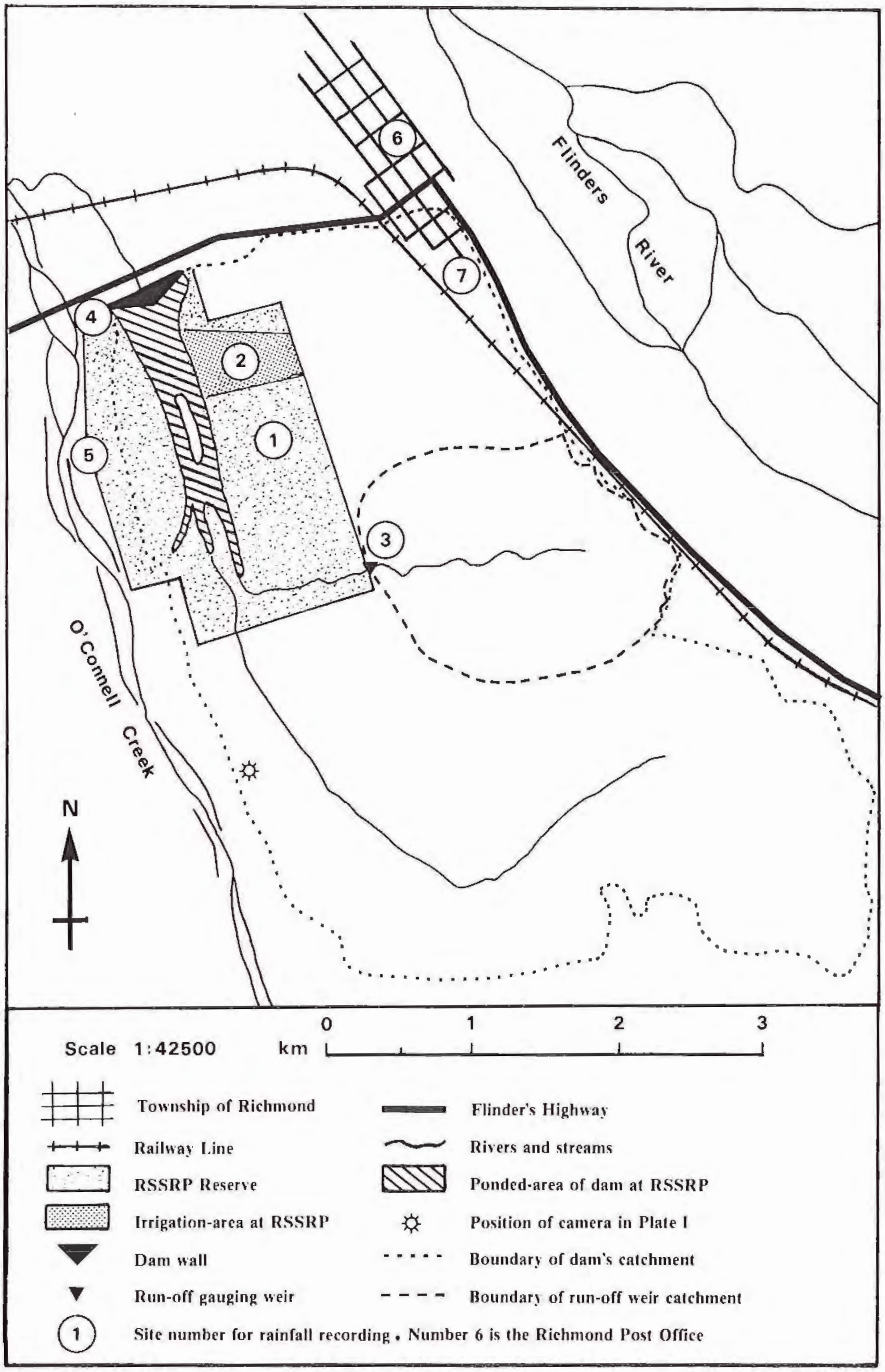


Figure 3.1 Site Plan of Richmond Shallow Storage Research Project (RSSRP)

Photographs of the soil surface and vegetation were used to record seasonal changes in pasture conditions on the catchment.

Gravimetric measurements of soil moisture were recorded on the gauged catchment on 35 occasions from 1970 to 1976. Duplicate soil samples were taken on each occasion from 3 sites at 5 cm intervals to a depth of 15 cm, and then at 15 cm intervals to a depth of 90 cm. Volumetric soil moisture per unit area was calculated from the gravimetric data for three layers of soil. These layers were: a surface layer (0–10 cm soil depth), a sub-surface layer (10–30 cm soil depth) and a sub-soil layer (30–90 cm soil depth).

In cracking clay soils, the calculation of volumetric soil moisture from gravimetric data requires information with respect to changes in bulk density with changes in soil moisture, and soil depth. The change in bulk density with soil moisture causes changes in soil layer thickness.

There is general agreement in the literature that shrinkage in swelling clay soils equals loss in soil moisture (Aitchison and Holmes 1953; Fox 1964; and Berndt and Coughlan 1976), however, the dimensionality of shrinkage is debated. Fox (1964) proposed shrinkage to occur as a two stage process with the stages separated by a cracking point. He defined the cracking point as the soil moisture content at which soil cracks were first visible. At soil moisture contents above the cracking point Fox proposed uni-dimensional shrinkage (in the vertical direction), and at soil moisture contents below the cracking point Fox proposed three dimensional shrinkage. This hypothesis was supported by Loveday (1972), but Berndt and Coughlan (1976), Yule and Ritchie (1980), and Yule (1981) concluded that shrinkage was three dimensional normal at all soil water contents.

The above conceptual difference in the dimensionality of soil shrinkage leads to small differences in the layer thickness of a constant soil mass, and thus to small differences in calculation of volumetric soil moisture from gravimetric data. However, it can be shown (Clewett 1982) that these differences are of negligible importance, particularly when compared to the spatial variation in soil moisture and bulk density that are encountered in field sampling.

An experiment designed to measure changes in bulk density through a number of drying cycles failed to fully achieve its objectives because of sampling inaccuracies. Samples were obtained with an hydraulically driven Vehmeyer tube of 5 cm diameter. In wet soils (>0.32 g/g) compaction occurred at the head of the tube and in dry soils (<0.15 g/g) the tube tended to split the soil mass. However, measurements of bulk density were thought to be reasonably accurate through the mid range of soil water contents (0.18 to 0.26 g/g). Field observations suggested that the cracking point of the soil occurred at a moisture content of approximately 0.24 g/g.

Volumetric soil moisture per unit area was calculated from gravimetric data in this study by the shrinkage model of Fox (1964). This calculation ensured that all estimates were made for a constant soil mass. The effect of soil depth on bulk density was determined by:

(i) measuring the bulk density of twenty four profiles (0–90 cm in 15 cm layers) in the moisture range 0.18 to 0.26 g/g,

(ii) adjusting these measurements to the bulk density predicted by the Fox model at 0.24 g/g, and

(iii) determining a regression equation for adjusted bulk density versus soil depth.

3.2.3 Results and Discussion of Field Observations

Field observations are given in the following sequence: daily rainfall, pasture conditions, run-off, soil moisture and bulk density, and effects of soil cracks and pasture conditions on infiltration.

Rainfall. Seasonal rainfall before and during the period of run-off gauging (1 October 1968 to 30 September 1978) may be summarized as: a run of seasons with below average rainfall in the 1960's with severe droughts in 1965, 1967 and 1969 followed by a run of good seasons with annual rainfall well above average in the 1970's (see Appendix A).

The five-year mean of rainfall recorded at the Richmond Post Office from 1965 to 1969 was 230 mm which is the lowest five year mean recorded during the last 80 years.

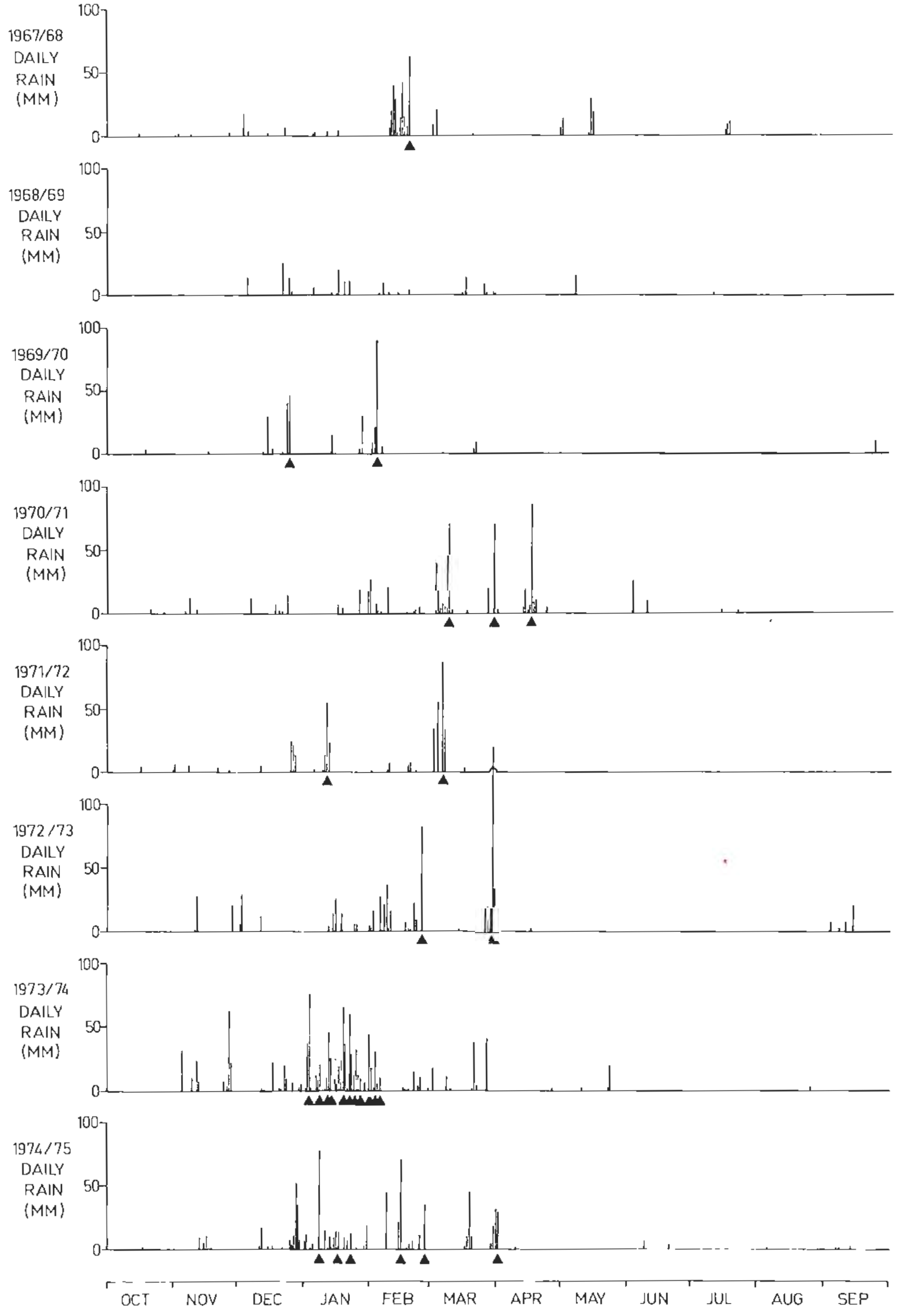


Figure 3.2 Seasonal patterns of rainfall and mean run-off at RSSRP. (▲ indicates observed run-off event from gauged catchment)

In contrast, the five year mean rainfall from 1971 to 1975 was 615 mm and is the highest on record. Rainfall in 1971 was conspicuous because it occurred much later than usual with rainfall totals for March and April the highest on record (304 and 173 mm respectively). Rainfall during the wet season of 1974 was exceptionally high (940 mm) and exceeded all other records by 58%.

Daily rainfall recorded at the weir at RSSRP is shown in figure 3.2. The strong variability and seasonal pattern of rainfall is evident in this figure.

Pasture Conditions on the Gauged Catchment. The switch from 'drought seasons' to 'good seasons' caused extreme changes in pasture conditions. Plate VI shows that pasture biomass on the gauged catchment was almost zero following the 1969 drought and that the soil surface was rough and deeply cracked. Plate VII shows that pasture biomass afforded no protection to the soil on 3 January 1970 when heavy rainfall (89 mm) flattened the micro-topography. Plate VIII shows the very limited pasture growth that resulted from the 1969/70 wet season and the redevelopment of soil cracks.

Plates IX and X contrast the above because they show the very dense pasture that developed following the 1972/73, 1973/74 and 1974/75 wet seasons. The deterioration of pasture biomass by September 1978 is shown in plate XI.

Run-off. Rainfall, peak rate of discharge over the gauging weir and the average depth of catchment run-off for each run-off event in the period, October 1968 to 30th September 1978 are shown in table 3.1.
The dates shown in this table are the dates on which rainfall was recorded for the previous 24 hours to 9 am. The run-off shown on each date is the total run-off resulting from the previous 24 hours rain. Maximum persistent rainfall was approximated to the nearest 10 mm/hr from pluviograph charts. This set of data shows:

(i) that run-off was only recorded in the months December to April inclusive,

(ii) that daily rainfall of up to 149 mm was recorded, whereas the maximum depth of daily run-off was 49 mm,

(iii) that the number of run-off events per year was nil in two years, between 1 and 6 in seven years and 35 in one year, and

(iv) that annual run-off was zero in two years, exceeded 10 mm in eight years and exceeded 50 mm in five years.

These results are in contrast to the estimates of annual run-off given in the literature review in chapter 1 (page 18). The experimental results reported here are much higher than previous estimates which in part is no doubt due to the record rainfall received between 1971 and 1976. It is likely that run-off would have been much less if the period of run-off gauging had been during the droughts of the 1960's.

Soil Moisture and Bulk Density Observations. The estimates of soil moisture (mm of equivalent ponded depth) calculated from gravimetric soil moisture observations by the method of Fox (1964) for a constant soil mass are shown in table 3.2. The effect of soil depth on soil bulk density used in these calculations was determined as follows. The mean bulk density of the 0-90 cm profile at a moisture content of 0.24 g/g was found to be 1.17 g/cm . The mean bulk density of the 0-15 cm layer at the same water content was 1.03 g/cm . Results in figure 3.3 show a small but significant increase in bulk density as soil depth increases from 15 cm to 90 cm. The regression equation found for bulk density (BD, in g/cm^3) versus soil depth (D,cm) between 15 and 90 cm was:

$$BD = 1.16 + 0.74 \times 10^{-3} D \qquad (15 < D < 90) \qquad (3.1)$$

Minimum and maximum depths of soil moisture storage in each soil layer were calculated by averaging the data recorded at the end of the dry season and immediately after sustained rainfall respectively. These values are shown in table 3.3. The most significant point in this table is the very high water holding capacity of the soil. The estimated available range (i.e. the difference between the maximum and minimum storage capacities) is very high when compared to the average annual rainfall of 471 mm.

Table 3.1 Rainfall and runoff observations from the gauged Mitchell grass catchment at RSSRP.

Date	Rainfall		Weir Discharge	
	Daily to 9 am (mm)	Persistent max rate (mm/hr)	Peak Rate (m^3/s)	Depth of run-off** (mm)
24 Dec 69	39	20		1.0
03 Feb 70	89	30	3.1	12.0
09 Mar 71	55	50	12.9	34.1
27 Mar 71	19	20	0.4	2.0
30 Mar 71	63	20	3.3	20.9
16 Apr 71	83	30	10.3	36.4
17 Apr 71	3	20	0.4	1.0
18 Apr 71	9	20	0.2	.3
11 Jan 72	70	20	.4	7.3
06 Mar 72	89	30	6.3	26.0
07 Mar 72	40	20	5.0	25.8
08 Feb 73	42	20	0.1	0.7
29 Mar 73	129	50	6.0	26.7
30 Mar 73	25	20	2.0	12.1
03 Jan 74	64	50	1.0	9.6
08 Jan 74	20	10	0.1	0.4
12 Jan 74	50	40	0.4	6.0
14 Jan 74	17	30	0.4	8.6
17 Jan 74	18	10	9.1	1.7
18 Jan 74	21	10	0.2	8.3
19 Jan 74	65	20	5.0	49.0
20 Jan 74	40	10	2.1	29.4
*21 Jan – 9 Feb 74	252		3.8	224.7
08 Jan 75	96	50	1.0	4.2
17 Jan 75	16	10	0.1	1.6
23 Jan 75	16	20	0.1	3.0
15 Feb 75	70	20	3.7	29.2
26 Feb 75	47	40	3.2	21.3
01 Apr 75	36	10	0.1	1.3
06 Feb 76	84	20	2.8	22.9
07 Feb 76	30	20	1.2	18.6
09 Feb 76	19	10	0.5	10.4
11 Feb 76	17	10	0.2	6.5
21 Dec 76	149		0.6	12.3

* Run-off resulting from daily rainfall in the period 21 Jan 74 to 9 Feb 74 has not been separated because of the almost continuous rainfall pattern.

** Mean depth over 260 ha catchment.

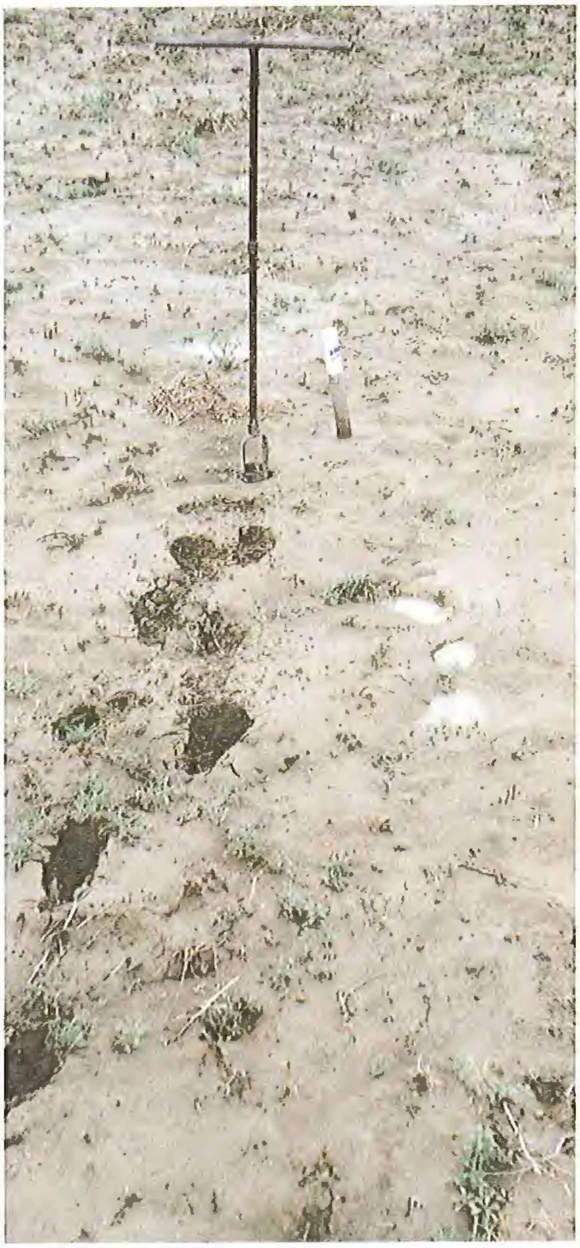


Plate VI Pasture condition on gauged catchment at RSSRP on 25 January 1970 (32 days after 39 mm of rain on 25 Dec 1969). The run-off gauging weir can be seen in the background.

Plate VII Pasture condition on gauged catchment at RSSRP on 3 February 1970 (The day after 89 mm of rain).

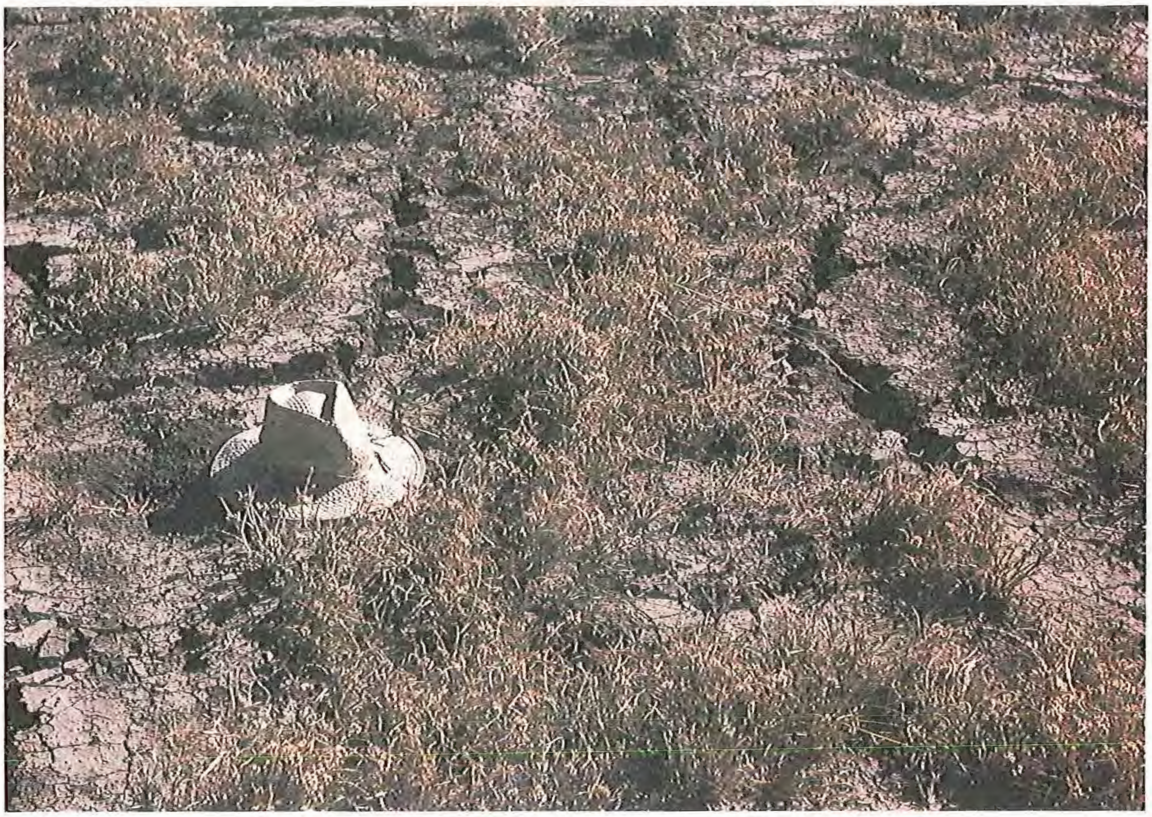


Plate VIII   Pasture condition on gauged catchment at RSSRP on 1 April 1970.

Plate IX   Pasture condition on gauged catchment at RSSRP on 8 April 1974

Plate X Pasture condition on gauged catchment at RSSRP on 5 February 1975

Plate XI Pasture condition on gauged catchment at RSSRP on 9 September 1978.

Table 3.2 Soil moisture observations on the gauged Mitchell grass catchment.

Date (yr,mth,dy)	Equivalent Ponded Depth of Soil Moisture (mm)*			
	Surface Layer (0–10cm)	Sub-Surface Layer (10–30cm)	Sub-Soil Layer (30–90cm)	Profile (0–90cm)
700114	11.8	25.8	79.1	116.7
700121	7.2	21.5	–	–
700128	6.8	18.0	–	–
700203	38.6	71.2	117.0	226.8
700210	24.9	59.8	119.6	204.3
700217	11.0	44.1	102.1	157.3
700319	9.3	32.8	103.4	145.5
700411	5.8	23.8	95.7	125.3
700507	6.1	21.3	92.8	120.2
700907	4.4	14.9	80.2	99.5
710115	4.8	16.0	78.7	99.4
710202	17.6	29.4	97.3	144.2
710302	6.9	21.5	93.2	121.6
710311	29.5	71.1	133.3	233.8
710402	28.6	72.4	158.9	259.9
710420	30.6	95.3	180.4	306.2
720114	30.3	71.0	143.2	244.4
720203	14.7	47.4	142.3	204.4
720218	9.6	35.2	115.6	160.4
720310	28.5	74.6	177.2	280.3
720328	13.3	51.6	150.3	215.2
720518	8.1	31.7	122.3	162.2
721018	3.4	13.9	79.8	97.1
730105	9.9	22.5	89.2	121.7
730212	29.6	77.6	166.0	273.3
730531	15.6	44.2	132.3	192.2
730829	6.4	27.1	112.9	146.4
740222	27.3	67.6	235.1	331.0
741218	8.2	25.6	114.5	148.3
750107	28.7	69.1	138.0	235.9
750205	22.3	58.3	184.8	265.3
750313	21.4	63.5	207.5	292.4
750404	32.5	76.8	197.2	306.5
751008	12.8	36.3	120.9	170.1

* Mean of six profiles.

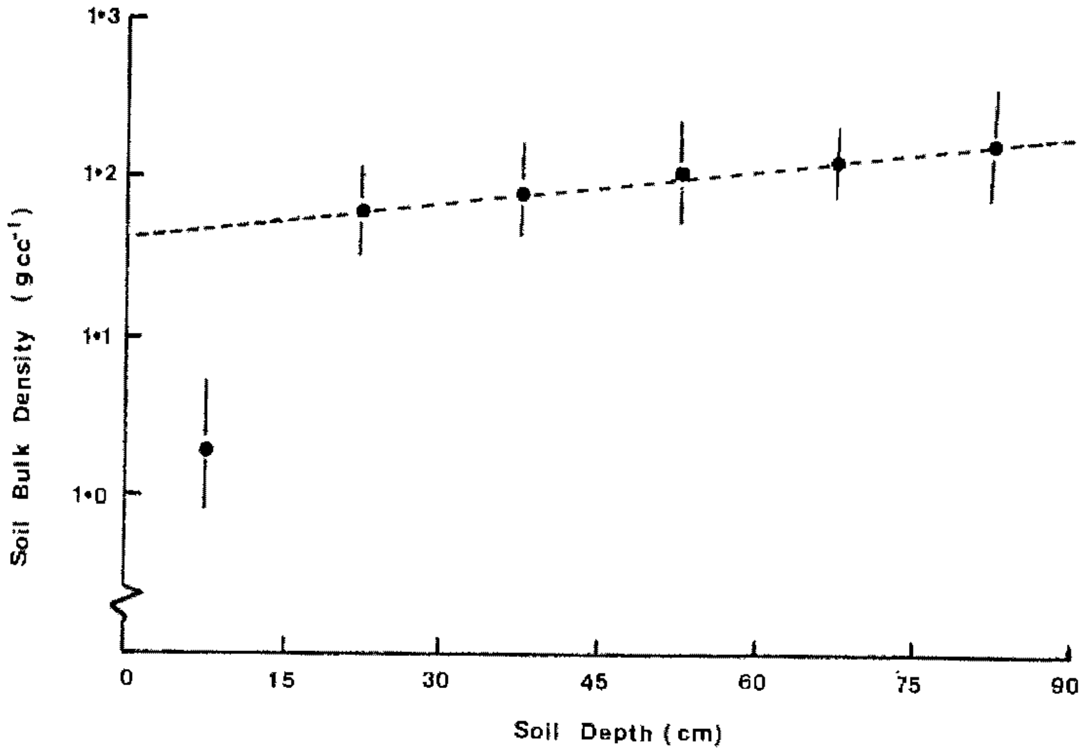


Figure 3.3 Relationship found between soil bulk density and soil depth when gravimetric water content was 0.24 g/g (Dashed line is equation 3.1 in text, vertical bars are standard deviations found at each soil depth).

Table 3.3 Estimated minimum and maximum equivalent ponded depths of soil moisture storage on the gauged Mitchell grass catchment.

Soil Layer	Depth (cm)	Soil Moisture Storage (mm) Minimum	Maximum	Available Range*
1. Surface	0 - 10	4	38	34
2. Sub-Surface	10 - 30	18	78	60
3. Sub-Soil	30 - 90	81	215	134
Profile	0 - 90	103	331	228

* Available range = maximum minus minimum water storage.

Effects of Soil Cracks and Pasture Biomass on Infiltration. Rainfall was observed to enter the soil profile via cracks so that pockets of wet and dry soil were frequently encountered when soil sampling after rain. When pasture biomass in the catchment was very low (<400 kg/ha of dry matter, as in plate VI) then soil cracks were observed to slump and erode during the course of storms. This process left large surface depressions and blocked further entry of water via cracks. If rainfall was sufficient to cause run-off then further soil movement occurred such that the micro-topography was levelled (as in plate VII).

Restriction of infiltration to the sub-soil was observed on 3 February 1970 when 89 mm of rain and 12 mm of run-off were recorded. On this occasion pasture biomass was close to zero (see plate VI) and antecedent soil moisture was low (21% of the available range). The results of soil sampling on the 3 February (table 3.2) show that soil moisture in the surface and sub-surface layers was recharged to near capacity but soil moisture in the sub-soil was recharged to only 117 mm (27% of the available range). Because significant run-off occurred it was concluded that infiltration to the sub-soil was restricted.

When the above-ground biomass of pasture on the catchment was high (approximately 3000 kg/ha of dry matter as in plates IX and X), then soil cracks were far more stable during the course of storms, and hence high infiltration rates were maintained for a long time. Presumably vegetation was able to absorb rainfall energy and bind the soil so that the rate of erosion around cracks was retarded. Slumping of cracks did occur but soil expansion due to water uptake assumed greater importance in filling cracks. Under thick vegetation the microtopography of the soil surface remained quite rough after heavy rainfall and run-off.

The maintenance of high infiltration rates during the course of storms when pasture biomass levels were high is best illustrated by the results of soil sampling on 7 January 1975, and by measurements of rainfall and run-off on the following day. On this occasion pasture biomass was estimated to exceed 3000 kg/ha. Rainfall in the previous two weeks was 142 mm so that soil moisture was recharged to 236 mm (58% of the available range) by the 7 January 1975 (see table 3.2). Pluviograph records show that an intense storm of 96 mm occurred that night between 8pm and 11pm with persistent intensities of 50 mm/hr. The average depth of run-off recorded from this storm was only 4 mm (see table 3.1). This data suggests that a high infiltration rate was maintained throughout the course of the stonn, and that soil moisture was recharged to capacity in all soil layers. This data contrasts the data discussed above where infiltration to the sub-soil on 3 February 1970 was apparently restricted. It was concluded that the difference in infiltration characteristics was primarily due to the effects of pasture biomass.

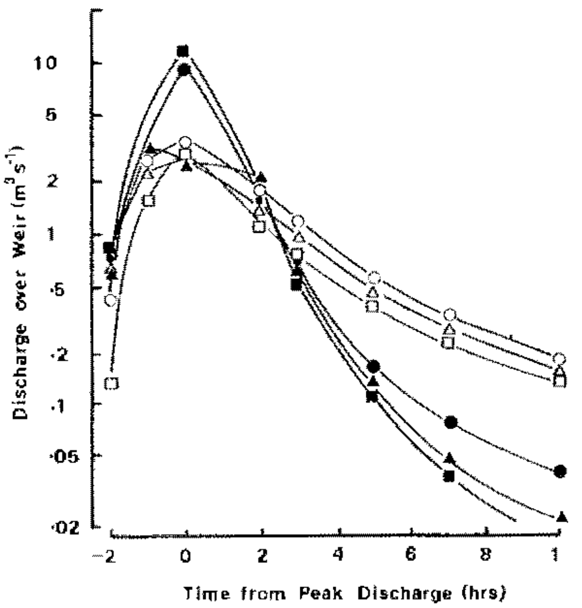
Soil moisture in the surface and sub-surface layers of soil was observed to be recharged to near capacity in each rainfall sequence that produced run-off. This suggests that it was changes in the rate of infiltration to the sub-soil that had the most influence on the partitioning of rainfall to run-off, rather than the rate at which rainfall could be absorbed by the surface layers.

To gain a better understanding of biomass effects on the characteristics of catchment run-off, a number of hydrographs were plotted and their shape analysed. Hydrographs used in this analysis were all those in which rainfall ceased before peak discharge occurred, and in which peak discharge equalled or exceeded 2.0 m^3/s. Six of these hydrographs (out of a total of ten) are shown in figure 3.4. The hydrographs in this figure fall into two groups, and may be separated by differences in pasture biomass. The first group, with the steeper recession curves, were observed in 1971 when pasture biomass was less than 400 kg/ha. The second group, with the flatter recession, was observed in 1975 and 1976 when pasture biomass exceeded 2000 kg/ha.

The shape of hydrographs was analysed by calculating hydrograph recession constants. This was done by fitting the following equation to the recession side of all the hydrographs selected above:

$$\ln D = kt + c \qquad (\text{for } D > 0.4 \text{ m}^3/\text{s}) \qquad (3.2)$$

where D = discharge over the weir (m^3/s), t = time after peak discharge (hr), k = hydrograph recession constant, and c = constant.



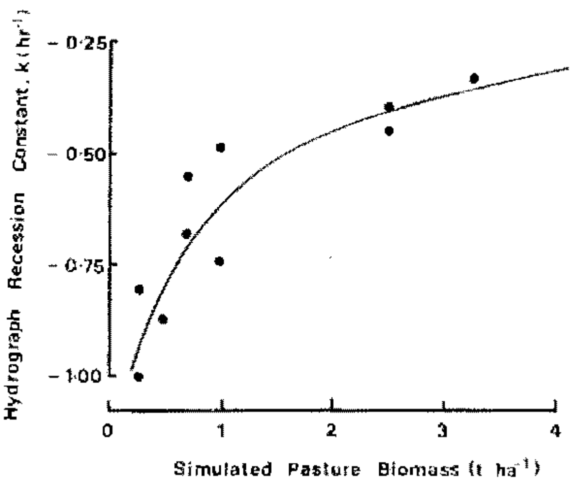


Figure 3.4 Observed hydrographs of discharge from gauged Mitchell grass catchment (The dates on which the hydrographs were observed were: ■ = 9 Mar 71, ▲ = 30 Mar 71, ● = 16 Apr 71, ○ = 15 Feb 75, □ = 25 Feb 75, △ = 6 Mar 75).

Figure 3.5 Relationship found between observed rate of hydrograph recession and simulated pasture biomass. While field measurements of pasture biomass were not recorded, the simulated values of biomass concur with visual approximations.

The hydrograph recession constants found in this way are plotted against pasture biomass in figure 3.5. This figure shows that increases in the hydrograph recession constants were associated with increases in pasture biomass. This relationship and the data in figure 3.4 suggests that increases in pasture biomass led to a reduced rate of over-land flow, and hence a greater opportunity for infiltration to occur.

3.2.4 Conclusions

The following conclusions were reached from the field observations:

(i) The duration of run-off records was not long enough to adequately determine the probability distribution of annual run-off.

(ii) Soil cracks and the slumping of cracks to form surface depressions have significant effects on infiltration of water to layers of soil below the surface layer.

(iii) Increased pasture biomass increases the structural stability of soil during storms, and reduces the rate of over-land flow. Both of these factors increase infiltration and reduce run-off.

(iv) A useful simplified description of the infiltration process might be: an unrestricted rate of infiltration to the surface 30 cm of soil until its water holding capacity is reached, followed by a restricted rate of infiltration to the sub-soil that is dependent on the level of sub-soil moisture and pasture biomass.

3.3 Derivation of Pasture Biomass Sub-Model

The previous section showed pasture biomass to have a significant effect on infiltration and run-off. Therefore the catchment run-off model was developed as two sub-models; a pasture biomass sub-model and a water balance sub-model.

The purpose of the pasture biomass sub-model was to predict temporal changes in pasture biomass that could be used in the water balance sub-model to regulate the infiltration/run-off process. A simple, pasture biomass sub-model was developed for this purpose.

Pasture biomass was considered to consist of only two pools. Firstly, an above ground pool of grass (G), and secondly, a detached pool of litter (L) lying on the soil surface. The rate variables considered to effect these pools were the growth of new grass, the consumption of grass by grazing animals, the detachment of grass to form litter and the decomposition of litter by weathering. At the level of detail required a time step (t) of one month was considered adequate for simulation.

The pasture biomass sub-model is shown as a flow chart in figure 3.6 and is mathematically represented by the following difference equations:

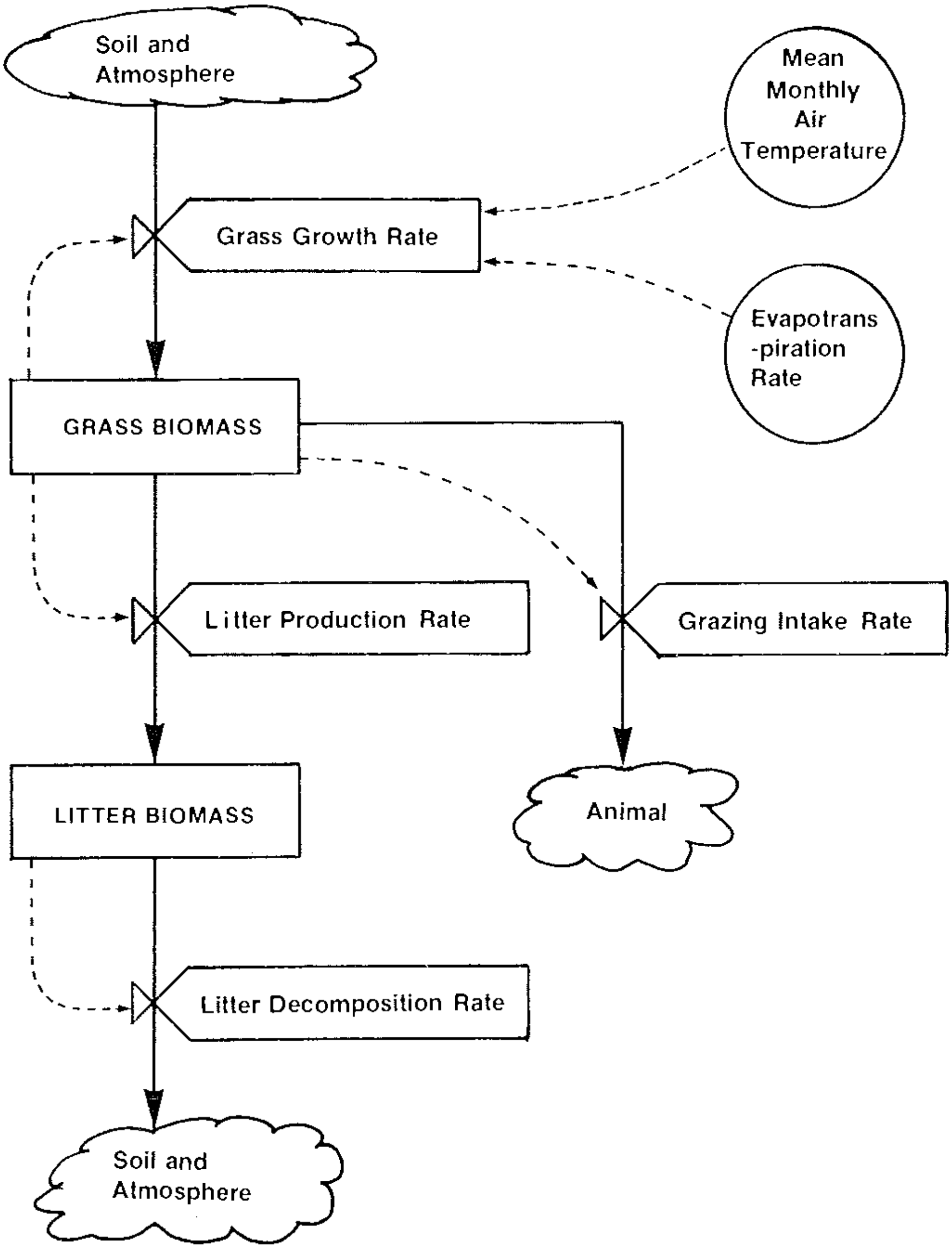


Figure 3.6 Flow chart of pasture biomass sub-model (Pools are shown as boxes, rates as valves, sources and sinks as clouds, exogenous variables as circles, solid lines with arrows show direction of mass flows, broken lines with arrows show information flows).

$$B = G + L \quad (3.3)$$
$$G(t) = G(t-1) + GG - GI - LP \quad (3.4)$$
$$L(t) = L(t-1) + LP - LD \quad (3.5)$$

where B = Above ground pasture biomass (kg/ha), G(t) = Level of grass pool at time t one month later than t–1 (kg/ha), L(t) = Level of litter pool at time t one month later than t–1 (kg/ha), GG = Rate of grass growth (kg/ha/month), GI = Rate of grazing intake (kg/ha/month), LP = Rate of litter production (kg/ha/month), LD = Rate of litter decomposition (kg/ha/month)

The rate variables in these equations were calculated in the following way. The rate of grass growth was calculated as the product of water use efficiency (WUE) and monthly evapotranspiration (ETM) estimated by the water balance sub-model. Thus:

$$GG = WUE * ETM \qquad \text{(kg/ha/month)} \quad (3.6)$$

Because the soil was observed to air dry it is necessary to estimate values of soil moisture below which evapotranspiration does not contribute to pasture growth. The only field data available to make this estimate was the data applicable to grain sorghum that is shown in figure 5.4. From this data it was assumed that estimates of ETM in equation 3.6 should not include soil moisture losses below 14 mm in the 0–10 cm layer, 40 mm in the 10–30 cm layer and 130 mm in the 30–90 cm layer of simulated soil moisture profiles.

The relationship in equation 3.6 is based on the work of de Wit (1958). de Wit showed on theoretical grounds, and supported with a wide range of experimental data, that plant growth in arid climates was proportional to the ratio of transpiration to evaporative demand. The assumptions of this theory are that the rate limiting factor of photosynthesis is the diffusion of carbon dioxide, and that the rate of diffusion of carbon dioxide is proportional to that of transpiration.

Where de Wit's theory is modified to model plant growth in proportion to evapotranspiration, as is the case in this and other studies (Ive et al. 1976, Stewart and Hagan 1973), then it is assumed that the ratio of transpiration to evapotranspiration can be adequately determined.

Salter and Goode (1967) and Stewart and Hagan (1973) show that equation 3.6 holds for many experiments, however, water use efficiency is dependent on species, site and climate (van Keulen 1975). Reported values of water use efficiency for Astrebla grasslands in summer range from 4 kg/ha/mm (Davies et al. 1938) to 6 kg/ha/mm (Roe and Allen 1945) which are similar to values for other semi-arid grasslands. Christie (1978) measured values of 3.9 kg/ha/mm for mulga grassland, and 6.9 kg/ha/mm for buffel grass. The maximum value adopted in this study was 5 kg/ha/mm. The maximum water use efficiency was reduced by a temperature index (TI) if temperature was below optimum (defined below) and a grass yield index (GYI) if pasture biomass was less than 1000 kg/ha. The relationship used to determine water use efficiency was:

$$WUE = 5 \times TI \times GYI \qquad \text{(kg/ha/mm)} \quad (3.7)$$

The optimum mean daily temperature for Mitchell grass growth and development appears to be 27 to 30°C. Jozwik (1970) found growth per tiller and leaf production increased as temperature increased from 21/16°C (day/night) to 30/25°C, and Christie (1975) found growth of seedlings at 20, 25 and 35°C to be 14%, 72%, and 40% respectively of growth at 30°C. Whalley and Davidson (1969) proposed that Mitchell grass enters an hormonally controlled state of dormancy during the winter, and in this state enzymes to hydrolyse starch for growth are not produced following light falls of rain. In an irrigated field study during winter (mean daily temperatures approximately 16°C) Scanlan (1980) measured very low water use efficiencies of 0.5 kg/ha/mm in a Mitchell grass dominant pasture. These findings were used to determine the relationship between temperature index and mean monthly temperature that is shown in figure 3.7 (a), and is calculated by:

$$TI = 0.33 + 0.67 \exp(-(T-27)^2/15) \qquad \text{if } T < 27,$$
$$TI = 1.0 \qquad \text{if } 27 < T < 30, \text{ and}$$
$$TI = 0.33 + 0.67 \exp(-(T-30)^2/15) \qquad \text{if } T > 30 \quad (3.8)$$

where T = (Tmax + Tmin)/2, Tmax = mean monthly maximum temperature at screen height (°C), and Tmin = mean monthly minimum temperature at screen height (°C).

Pasture growth rate was related to pasture biomass because the rate of carbon fixation by the pasture is dependent on the area of green leaf present. The relationship between grass yield index and biomass of the grass pool used to modify water use efficiency was adapted from the buffel grass data of Peake et al. (1979), and the Mitchell grass model of White (1978). The relationship is shown in figure 3.7 (b) and is:

$$GYI = \min(1.0,\ (0.4 + 0.6 \times 10^{-3} G)) \qquad (3.9)$$

Grazing intake was estimated from grass biomass with the relationship shown in figure 3.7 (c). This relationship is a simplified form of the relationship used by White (1978).

The rates of litter production and litter decomposition per month were estimated in proportion to the grass yield and litter yield present at the start of each month. Losses from the pasture due to trampling were conceived as forming part of litter production and decomposition processes. The following relationships were used:

$$LP = 0.09\ G \qquad \text{(kg/ha/month)} \qquad (3.10)$$
$$LD = 0.20\ L \qquad \text{(kg/ha/month)} \qquad (3.11)$$

Initially the litter production and decomposition proportionality constants were set at 0.045 and 0.07 in accordance with the work of Christie (1975). However, at these values the model tended to over-estimate pasture biomass. While Christie's value of 0.045 for

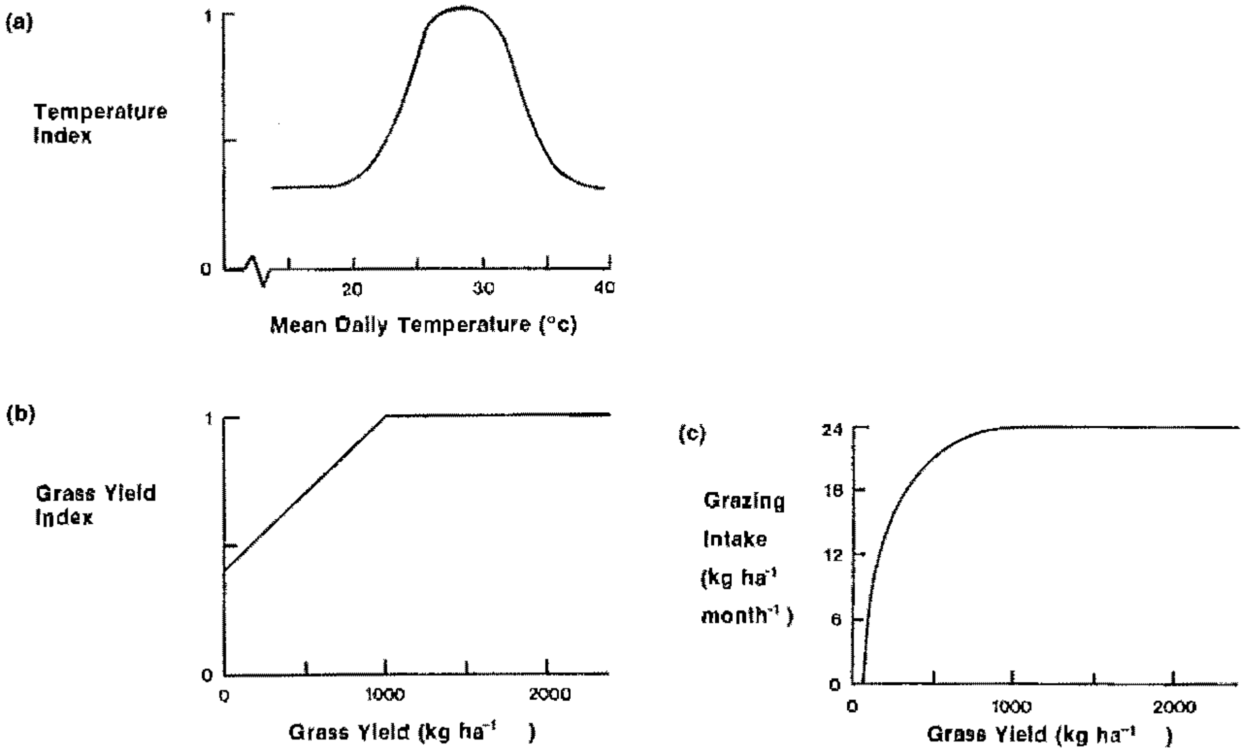


Figure 3.7 Relationships used in pasture biomass sub-model to calculate (a) temperature index, (b) grass yield index and (c) grazing intake.

litter production was obtained during winter, he also found that litter production in summer was variable but higher in general.

3.4 Derivation of Water Balance Sub-Model

3.4.1 General Description

A daily water balance model interacting with the pasture biomass sub-model was developed to simulate the average depth of run-off per day from the gauged Mitchell grass catchment. Factors contributing to the structure of the water balance were: the fact that rainfall was the only source of water to the catchment; that losses of water from the catchment could occur as evapotranspiration to the atmosphere, overland flow of run-off to streamflow and deep drainage to ground-water; the assumption that the catchment area was uniform with respect to climate, soil type, vegetation and run-off, so that depth of soil water storage at any time over the catchment was considered to be uniform; and the assumption that groundwater made no contribution to stream flow, and thus streamflow was produced entirely by overland flows of run-off.

From the above considerations the equation to conserve mass of water per unit ground area as time (t) is incremented by one day (9am to 9am) is:

$$S(t) = S(t-1) - ET + R - Q - G \qquad (3.12)$$

where S_t = Depth of soil moisture storage (mm) at 9am on day t, ET = Rate of evapotranspiration (mm/day), R = Rate of rainfall (mm/day), Q = Rate of run-off (mm/day), and G = Rate of deep drainage (mm/day).

In the calculations of S(t), evapotranspiration losses were deducted before rainfall was added because rainfall in the dry tropics usually occurs in the late afternoons or at night.

A flow diagram of the water balance sub-model is shown in figure 3.8. This figure shows that rainfall is received by a pool at the soil surface, and then redistributed to three layers of soil and to run-off. Redistribution of water from the surface pool was considered to occur before the start of the next day and thus no evaporation losses were deducted from the surface pool. Figure 3.8 also shows direct infiltration of water from the surface pool to all soil layers (via cracks) as well as percolation of water from one soil layer to the next. Pasture biomass is shown to effect only the rate of water flow into the third soil layer. Evapotranspiration is shown to occur from all three soil layers.

The following sections discuss characteristics of soil water storage, and derive the relationships used to estimate evapotranspiration, infiltration, run-off and deep drainage. However, details of parameter optimization methods are given first so that the optimized parameter values may be given when describing evapotranspiration and infiltration relationships.

3.4.2 Parameter Optimization Methods

The value of parameters defining rates of evapotranspiration and infiltration were optimized separately. The objective function used to optimize evapotranspiration parameters was the root mean square(RMS) of differences between simulated soil moisture (Ss) and the observed soil moisture (So) data given in table 3.2. By definition:

$$RMS = (So - Ss)^2/N \qquad (3.13)$$

where N = number of comparisons.

Run-off is the difference between rainfall and infiltration and hence the infiltration parameters were optimized by minimizing differences between simulated run-off (Qs) and the observed run-off (Qo) data in table 3.1. Values were raised to the power 0.75 before differences were calculated so that the weighting given to large run-off events was reduced. The objective function for optimization was the root mean square calculated from:

$$RMS = (Qo^{0.75} - Qs^{0.75})^2/N \qquad (3.14)$$

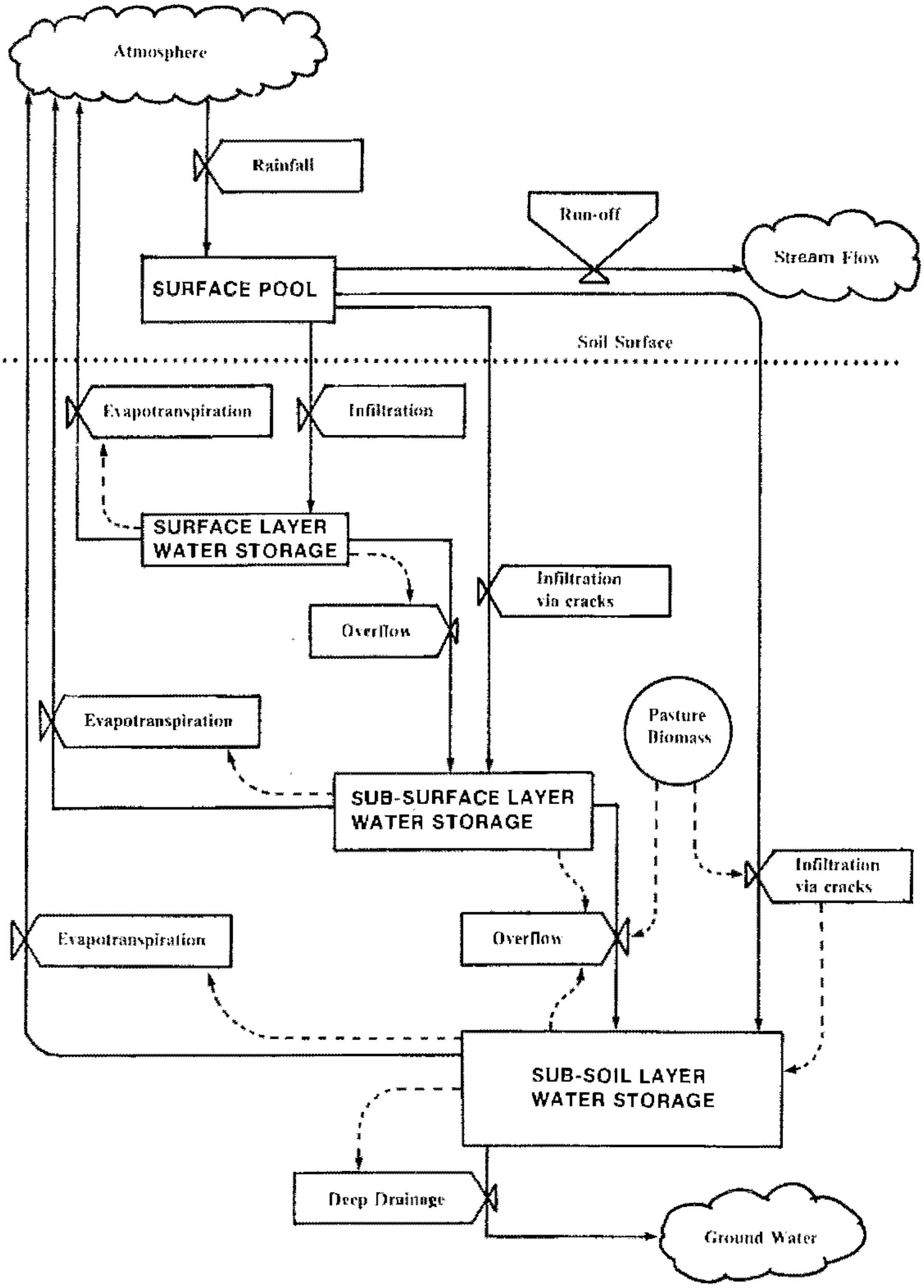


Figure 3.8 Flow chart of catchment water balance sub-model. (Level variables are shown as boxes, rate variables as valves, exogenous variables as circles, sources and sinks as clouds, mass flows as solid arrows and information flows as broken arrows).

In optimizing the infiltration parameters the run-off events during the last half of the record 1974 flood from 21st January to the 10th February were deleted because flows on the run-off hydrograph during this period could not be adequately separated and attributed to daily rainfall records.

Parameters were optimized iteratively in factorial combinations using the method of Cochran and Cox (1966). Three cycles of optimization were used. In each cycle the evapotranspiration parameters were optimized first so that the infiltration parameters would develop from a model which gave reasonable estimates of soil moisture.

The calibration period for parameter optimization was 1st October, 1966 to 30th September 1978. This gave the model a 'warm up' period of two years before simulated data was compared to observed data. Daily rainfall recorded at the weir of the gauged catchment was used in simulation.

3.4.3 Soil Water Storage Characteristics

A model with three soil water storages was chosen because single layered models tend to over-simplify evaporation and infiltration processes, and a model with more than about three layers possibly represents unjustified complexity. A small surface soil storage (0–10 cm soil depth) was chosen so that the model could simulate rapid evapotranspiration following light falls of rain. The lower level of the second (sub-surface) soil layer was set to 30 cm because soil profiles were observed to wet up completely to this level at least in rainfall sequences producing run-off. The lower level of the third (sub-soil) layer was set at 90 cm because at approximately this depth soil type changed from a uniform brown cracking clay to an impervious, non-cracking, yellow clay. Soil samples taken from below 90 cm showed only very slight changes in soil water content with time.

The levels of soil water storage in the surface, sub-surface and sub-soil layers are referred to as S1, S2 and S3 respectively. The minimum levels to which evapotranspiration can reduce soil moisture (S1min, S2min and S3min respectively), and uhe maximum levels to which infiltration can recharge soil moisture (S1max, S2max and S3max respectively) are those shown in table 3.3.

3.4.4 Evapotranspiration Relationships

Evapotranspiration is controlled by a complex set of soil, plant and meteorological factors so that a detailed description of the evapotranspiration process requires both energy balance equations and soil-plant-atmosphere mass transfer equations (Hagan and Halse 1967). This approach is not suitable where meteorological data are restricted to monthly temperature records as is the case in this study, and thus a simpler empirical approach was adopted.

Many successful water balance models use simple empirical relationships to modify evapotranspiration as evaporative demand and soil water availability change (Baier 1969; Fitzpatrick and Nix 1969; Eagleman 1971; McCowan 1973; Rosenthal et al. 1976). One group of these models uses the assumption that the ratio of actual to potential evapotranspiration can be calculated from soil water status without reference to the prevailing evaporative demand. A second group alters the ratio as evaporative demand changes in accord with the results of Denmead and Shaw (1962), and Makkink and van Heemst (1975). Johns and Smith (1975) examined these approaches by comparing six separate models of evapotranspiration in a soil water budget. They found an overall similarity among models in computed soil water deficits and attributed this to strong negative feedback influences. These influences were firstly, the limits set on the upper and lower bounds of water storage and secondly, over- or under-estimates of evapotranspiration were compensated in subsequent periods by decreased or increased estimates of evapotranspiration.

Evapotranspiration is often separated in water balance models to soil evaporation and plant transpiration (Ritchie 1972; Hammer and Goyne 1982; Rickert and McKeon 1982). This separation is used to account for the effects of factors such as root distribution, soil surface tilth or mulch and plant cover on evapotranspiration. While large changes in pasture biomass were observed on the catchment, the relationships given below do not separate ET to E and T because: (i) the effects of pasture dynamics on ET were considered to be far less important than the effects of soil moisture and evaporative demand, and (ii) the canopy structure of Mitchell grass pasture is quite complex and hence in the absence of data the division of ET to E and T would be artificial.

Estimates of evaporative demand (Eo) were calculated each month from mean monthly temperature data using the method of Fitzpatrick (1968). This method calculates Eo from the vapour pressure deficit of the atmosphere that is weighted according to the mean maximum screen temperature, with a further adjustment for relative humidity to account for advective energy.

This method of calculating evaporative demand was chosen for the following reasons:

(i) The equation was developed specifically for use in situations where meteorological information was restricted to simple climatic variables such as those available in the long-term climatic records of Richmond,

(ii) the equation was calibrated to approximate Penman's estimation (Penman 1948) of potential evaporation which is generally regarded as a well based physical model of the process,

(iii) the equation was developed in tropical, semi-arid Australia and therefore in a climate similar to the Mitchell grass plains, and

(iv) the equation has been shown to give reasonably accurate estimates of monthly evaporation in both the 'wet' and 'dry' seasons of both tropical and temperate regions of Australia.

The functional relationship chosen to estimate evapotranspiration follows the results of Johns and Smith (1975). The rate of daily evapotranspiration (ET) for any soil layer (k) was related to the level of available soil water storage in that layer, and to the rate of atmospheric evaporative demand (Eo) as follows:

$$ET = a \times \exp(b \times SAVk) \times Eo \qquad (3.16)$$

where SAVk = Percent available soil water storage of layer k (i.e. $100 \times (Sk-Skmin)/(Skmax-Skmin)$, and where a and b are empirical constants for layer k.

Values of the evapotranspiration parameters a and b in equation 3.16 for each layer of soil were found by the optimization methods described earlier. The values thus obtained were:

Surface soil layer; a = .0107, b = .054,
Sub-surface layer; a = .0107, b = .051, and
Sub-soil layer; a = .0061, b = .050.

The relationships found between the ratio of ET/Eo and available soil moisture for each soil layer, and the whole profile are shown in figure 3.9. Features of this figure are: (i) the potential rate of evapotranspiration (ie. ET/Eo = 1.0) was only maintained at very high levels of soil moisture, and thus for only a short duration after rainfall, and (ii) when soil moisture in each layer exceeds 70% of the available range then the sum of the ratios of ET/Eo from each layer exceed 1.0.

Calculations of evapotranspiration from the profile using equation 3.16 were restricted as follows: (i) soil moisture in each layer was not reduced below the minimum soil water storage shown in table 3.3; (ii) the maximum rate of evapotranspiration from the 0-90 cm soil profile was set equal to the evaporative demand; and (iii) the rate of evapotranspiration from each soil layer was reduced in equal proportions to satisfy (ii) if initial calculations of evapotranspiration from the profile exceeded evaporative demand.

3.4.5 Infiltration and Run-Off Relationships

The infiltration of water into soils that are uniform and non-compressible is well understood (Childs 1969; Philip 1969; and Rose 1966). The theory is based upon Darcy's law which specifies the rate of flow as proportional to the hydraulic gradient where the co-efficient of proportionality (hydraulic conductivity) is strongly dependent upon pore size geometry and soil water content. Fleming and Smiles (1975) show that soil physicists and hydrologists have met with varying degrees of success in applying the theory to simulate infiltration under field situations. However, the theory is not applicable to cracking clay soils where infiltration via cracks and other preferred pathways is a dominating factor of the process. For this reason, and also because long-term rainfall data were limited in this study to 24 hour totals, an empirical approach was adopted for estimating infiltration.

Relationships, similar to those used in the Boughton model (Boughton 1966) were used, with parameters defined by least squares optimization. Field observations showed the importance of infiltration via preferred pathways such as cracks, and the influence of vegetation on infiltration. Therefore these factors were represented in the model.

Figure 3.8 shows that rainfall was considered to be received by a surface pool and then distributed to infiltration and run-off. The possible retention of rainfall on foliage was ignored. Distribution of water from the surface pool was considered to be instanteneous so that there was no carry over from one day to the next. Thus, run-off (Q) is the difference between rainfall (R) and infiltration (F) (i.e. $Q = R - F$).

Infiltration was calculated as the summation of water distributed to the surface, sub-surface and sub-soil layers (F1, F2 and F3 respectively) plus loss of water to deep drainage (G). Thus:

$$F = F1 + F2 + F3 + G \qquad \text{(mm/day)} \qquad (3.17)$$

The proportions of rainfall distributed to the surface, sub-surface and sub-soil layers were calculated from daily rainfall rate, antecedent soil moisture conditions and pasture biomass. In situations where rainfall was light (e.g. 10 mm/day) and the soil was dry and cracked, then 70% of rainfall (i.e. 0.7 R) was considered to infiltrate the surface soil layer, and 15% to infiltrate to each of the sub-surface and sub-soil layers via preferred pathways.

It was assumed that infiltration to the surface soil layer could occur without restriction until its capacity was reached. Thus the proportion of rainfall distributed to the surface soil layer was calculated from:

$$F1 = \min(0.7\ R,\ S1max - S1) \qquad \text{(mm/day)} \qquad (3.18)$$

where $S1max - S1$ = water storage deficit in surface layer (mm)

Distribution to the sub-surface soil layer was calculated as the minimum of: (i) the water storage deficit of the sub-surface layer (S2max–S2), or (ii) 15% of rainfall (0.15 R) plus any excess rainfall from the surface soil layer (i.e. 0.7 R–F1). Thus:

$$F2 = \min(S2max - S2,\ 0.15\ R + 0.7\ R - F1) \qquad \text{(mm/day)} \qquad (3.19)$$

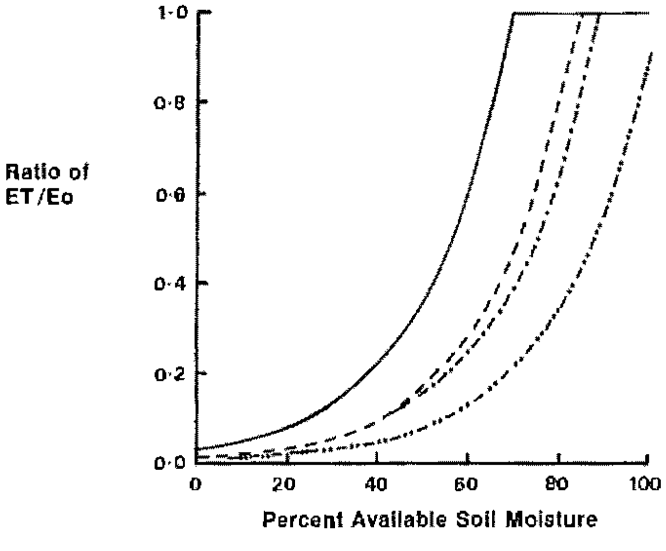


Figure 3.9 Effect of percent available soil moisture on the ratio of actual evapotranspiration (ET) to evaporative demand (Eo) found in each soil layer of the catchment water balance sub-model. The curves are: —— for 0–90 cm profile, – – – for 0–10 cm soil layer, –·– for 10–30 cm soil layer, and –··· for 30–90 cm soil layer.

Infiltration to the sub-soil layer (F3) was considered as a rate controlled process and was calculated using the hyperbolic tangent function of Boughton (1966) as follows:

$$F3 = F3max \times \tanh(XS / F3max) \qquad (3.20)$$

where XS = The rainfall excess not distributed to the surface and sub-surface layers (i.e. R - F1 - F2 (mm/day)), and F3max = maximum rate at which infiltration to the sub-soil can occur and is dependent on sub-soil moisture and pasture biomass conditions (mm/day).

The relationship between F3 and XS is shown in figure 3.10 (a) for two levels of F3max. This figure shows that F3 approaches XS when XS << F3max, and F3 approaches F3max when XS >> F3max.

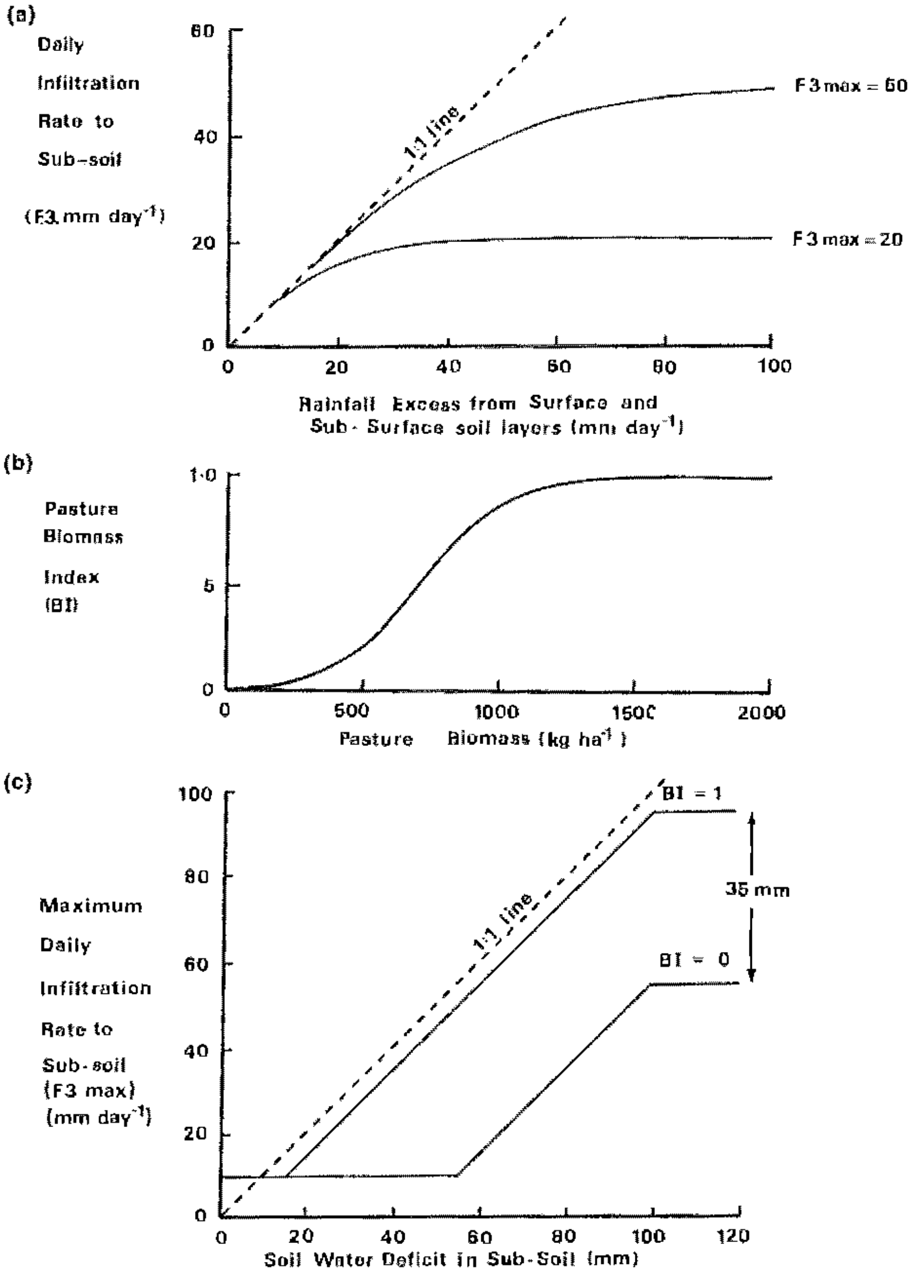


Figure 3.10 Relationships used in catchment run-off model to calculate: (a) daily infiltration rate to the sub-soil, (b) pasture biomass index and (c) maximum daily infiltration rate of the sub-soil.

F3max was calculated by Boughton (1966) as a function of antecedent sub-soil moisture in which F3max was decreased exponentially as the soil moisture deficit decreased. A similar relationship was used in this study but with two important differences. The differences were: (i) F3max was decreased equally with decreases in the water storage deficit of the sub-soil (i.e. S3max – S3), until a minimum value (fo) of F3max was reached, and (ii) F3max was increased with increases in pasture biomass.

The effect of pasture biomass on F3max was considered to be zero when pasture biomass was zero and to have its maximum effect when pasture biomass was approximately 1500 kg/ha or greater. A biomass index was calculated that would have a linear and additive effect on F3max. The relationship used between biomass index (BI) and pasture biomass (B) is shown in figure 3.10(b) and is mathematically given by:

$$BI = 0.5 + 0.5 \tanh((B-a)/b) \qquad (3.21)$$

where a and b are optimized parameters and were found to be: a = 700 kg/ha, and b = 300 kg/ha.

Changes in F3max were calculated by:

$$F3max = \max(fo, \min(100, (S3max - S3) - c + d\ BI) \qquad (3.22)$$

where fo, c and d are optimized constants and were found to be: fo = 10 mm/day, c = 40 mm/day, and d = 35 mm/day.

Figure 3.10(c) shows this relationship when BI = 0 (i.e. when pasture biomass is zero) and when BI = 0.99 (i.e. when pasture biomass equals 1500 kg/ha).

Physical meanings of the optimized constants in equation 3.22 are as follows. The value of fo = 10 suggests that the maximum rate of deep drainage is less than 10 mm/day. The value of b = 35 suggests that increases in pasture biomass from zero to 1500 kg/ha (approximately) will decrease run-off by up to 35 mm/day. The value of a – b = 5 suggests that soil moisture must be recharged to near capacity before significant run-off will occur when pasture biomass exceeds 1500 kg/ha approximately.

Figure 3.10(c) shows this relationship when BI = 0 (i.e. when pasture biomass is zero) and when BI = 0.99 (i.e. when pasture biomass equals 1500 kg/ha).

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The daily loss of water from the catchment by deep drainage to ground water was calculated as overflow from the subsoil.

3.5 Evaluation of Catchment Run-off Model

3.5.1 Comparison of Simulation Results to Observed Data

The performance of the model in simulation is given firstly with respect to run-off, and then with respect to soil moisture storage.

After the first three rounds of optimizing evapotranspiration and infiltration parameters, the model explained 65% of the variation in daily run-off. However, there were two events where simulated and observed run-off was considerably different. These differences occurred on the 9 March 1971 and 12 January 1974, and are shown as ringed points in figure 3.11(a). These large differences affected the optimization of parameters so that the fit of simulated to observed run-off for other run-off events was also poor.

On 9 March 71 predicted run-off was much less than observed run-off. On this occasion rainfall over the catchment and surrounding areas was of high intensity and showed greater areal variation than normal (see table 3.4). This table, when used with the site plan of RSSRP in figure 3.1, shows that rainfall on 9 March 71 had a steep east-west gradient. It was therefore concluded that the average rainfall received over the gauged catchment was much greater than that recorded at the weir, and hence a considerable under-estimate of run-off by the model on 9 March 71 was to be expected.

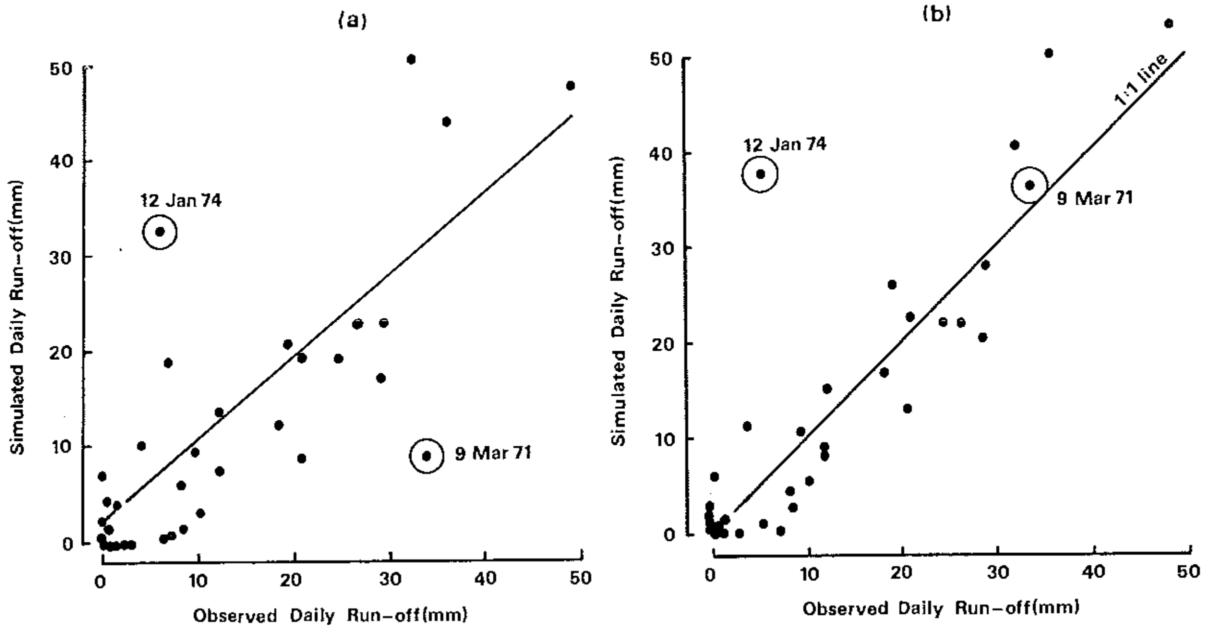


Figure 3.11 Comparison of simulated to observed daily run-off. (a) Relationship found after first round optimization (see text). (b) Relationship found after second round of optimization.

Table 3.4 Areal variation of daily rainfall on days of observed run-off for the period 1 October 69 to 20 January 74.

Date	Rainfall at Richmond Post Office (mm)	Rainfall at RSSRP (mm)* (1)	(2)	(3)	(4)	(5)	Mean Rainfall (mm)	Coeff. of Variation (%)
24 Dec 69	59	46	57	39	58	50	51.5	15.4
03 Feb 70	76	88	96	89	97	74	86.7	11.3
09 Mar 71	152	70	75	55	37	41	71.7	58.8
27 Mar 71	19	19	24	22	10	9	17.2	36.4
30 Mar 71	50	69	52	63	67	62	60.5	12.9
16 Apr 71	97	85	88	83	85	84	87.0	5.9
17 Apr 71	12	8	9	8	9	9	9.1	17.5
18 Apr 71	24	10	9	9	10	8	11.7	52.2
11 Jan 72	63	55	62	70	65	50	60.8	11.8
06 Mar 72	96	86	89	89	99	96	92.5	5.5
07 Mar 72	37	33	34	40	33	36	35.5	7.7
08 Feb 73	47	36	41	42	43	41	41.7	8.5
29 Mar 73	143	145	136	128	149	145	141.0	5.1
30 Mar 73	44	33	27	25	26	27	30.3	23.9
03 Jan 74	96	75	71	64	84	75	77.5	14.4
08 Jan 74	21	20	20	20	9	12	17.0	30.2
12 Jan 74	42	45	45	50	38	48	44.7	9.5
14 Jan 74	37	25	15	17	23	31	24.7	33.8
17 Jan 74	25	18	18	18	20	23	20.3	14.8
18 Jan 74	19	23	20	21	20	21	20.7	6.6
19 Jan 74	61	64	63	65	61	60	62.3	3.1
20 Jan 74	37	37	39	40	34	30	36.2	10.1

* Numbers identity rainfall recording site. Their locations are shown in figure 3.1

Simulated run-off was much greater than observed run-off on 12 January 74. On this occasion rainfall was contained within a rainfall sequence which produced run-off before and after run-off on 12 January. Since simulated run-off showed reasonable agreement with observed run-off on these events, it is unexpected that simulated run-off on 12 January should differ so much from the observed.

Since the objective of simulation was to extend the duration of catchment yield records, it was assumed more appropriate to use a model which gave close agreement to observed run-off in a large proportion of cases and a poor fit on some, than it was to use a model which gave a mediocre fit to all observations. Therefore, rainfall on 9 March 1971 was adjusted to the mean of the weir and Post Office records. Run-off on 12 January 1974 was excluded from the objective function and other statistical measures, and parameters in the model were re-optimized. The value of parameters so obtained were those given for equations 3.16, 3.20 and 3.21.

These adjustments markedly increased the fit of simulated run-off to observed run-off (see figure 3.11(b) and table 3.6). The coefficient of determination increased from 0.65 to 0.89. Table 3.5 shows that the regression slope and intercept of simulated run-off versus observed run-off were not statistically different from 1.0 and zero respectively.

The data in table 3.6 shows that the model performed equally well in predicting run-off at all levels of antecedent moisture and pasture biomass conditions, and in all years.

The contribution of the pasture biomass sub-model to the accuracy of estimating run-off was tested: (i) by deleting the effect of pasture biomass in equation 3.21, and (ii) by re-optimizing the parameters fo and a in equation (3.21). These changes caused the run-off objective function to increase by 21% and the coefficient of determination to decrease by 6%. Considerable under-estimates of run-off occurred when pasture biomass was low. For example, when pasture biomass was less than 500 kg/ha in 1970 and 1971, then simulated run-off was only 35% and 71% respectively of observed annual run-off.

A single factor sensitivity analysis showed most parameters were at optimum levels to minimize the run-off objective function. However, there were some remaining at sub-optimum values. Perturbations of ±10% in parameter values showed that some changes in soil water storage, evapotranspiration and pasture biomass index parameters would marginally increase the statistical agreement between simulated and observed run-off (see table 3.7). The decision to cease optimization was a subjective judgement. It was guided by criticisms that may be levelled at statistical measures of model adequacy, and by the experiences of Johnston and Pilgrim (1973) and Pickup (1977), who show the irrelevancy of seeking a global optimum.

Table 3.5 Statistical comparison of simulated daily run-off by catchment water balance sub-model to observed daily run-off, for the period 1 October 1969 to 30 September 1978.

No. of events observed	32
No. of events modelled	30
No. of comparisons	36
Mean observed run-off (mn)	14.0
Mean simulated run-off (mm)	14.8
Arithmetic mean difference (mm)	0.7
Mean of absolute differences (mm)	3.7
Std. dev. of differences	2.9
Coefficient of determination	0.89
Regression slope	1.03
std. error of slope	0.06
Regression intercept	-0.57
std. error of intercept	4.82
Value of objective function (see eq. 3.14)	2.17

Table 3.6 Comparison of simulated run-off predicted by the catchment run-off model to run-off observed from the gauged Mitchell grass catchment at RSSRP.

Date	Observed Run-off (mm)		Simulated Run-off (mm)	
	daily	annual	daily	annual
Total for 68/69		nil		nil
24 Dec 69	1.0		0.0	
03 Feb 70	12.0		9.0	
Total for 69/70		13.0		9.0
09 Mar 71	34.1		35.1	
27 Mar 71	2.5		0.0	
30 Mar 71	20.9		12.8	
16 Apr 71	36.4		49.4	
17 Apr 71	1.0		0.5	
18 Apr 71	0.4		0.8	
Total for 70/71		95.3		98.6
11 Jan 72	7.4		0.0	
12 Jan 72	0.0		2.1	
06 Mar 72	32.6		40.3	
07 Mar 72	19.4		26.0	
Total for 71/72		59.4		68.4
08 Feb 73	0.7		0.0	
29 Feb 73	26.8		21.9	
30 Feb 73	12.1		8.0	
Total for 72/73		39.6		29.9
03 Jan 74	9.6		10.6	
08 Jan 74	0.4		6.0	
11 Jan 74	0.0		1.5	
12 Jan 74	6.0		37.8	
14 Jan 74	8.6		2.6	
15 Jan 74	0.0		0.6	
17 Jan 74	1.7		6.6	
18 Jan 74	8.3		9.3	
19 Jan 74	49.0		52.8	
20 Jan 74	29.4		27.8	
Total for 73/74*		337.7		276.8
08 Jan 75	4.2		11.3	
17 Jan 75	1.6		0.0	
23 Jan 75	3.0		0.0	
15 Feb 75	29.2		20.1	
26 Feb 75	21.3		22.5	
20 Mar 75	0.0		3.1	
01 Apr 75	0.5		1.9	
Total for 74/75		59.8		58.9
06 Feb 76	24.9		22.0	
07 Feb 76	18.6		16.7	
09 Feb 76	10.4		5.4	
11 Feb 76	6.5		1.1	
Total for 75/76		60.4		45.2
21 Dec 76	12.3		14.9	
Total for 76/77		12.3		14.9

* Daily run-off during the 1974 flood from 21 January to 9 February is not shown.

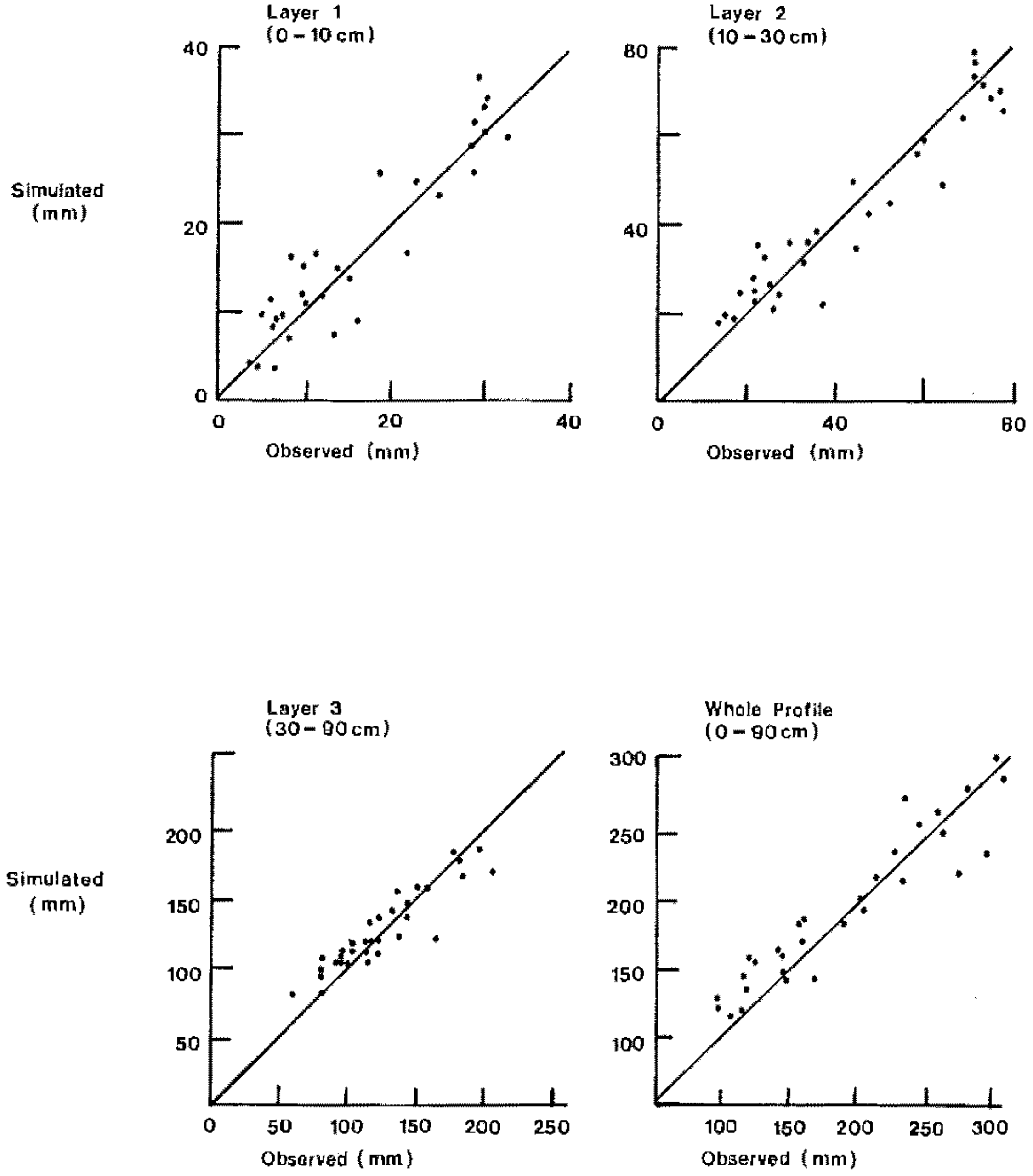
Table 3.7 Single factor sensitivity analysis of simulated run-off to changes in the parameter values of the catchment run-off model.

Parameter Value (X–10%, X+10%)		RMS** at X–10%	RMS** at X+10%
Soil water storage capacity			
Surface layer	S1max = 34.2, 41.8	103.6	99.4
Sub-surface layer	S2max = 70.2, 85.8	109.3	102.3
Sub-soil layer	S3max = 193.5, 236.5	121.1	113.4
Whole profile	Smax = 292.5, 368.5	164.6	138.0
Evapotranspiration parameters in eqn 3.6			
Surface layer	a = .0096, .0118	100.9	99.6
	b = .0486, .0594	103.2	100.6
Sub-surface layer	a = .0096, .0118	100.9	99.9
	b = .0459, .0561	104.0	102.2
Sub-soil layer	a = .0055, .0067	102.1	100.3
	b = .0450, .0550	107.6	102.1
Rainfall Distribution parameter			
Proportion of rain directed to surface layer	= 0.63, 0.77	102.0	104.1
Pasture Biomass Index parameters in eqn 3.21			
	a = 630, 770	98.9	101.6
	b = 270, 330	100.1	99.8
Infiltration parameters in eqn 3.22			
	fo = 9.0, 11.0	105.0	105.0
	c = 36.0, 44.0	105.0	105.0
	d = 31.5, 38.5	105.0	105.0

* Parameter values at –10% and +10% of their optimum value.

** Value of root mean square (RMS) of run-off objective function (eqn. 3.14 in text) when expressed as a percentage of the RMS found when using the optimum parameter value. A value of 100 indicates no change in RMS. Values less than and greater than 100 indicate increases and decreases respectively in the agreement between observed and simulated run-off.

The agreement found between simulated and observed soil moisture in each layer is shown in figure 3.12. The regression analyses in table 3.8 show that in the sub-surface and sub-soil layers the model consistently over-estimated soil moisture when the soil was dry. The regression slopes are significantly less than one and the regression intercepts are significantly greater than zero. A reduction of the evapotranspiration rates when the soil was wet, and an increase in evapotranspiration when the soil was dry did not improve the relationships as other losses in model accuracy occurred. Therefore, it would seem that the infiltration model could be improved, by distributing a greater proportion of rainfall directly to the sub-surface and sub-soil layers. Since the model gave reasonably accurate estimates of run-off and soil moisture, a re-examination of the rainfall distribution parameters to marginally improve the models fit to soil moisture observations could not be justified.



<u>Figure 3.12</u> Comparison of simulated to observed soil moisture for each layer of the catchment water balance sub-model.

Table 3.8 Statistical comparison of soil moisture estimated by catchment water balance sub-model to observed soil moisture.

	Surface layer 0-10cm	Sub-surface layer 10-30cm	Sub-soil layer 30-90cm	Whole profile 0-90cm
Mean observed soil moisture (mm)	16.3	44.4	123.1	183.8
Mean modelled soil moisture (mm)	18.0	43.0	125.4	186.4
Number of comparisons	33	32	31	33
Arithmetic mean difference (mm)	1.7	-1.4	3.4	2.6
Mean of absolute differences (mm)	3.5	6.0	12.0	18.8
Std. dev. of differences	2.8	4.8	10.2	14.4
Root mean square of differences	4.44	7.70	15.69	23.53
Coefficient of determination	0.84	0.90	0.91	0.90
Regression slope	0.91	0.86	0.81	0.76
std. error of slope	0.07	0.05	0.04	.046
Regression intercept	3.01	5.21	27.30	45.30
std. error of intercept	4.15	6.21	9.44	18.03

Table 3.9 Comparison of observed run-off from gauged catchment to observed run-off from catchment of dam at RSSRP.

Date	Gauged catchment run-off (mm)	Dam catchment run-off (mm)
09 Mar 71	34.1	23.
27 Mar 71	2.5	3.
11 Jan 72	7.3	4.
06 Mar 72	32.6	22.
08 Feb 73	0.7	4.
29 Mar 73	26.8	32.
03 Jan 74	9.6	10.
08 Jan 75	4.2	11.
15 Feb 75	29.2	22.
01 Apr 75	0.5	1.
21 Dec 76	12.3	10.
Mean	14.5	12.9

3.5.2 Application of the Model

Results in the previous section showed that the model gave reasonably accurate estimates of daily run-off from the gauged catchment for the calibration period 1 October 1968 to 30 September 1978. Since this calibration period included a wide range of environmental conditions from extreme drought to extreme flood, the catchment run-off model should give satisfactory estimates of daily run-off from the gauged catchment when used in simulation experiments involving long-term (60 year) weather data as input to the model.

The run-off weir catchment was nested within the catchment of the shallow storage dam at RSSRP. Therefore comparison between run-off data from the weir and observations of inflow to the dam provides one measure of areal variation in runoff. The depth of run-off from the dam's catchment was calculated from changes in the dam's water storage level, and a storage depth to volume relationship established for the dam from survey data provided by Queensland Water Resources Commission. Catchment run-off into the dam was slightly under estimated because bywash losses and losses into the bed of the dam were not taken into account. Nevertheless, the results in table 3.9 show there to be reasonable agreement ($R^2 = 0.82$) in the behaviour of the gauged catchment and the dam's catchment. The lower mean yield of the dam's catchment was possibly due to the losses described above.

Because of the homogeneity of soils and vegetation on the gauged and dam catchments, the main reason for the variation in run-off between these catchments was probably due to areal variation in rainfall. Areal variation in rainfall increases as catchment size increases. Therefore use of the model in simulation experiments which do not account for areal variation in rainfall, should be restricted to catchments that are of a similar size to the gauged and dam catchments.

Grazing pressure and fires have large effects on the vegetation of the Mitchell grass plains. Grazing pressure also has significant effects on the structure of the surface soil because of trampling. However, no attempt was made to determine the effect of these factors on the predictive accuracy of the model.

3.6 Conclusions

The main conclusion of this chapter is that the run-off model should have reasonably general application to the Mitchell grass plains, and hence should provide sufficiently accurate estimates of catchment yield to be useful in evaluation of shallow storage irrigation.

Other conclusions were:

(i) Antecedent soil moisture conditions had the greatest effect on the redistribution of rainfall to infiltration and run-off. However, temporal changes in the biomass of Mitchell grass pastures also had a significant effect on run-off.

(ii) Rainfall must recharge soil moisture to almost capacity, particularly at high levels of pasture biomass, before appreciable run-off occurs. The very slow rate of deep drainage (10mm/day) causes the redistribution of rainfall almost to switch from infiltration to run-off.

(iii) The switching of infiltration to run-off, the high water holding capacity of the soil in relation to annual rainfall, and the high variability of annual rainfall suggests that: the long term probability distribution of annual run-off will show a significant proportion of years with zero run-off and a significant proportion of years with very high run-off.

CHAPTER 4

WATER. STORAGE MODEL

The water storage model provides the link between the four physical components of the shallow storage irrigation system as shown in figure 4.1. The physical dimensions of the water storage are important because they determine the proportion of run-off from the catchment that is retained for subsequent irrigation, the surface area of land that is flooded for subsequent ponded-area cropping, the volume of water that is lost by evaporation and the cost of constructing the dam wall.

This chapter develops relationships that describe the physical characteristics of shallow storage dams, and then derives a water balance sub-model for calculation of changes in the volume, height and surface area of water storage.

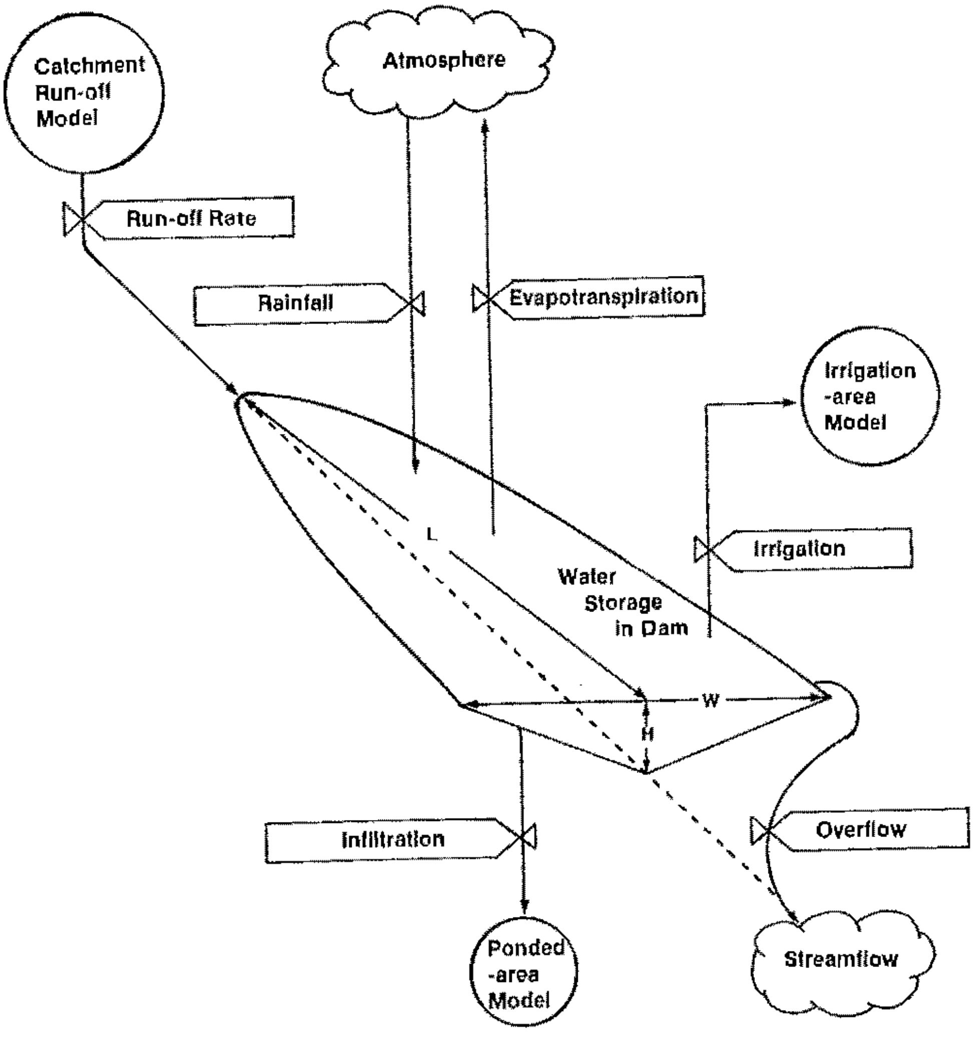


Figure 4.1 Flow diagram of dam water balance sub-model. (Water storage in the dam is shown as half an eliptical cone of height H, length L and width W. Rates are shown as valves, sources and sinks as clouds, exogenous variables as circles and material flows as arrows.)

4.1 Physical Characteristics of Dam

It was noted in chapter 1 that shallow storage dams are constructed by forming an earth wall across a small water-course. The volume of water in such a storage is related to the height and width of the wall and the gradient of the stream bed.

The surface area of gully dams often have the shape of half an ellipse and the cross section of the gully at the dam wall is often 'V' shaped (see figure 4.1). Thus, water storage in such a dam approximates half an inverted elliptical cone where the long radius of the ellipse is the length (L) of the dam, the short radius of the ellipse is half the width (W) of the dam at the dam wall, and the height of the cone is the height (H) of water storage in the dam at the center of the dam wall. The volume of water storage in half an eliptical cone is given by:

$$V = \frac{1}{2}\left(\frac{1}{3}\pi\left(\frac{1}{2}W\right)LH\right), \qquad (4.1)$$

and the surface area (A) of water storage is given by:

$$A = \frac{1}{2}\left(\pi\left(\frac{1}{2}W\right)L\right) \qquad (4.2)$$

The gradient (G) of the stream bed and the gradient (g) of the bank at right angles to the stream bed at the dam wall are given by:

$$G = H/L \quad \text{and} \quad g = H/\tfrac{1}{2}W.$$

If these gradients are assumed constant then H/L and H/W are also constant. When expressions for these constant shapes are substituted into equations 4.1 and 4.2, then the volume of water storage and the surface area of water storage are proportional to the cube and square respectively of the height of water storage as follows:

$$V = pH^3 \quad \text{and} \qquad (4.3)$$
$$A = 3pH^2 \qquad (4.4)$$
$$\text{where } p = \tfrac{1}{2}.\tfrac{1}{3}.\pi.1/g.1/G = \text{constant}.$$

The realism of using half an eliptical cone to define the relationship between V and H was tested by comparing predicted values of V against observed values of water storage in the dam at RSSRP. Testing was as follows: a grid survey of the ponded-area was used to determine the observed values of V for increments in H. This survey showed the dam to have the following characteristics when it was filled to capacity: maximum volume = 439 ML, maximum depth = 2.0 m, maximum length = 1954 m (thus G = 1:977), and maximum width = 396 m (thus g = 1:99).

The value of p in equation 4.3 was calculated in two ways. Firstly, from the values of g and G (p = 50644), and secondly, from the values of V and H when the dam was at maximum capacity (p = 54875). Table 4.1 shows that as H increases from 0.2 to 2.0m that there is not only close agreement between these two predicted values of V, but also close agreement between predicted and observed values of V for all values of H.

It was concluded that use of half an elliptical cone to describe the characteristics of water storage in a shallow storage dam was physically realistic.

Normal engineering practice was used to specify the following design characteristics for construction of the dam wall across a 'V' shaped gully: a crest level 1.0m above maximum water storage level, a crest width of 2.5m, a slope of 1:3 on the side batters, and a core trench below ground level that is 2.5m wide and slopes from ground level at the extremities to 1.5m below ground level at the centre of the gully.

The height (h) and width (w) of the dam wall were calculated from:

$$h = H_{max} + 1 \quad \text{and} \quad w - 2\,h/g \qquad (4.5) \text{ and } (4.6)$$

where H_{max} = maximum height of water storage in dam (m^3).

Table 4.1 Comparison of observed to predicted volumes of water storage in the dam at RSSRP.

Height (H) of water in dam (m)	Observed volume of dam (ML)	Predicted* volume of dam	
		$V = 50644\ H^3$	$V = 54875\ H^3$
0.2	3	1	
0.4	7	3	4
0.6	16	11	12
0.8	36	26	28
1.0	65	51	54
1.2	105	88	95
1.4	158	139	151
1.6	222	207	225
1.8	304	295	320
2.0	439	405	439

* using equation 4.3 in text.

The volume (v) of earth required for dam wall construction was calculated from:

$v = va + vb + vc$ (4.7)
where va = volume of earth below crest to ground level (m^3) = $(2.5\ h\ w)/2$, vb = volume of earth in core trench (m^3) = $(2.5 \times 1.5\ w)/2$, vc = volume of earth in batters (m^3) = $(3\ h^2 w)/2$.

The storage to excavation (SE) ratio of a dam is the ratio of water storage capacity to volume of earth required to construct the dam wall. For example, the dam at RSSRP had a capacity of 439ML and required 11500 m of earth for construction. Therefore, its SE ratio was 38:1. This ratio is very high when compared to farm dams that are constructed on steeper topography. The SE ratio of such dams is frequently less than 10:1.

The high SE ratios of shallow storage dams reduces the cost per unit of water storage. This is an important attribute and compensates for the large proportion of water that is lost by evaporation.

4.2 Dam Water Balance Sub-Model

The variables effecting the water balance of a shallow storage dam that is constructed across a small water course are shown in figure 4.1 and are discussed below.

The volume of water held in the dam at the beginning of each water year (1st October) is generally but not necessarily zero. Increases in water storage are mainly due to run-off from the catchment and this normally occurs during the period January to March. Rainfall is also a direct input to the dam, but is of much lesser importance than run-off.

When the depth and surface area of the dam is increased by run-off, a proportion of the water is lost by infiltration into the bed of the dam (i.e. to the soil of the ponded-area). Soil samples taken from the ponded-area after 2-3 months of flooding showed that infiltration from the dam did not penetrate to a depth greater than approximately 1.5m. Dry soil was often encountered at this depth. Thus, infiltration to the ponded-area was considered as an instantaneous process wetting the soil to a depth of 1.5 m.

If the sum of run-off and rainfall exceed the dam's capacity then the excess water is lost through the dam's bywash to stream flow. Other losses from the dam occur as evaporation to the atmosphere and supply of water to the irrigation area. These losses generally reduce the dam's water level to zero by the month of September in any year.

In some situations it is necessary to locate the irrigation-area upstream of the dam so that it is necessary to pump irrigation water. This was the case at RSSRP. However, it is preferable to locate the irrigation-area downstream of the dam so that water can be delivered by gravity flow.

The conservation equation used to simulate changes in the volume (V) of water storage in the dam between times t_1 and t_2 was:

$$V_2 = V_1 - \sum_{t_1}^{t_2} (VEVAP+VRAIN+VRUN-VINFIL-VOVER-VIRRIG) \qquad (4.8)$$

where V_1 = Volume of water storage at time t_1 (m^3), V_2 = Volume of water storage at time t_2 (m^3), VEVAP = Rate of evaporation from dam's surface (m^3/day), VRAIN = Rate of rainfall to dam's surface (m^3/day), VRUN = Rate of run-off from catchment (m^3/day), VINFIL = Rate of infiltration to ponded-area (m^3/day), VOVER = Rate of over-flow through dam's bywash (m^3/day), and VIRRIG = Rate of irrigation supply to irrigation-area (m^3/day).

The order of presentation in this equation was the order of computation during simulation. Evaporation losses from the dam were deducted first because an event stepping method of water balance calculation was used. The minimum time step was one day, but this was extended so that the water balance model was accessed only when rainfall or run-off occurred or when irrigation and planting on the ponded-area was scheduled.

<u>Calculation of VEVAP</u>. Evaporation is assumed to occur uniformly from the surface of a dam. If DEVAP is the depth of evaporation between times t1 and t2, then the volume of water remaining in the dam at t2 was calculated from equation 4.3 as follows:

$$V_2 = \max(0,\ p(H_1 - DEVAP)^3) \qquad (4.9)$$

where H_1 = Height of water in dam at t_1 (m) = $(V_1/p)^{0.333}$.

The depth of evaporation was calculated as a fixed proportion of the daily evaporative demand (Eo) that was accumulated between t_1 and t_2 as follows:

$$DEVAP = 0.99 \sum_{t_1}^{t_2} Eo \qquad (4.10)$$

The proportionality constant in equation 4.10 was derived in the following way.

The height of water in the dam at RSSRP was measured twice weekly in 1970, 71, 73, 75 and 76 by a gauge located on the downstream side of the dam wall. Water height was observed with an accuracy of ± 1.0 mm. Monthly evaporation loss was calculated from these height recordings after they had been corrected for rainfall run-off and irrigation use. Monthly evaporation loss was then calculated as a proportion of monthly evaporative demand as shown in table 4.2. Missing values occur each year in this table because irrigation use and evaporation depleted water supplies within eight months of the dam being filled. No measurements were taken in 1972 and 1974.

The results in table 4.1 show that the ratio of observed evaporation to evaporative demand varied between 0.84 and 1.13. This variation was not related to the level of evaporative demand or the height of water in the dam, and thus the mean ratio of 0.99 was adopted as the proportionality constant in equation 4.10.

<u>Calculation of VRAIN and VRUN</u>. The increase in storage volume due to rainfall was calculated by increasing the height of water storage by the depth of rainfall and then recalculating storage volume using equation 4.3. The method of calculating the volume of run-off was described in the previous chapter.

<u>Calculation of VINFIL and VOVER</u>. Run-off from the catchment not only causes an increase in storage volume, but also infiltration to the bed of the dam over the dam's incremented surface area. Let V and A be the increase in storage volume and surface area due to run-off alone. Provided the dam does not overflow, the following relationship holds:

$$VRUN = V + VINFIL \qquad (4.11)$$

Table 4.2 Observed monthly evaporation losses from the dam at RSSRP (Edam) as a proportion of monthly estimates of evaporative demand (Eo)*.

	Ratio of Edam/Eo						Predicted** Evaporation (mm/month)
	1970	1971	1973	1975	1976	Mean	
Jan	0.95	-	-	-	-	-	233
Feb	1.01	-	0.95	-	-	0.98	170
March	0.87	1.12	1.09	1.13	0.92	1.03	178
April	-	1.01	1.07	0.84	0.92	0.96	149
May	0.99	0.98	0.93	1.13	0.93	0.99	121
June	1.02	0.90	0.92	0.98	1.13	0.99	99
July	0.98	1.09	0.95	1.00	-	1.01	113
Aug	-	-	-	0.92	-	-	134
Sept	-	-	-	1.04	-	-	165
Oct	-	-	-	-	-	-	210
Nov	-	-	-	-	-	-	242
Dec	-	-	-	-	-	-	257
Mean	0.97	1.02	0.99	1.01	0.98	0.99	

* Monthly values of Eo were estimated by the method of Fitzpatrick (1968).

** Values predicted by equation 4.10 in text with the long term mean monthly values of Eo are shown in Appendix A.

Both V and VINFIL in this equation are unknown. To determine their values it is necessary to express both in terms of H. The following procedure of three steps was used for this purpose.

(i) Increases in the volume and surface area of water storage caused by run-off are given by:

$$V = pH_4^3 - pH_3^3 \text{ and } A = 3pH_4^2 - 3pH_3^2 \qquad (4.12) \text{ and } (4.13)$$

where H_3 = height of water in dam after VEVAP is deducted and VRAIN added (m), and H_4 = height of water in dam after VRUN is added (m).

(ii) The depth of water infiltrating (DINFIL) to the bed of the dam over the incremented surface area was assumed to be 64 mm. This is the available range of soil water holding capacity of the ponded area (292 mm, see section 6.3.2) minus the available range of soil water holding capacity of the catchment area (288 mm, see table 3.3). Thus:

$$VINFIL = DINFIL \times A = 64\ (3pH_4^2 - 3pH_3^2) \qquad (4.14)$$

(iii) Substitution of equations 4.12 and 4.14 into equation 4.11 gives:

$$VRUN = (pH_4^3 - pH_3^3) + 64\ (3pH_4^2 - 3pH_3^2) \qquad (4.15)$$

The value of H_4 in this equation was found using Newton's numerical iteration method (Petersen 1969). Values for V, A and VINFIL were then found by substituting the value of H_4 into equations 4.12, 4.13 and 4.14 respectively.

If the value found for H_4 was greater than the dam's maximum height for water storage then the volume, height and surface area of water storage were set to their maximum values (Vmax, Hmax and Amax respectively) and V, VINFIL and VOVER were calculated from:

$$V = Vmax - pH_3^3 \tag{4.16}$$

$$VINFIL = 64\ (3pHmax^2 - 3pH_3^2) \tag{4.17}$$

$$VOVER = pH_4^3 - Vmax \tag{4.18}$$

Calculation of VIRRIG. The volume of water supplied to the irrigation area is dependent on: the volume of water in the dam, the area of crops on the irrigation-area, the soil moisture deficit in the root zone of the irrigated crops, and the timing and number of future irrigations. Where future irrigations remain on the irrigation schedule then calculations of VIRRIG must take into account the volume of water required for these irrigations and future changes in storage volume caused by evaporation, rainfall and run-off.

The method used to relate all of the above factors and then calculate VIRRIG is given in chapter 8.

CHAPTER 5

IRRIGATED GRAIN SORGHUM PRODUCTION MODEL

Production of grain sorghum from the irrigation-area of a shallow storage irrigation system is the product of area of cropping by average yield per unit area. Chapter 1 showed that both area of cropping and yield per unit area could vary from year to year depending on seasonal conditions and management factors. Chapter 1 also showed that portions of the irrigation-area could have different yields per unit area if the supply of irrigation water was not sufficient to allow use of the same watering regime over all portions of the irrigation-area.

If the irrigation-area is divided on the basis of irrigation strategy (i.e. frequency and timing) into n portions, and if AC(i) and GY(i) are the area and grain yield per unit area respectively of portion 'i', then the grain production (GP) from the whole irrigation-area is given by:

$$GP = \sum_{i=1}^{n} AC(i) \times GY(i) \qquad (5.1)$$

Effects of the weather, shallow storage design and management on AC(i) are investigated in chapter 8. This chapter gives:

(i) A literature review of environmental factors affecting the yield of grain sorghum, particularly those factors which may be expected to apply on the Mitchell grass plains. A discussion of models used to predict grain yield is included in this review.

(ii) The methods and results of field experiments at RSSRP which investigated the effects of irrigation strategy on grain sorghum yield.

(iii) The derivation of a mathematical model to predict yield of grain sorghum from weather data.

5.1 Literature Review

Grain sorghum, Sorghum bicolor (L. Moench) is an annual, summer growing, determinate grass. It has the C4 pathway of carbon fixation (Hatch et al. 1967), and thus its maximum growth rate is attained under conditions of high temperature and radiation (El-Sharkawy and Hesketh 1964, and Ludlow 1976). Physiological advantages allow the Sorghum genus to use water efficiently, particularly under conditions of water stress (Ludlow 1976, Brown 1978, Anderson 1979).

The final expression of grain yield in a cereal crop is dependent upon the interaction of genotype with sequential changes in environmental factors such as: radiation, daylength, temperature, evaporative demand, soil water availability, soil fertility, weed competition and predation by pests and pathogens.

Genotype by environment interactions are complex but division of grain yield into its components is useful because it often leads to simplification since the development of grain occurs in a sequential manner. Grain yield per hectare may be decomposed into the factors: plants per hectare, fertile tillers per plant, grain number per fertile tiller, grain size and fraction of grain lost to lodging. Lodging is a term used to describe the collapse of the stalk supporting the panicle so that recovery of grain by machinery at harvest is difficult and often not possible.

The amount of grain lost to lodging depends on stem strength, windiness, the timing of harvest and the efficiency of the harvesting operation. Crop density is also a factor because mutual support frequently occurs among plants that would otherwise lodge. The term "stem strength" is used to imply resistance to lodging and includes factors such as stem diameter, stem pith disintegration, plant height and panicle weight. Stem strength is a function of genotype, the duration and intensity of moisture stress, and the incidence and vigour of fungal stem infection such as charcoal rot (Macrophomina phaseoli) (Chamberlain 1978).

The terminology of Vanderlip and Reeves (1972) is used to describe phasic development in this study. The main stages of phasic development and the approximate time after planting that these stages occur under average field conditions are:

(i) emergence ($\approx$ 4 days),
(ii) floral initiation (i.e. differentiation of the growing point from leaf production to development of floral organs) ($\approx$ 30 days),
(iii) booting (i.e. final leaf fully expanded with the panicle enclosed by the sheath of the final leaf) ($\approx$ 50 days),
(iv) half bloom (i.e. 50% of heads in flower) ($\approx$ 60 days),
(v) dough (i.e. approximately one half of the grain dry matter has accumulated) ($\approx$ 80 days), and
(vi) physiological maturity (i.e. maximum dry weight of the grain has been reached) ($\approx$ 95 days).

Distinction is made between a development stage which is a point in time and a phenophase which is a period of time. For example, the half bloom development stage is the point in time when 50% of heads reach flowering, whereas, the anthesis phenophase is a period of time spanning the whole flowering period.

5.1.1 Factors Effecting Phasic Development

Maturity in sorghum is controlled by dominant and recessive genes at four gene locii, the degree of heterosis present and the sensitivity of alleles at each locus to environmental conditions (Quinby 1967, Quinby et al. 1973). The rate of phasic development is mainly the result of interaction between genotype and temperature, but it is also influenced by other environmental conditions such as daylength and water stress (Coleman and Belcher 1952, Quinby and Karper 1961, Pauli et al. 1964, Whiteman and Wilson 1965, Quinby 1967, Caddel and Weibel 1971,1972).

Sorghum is a quantitative short day plant (Major 1980) and therefore if daylength is longer than the critical photoperiod then time to floral initiation increases as daylength increases. However, most commercially available grain sorghum hybrids are insensitive to daylength under normal field conditions because daylength is shorter than the critical photoperiod (Quinby and Karper 1961, Miller 1968, Major 1980). The grain sorghum hybrid used in the experiments at RSSRP (Dekalb E57) is in this category, and thus further consideration of the effects of daylength on phasic development is not needed.

Severe moisture stress has been observed to delay phasic development of sorghum in glasshouse pot trials (Whiteman and Wilson 1965, Langlet 1973). However, similar results have not been reported from field experiments, presumably because the level of stress at floral initiation is not so severe. Some field trials have shown that milder moisture stress can slightly hasten development (Salter and Goode 1967, Turner and Begg 1981) possibly because of increased leaf temperature.

Summation of temperature for prediction of phasic development has been used for two and a half centuries, and has been found to be accurate for many crops (Wang 1960, Waggoner 1974). This method was traced by Wang (1960) to the work of Réaumur (1735). The principle of Réaumur's heatsum is that the rate of phasic development increases as temperature increases so that the integral of temperature (T) over time (t) is a constant when calculated over the duration of a phenophase. Thus:

$$H = \int_1^N T \, . \, dt \qquad (5.2)$$

where H = Réaumur's thermal constant or heatsum (usually expressed in units of 'heat units', 'degree days' or 'growing degree days'), and N = duration of phenophase (days).

This equation has been adapted in many ways to improve its predictive capacity (Nuttonson 1948, Robertson 1968, Cross and Zuber 1972, Maas and Arkin 1978). The most frequently used adaption is the 'remainder index method' (Wang 1960). This method subtracts a base temperature (Tbase) from the mean of daily maximum and minimum temperature (Tmax and Tmin respectively), so that the thermal constant is calculated by:

$$H = \int_1^N (DMT - Tbase) \, . \, dt \qquad (5.3)$$

where DMT = Daily mean temperature (°C) = (Tmax + Tmin)/2.0.

Values of DMT during the summer growing season of Sorghum in tropical regions are usually 15 to 30°C, whereas, values of Tbase for grain sorghum have been found to be 4 to 10°C (Vanderlip and Arkin 1977, Gelroth and Vanderlip 1978, and Schaffer 1980). Thus, H is proportional to DMT in tropical environments and hence integration of (5.3) gives:

$$H = N(PMT - Tbase) \qquad (5.4)$$

where PMT = phenophase mean temperature (°C) = $(\sum_1^N(Tmax + Tmin)/2)/N$.

The appropriate values of H and Tbase in this equation that are applicable to the phasic development of a particular sorghum hybrid may be determined experimentally from observations of N and PMT. Re-arrangement of (5.4) for interpolation of experimental data by linear regression gives:

$$1/N = (1/H)PMT - (1/H)Tbase \qquad (5.5)$$

Planting dates for grain sorghum on the Mitchell grass plains are expected from December to April. Long-term mean daily temperatures for the months of January, March and May at Richmond are 29.6, 27.5 and 20.6 °C respectively. Therefore, the rate of phasic development of crops growing in January should be slightly faster than for crops growing in March and considerably faster than for crops growing in May. The importance of these changes on the rate of phasic development become evident in the next section, where the sensitivity of grain yield to water stress at different stages of growth is discussed.

5.1.2 Effects of Water Stress on Grain Yield

Plant water stress develops when plants cannot extract sufficient soil water to meet the rate of atmospheric evaporative demand. The result is a decrease in leaf water potential, an increase in resistance to the diffusion of water vapour and carbon dioxide and a decrease in the rates of both transpiration and photosynthesis (Milthorpe and Moorby 1974). This causes a reduction in growth rate.

The rate at which water stress develops is dependent on soil factors (such as hydraulic conductivity and water holding capacity), plant factors (such as root distribution and leaf area) and atmospheric conditions (such as radiation and wind) (Hagan et al. 1967). Prolonged and severe water stress can be expected in dryland crops grown on the Mitchell grass plains because of the hot, arid conditions. However, the soil has a high water holding capacity, and thus water stress should not develop quickly after soaking rains or irrigation.

Water stress decreases the yield of grain sorghum by:

(i) reducing emergence (Evans and Stickler 1961 and Radford 1983),

(ii) limiting root expansion and thus subsequent ability to withstand moisture stress (Whiteman 1962),

(iii) reducing leaf area expansion, and thus subsequent photosynthetic capacity (Vanderlip and Arkin 1977),

(iv) reducing tiller number per plant (Blum 1973),

(v) reducing grain number per panicle (Bielorai et al. 1964, Griffin et al. 1966, Langlet 1973 and Brown 1978) by reducing the development of florets, reducing the viability of gametes at anthesis, and by causing abortion of grain embryo during the early grain filling period,

(vi) reducing grain size (Bielorai et al. 1964, Plaut et al. 1969, Langlet 1973), and

(vii) increasing lodging losses (Bond et al. 1964, Chamberlain 1978).

The above findings show that water stress can reduce grain yield at all stages of crop development, and that all components of grain yield are effected.

Because of compensation between the components of yield, the effect of water stress on a component is not only related to the level of stress imposed at the time of its development, but is also related to the stress imposed at previous growth stages (Aspinal et al. 1964, Grafius 1972). Grain number per panicle is not only dependent on the level of water stress during floral development and early development of the grain embryo, but is also dependent on the number of plants established and the number of fertile tillers per plant.

Cereal grains have some capacity to boost the supply of photosynthate to grain sites under conditions of moisture stress during grain filling. Some carbohydrate stored in the stem can be translocated to the grain or the proportion of assimilates directed to the grain can be increased at the expense of assimilates directed to stem maintenance (Chamberlain, 1978). Whilst Chamberlain did not find clear evidence of the above mechanisms in sorghum, he did find a strong association between pith disintegration and the availability of carbohydrates in the stem. Lower supplies of assimilates in consequence of reduced photosynthesis caused by water stress led to increased pith disintegration and lodging. This suggests that grain size could provide a useful measure or index of the resistance of plants to lodging.

The yield of grain sorghum is most sensitive to the effects of water stress at booting and during the anthesis phenophase (Painter and Leamer 1953, Musick 1960, Musick et al. 1963, Swanson and Thaxton 1957, Bielorai et al. 1964, Henderson 1967, Finker and Malm 1971, and Hiler and Clark 1971). This sensitivity is common to all cereal grains (Salter and Goode 1967) and has led to the general recommendation that irrigation schedules should give priority to irrigation between booting and half bloom (e.g. Robins et al. 1967, McNee 1971, Hiler et al. 1974, Keefer 1981). The benefit of irrigation at this time can carry through to the dough phenophase so that severe reduction in both grain number and grain size is avoided.

It follows from the above that accurate prediction of phasic development is important for both grain yield estimation and optimal allocation of irrigation water.

5.1.3 Effects of Temperature on Grain Yield

The nett assimilation rate of C4 grasses is close to zero at temperatures of 5–10 °C, and reaches a maximum at temperatures of 35–45 °C (Ludlow 1976). However, daily dry matter accumulation is maximized at lower temperatures because of night-time respiration. For example, Downes (1972) found that dry matter accumulation of sorghum was greater at day/night temperatures of 27/22 and 30/25 °C than it was at day/night temperatures of 21/16 and 33/28 °C. He also found that changes in daytime temperature of 24 to 36 °C had little effect on dry matter accumulation, but that increases in night time temperature from 19 to 31 °C reduced dry matter accumulation by sixty percent.

Sorghum is not tolerant of frost (Ludlow 1976), and large losses in yield can occur if frost occurs at anthesis. Dessication of floral parts can also occur under heatwave conditions (Skerman 1978).

Since Sorghum is a genus of tropical origin (Anderson 1979), most commercial hybrids of grain sorghum have been bred in warm temperate climates. It has been suggested that these hybrids lack tropical adaptation and give lower grain yields when grown in the tropics (Downes 1972, Ludlow 1976, Henzell 1980, and Leslie and Keefer 1982). For example, the maximum grain yield recorded in tropical Queensland of 8 t/ha (Keefer 1981) is some 6–8 t/ha less than maximum recorded yields (Heslehurst 1982). A yield of 10 t/ha has been recorded in the tropics (Wright 1982), but this crop was grown during winter.

It is possible that yield depression in the tropics is only apparent because agronomic factors affecting yield have not been exhaustively investigated (Leslie and Keefer 1982). However, it is unrealistic to expect that yield will not be affected in some way by the large differences in temperature and radiation conditions that exist between warm temperate and tropical climates. These differences can be exacerbated by local conditions which affect time of planting.

Ludlow (1976) and Henzell (1980) suggest that the higher temperatures of tropical conditions cause the rate of phasic development to increase more than the daily rate of nett assimilation. While factors contributing to a lower assimilation rate (relative to phasic development) in tropical conditions may be shorter daylength, greater cloud cover, higher respiration losses and higher evaporative demand, the net result of this hypothesis is less dry matter accumulation per phenophase. The main consequence is less assimilate available for development of the panicle.

5.1.4 Soil Nutrient Availability

Information on the fertility of the Mitchell grass plains for crop production is limited. Because of the region's short history of cropping there is no literature describing long term effects of cropping on soil fertility.

The chemical analysis of soils given in table 1.2 showed that most soil nutrients were in adequate supply except nitrogen and phosphorus, and possibly zinc.

At a number of sites on the Mitchell grass plains Skerman (1958) found that nitrogen deficiency reduced the yield of dryland forage sorghum when the land was continually cropped for three years. A nutrient omission trial showed that nitrogen applied at 48 kg/ha significantly increased yield of Italian forage sorghum by 35%, but the omission of the following nutrients did not affect yield: phosphorus, potassium, boron, manganese, molybdenum, copper, zinc and magnesium.

The recommendation developed from commercial experience with crops of forage sorghum irrigated with bore water during the drought years of the 1960's, was to withhold fertilizer at planting and apply 60 kg/ha of nitrogen to ratoon crops (E.J. Weston, personal communication). No other nutrients were found to increase yield.

In contrast to the above findings, an experiment on the irrigation-area of RSSRP showed that nitrogen applied at planting had either little or no effect on grain sorghum yield (Clewett and Weston 1980). The experiment tested the effect of plus and minus nitrogen and phosphorous fertilizer on grain yield and was repeated for six years over an eight year period. The experiment was initially planted into recently ploughed Mitchell grass pasture and was thereafter sown into land which had been continually cropped but not fertilized. No differences in grain yield, nitrogen content or phosphorous content were found in the sixth year of cropping. The mean nitrogen content of the non-fertilized treatment was 1.9%, which is well above the Australian average (Reid 1981), and much higher than values reported in the literature for crops grown in nitrogen-deficient circumstances (Herron et al. 1963 and Mackenzie et al. 1970). It was concluded that nutrients were not limiting the grain yields of the irrigation experiments at RSSRP.

5.1.5 Effects of Plant Density on Grain Yield

Grimes and Musick (1960) reported rapid increases in irrigated grain sorghum yields with increasing plant density up to 10 plants/m^2, but minimal effects of density on yield above this level. Yield was only reduced by 10% in their experiments when plant density was increased to 170 plants/m^2. Under dryland conditions, the data of Brown and Shrader (1959), Philips and Norman (1962), Bond et al. (1964) and that of Karchi and Rudich (1966), show only marginal differences in grain yield over a population density of 4.5 to 20 plants/m^2. The results of Brown and Shrader (1959) also show that the optimum plant density for grain production decreases as the level of water stress increases. In conditions of severe stress they found the optimum density to be less than 4 plants/m^2.

In Central Queensland, Thomas et al. (1981) conducted seven grain sorghum population density experiments over 4 years. In these experiments environmental conditions were similar to those found at Richmond and the density treatments were 3.7, 8.6, 13.6 and 18.5 plants/m^2. On pooling the results they found the mid-range densities to be marginally superior, but in all experiments the effects of plant density were small, and in three experiments plant density had no statistically significant effect. Their results do not show an interactive effect of density with water supply.

Harper (1977) concluded that over a large range of plant densities the effect of density on yield is minimal and often absent because individuals in the population compensate changes in plant density with changes in yield per plant. However, at low densities individual plants do not have the capacity to entirely compensate for changes in density, and so the effect of density on yield per unit area assumes importance.

Since yield per unit area is the product of yield per plant and plant density, Holliday (1960) and Harper (1977) suggest that relationships between yield and plant density should be established by determining the relationship between yield per plant (GY/D) and plant density (D) as follows:

$$GY/D = a/(1 + abD) \qquad (5.6)$$

$$\text{therefore } GY = aD/(1 + abD) \qquad (5.7)$$

where a and b are constants.

The reciprocal of equation 5.6 has been shown by Holliday (1960) to be linear for a wide range of crops and is known as the 'Reciprocal Yield Law'. The reciprocal equation is:

$$1/(GY/D) = 1/a + bD \qquad (5.8)$$

The values of a and b in this equation can be established from experimental data by linear regression.

5.1.6 Structure of Grain Yield Models

This section gives background concepts on modelling grain yield. Discussion begins with simple statistical models and flows through to complex, process orientated models.

(i) Yield = f (simple climatic variables).

Lewin and Lomas (1974) found good agreement between wheat yield and total precipitation during the growing season ($R^2 = 0.7$) in semi-arid regions of Israel. However, in more humid regions the model was inadequate and it was necessary to use water balance techniques to gain accuracy in yield estimation. Nix (1976) used a similar model to show that a considerable proportion of the variation in the long term mean wheat yields of statistical divisions in the Australian wheat belt could be attributed to rainfall after half bloom ($R^2 = 0.61$, $n = 20$).

(ii) Yield = f (evapotranspiration accumulated over entire growing season).

This approach has been used successfully in pasture models where total above ground biomass is of interest (Rose et al. 1972; Stewart and Hagan 1973). However, the relationship may be expected to break down where it is used to predict the yield of specific plant parts such as grain, because the effect of water stress on grain yield is largely dependent on the stage of development at which stress is imposed. There are of course exceptions. For example, Greacen and Hignett (1976) successfully predicted the yield of wheat in South Australia from seasonal evapotranspiration. However, in this region the availability of water to wheat crops before flowering is relatively constant (Nix 1976).

Downey (1972) reviewed the results of 14 authors who reported both grain yield and seasonal evapotranspiration. Although a trend line was clearly evident when relative yield was plotted against relative evapotranspiration, Downey concluded that the concept of critical phenophases was necessary for accurate estimation of grain yield.

(iii) Yield = f (water stress during one phenophase)

This approach has been applied to cereal grains and uses the finding that cereal grains are most sensitive to the effects of water stress during the anthesis phenophase. For example, Nix and Fitzpatrick (1969) found that a water stress index, computed for the anthesis phenophase from the results of water balance simulation, accounted for 60–83% of the variation in wheat and grain sorghum yields in Central Queensland. The water stress index was calculated as a function of soil moisture availability and evaporative demand.

(iv) Yield = f (water stress in two or more phenophases in an additive model).

Hiler and Clark (1971) and Mapp et al. (1975) modelled yield as linear functions of daily water stress indices that were accumulated over the growing season. In their models the daily stress indices were computed from the degree of water stress and the susceptibility of yield to stress at each growth stage. Mapp et al. calculated daily water stress as a function of soil water availability and evaporative demand, whereas, Hiler and Clark calculated water stress from the ratio of evapotranspiration to evaporative demand.

These models recognize that water stress depresses grain yield in all phenophases, but that the magnitude of yield reduction to a given stress varies according to the phenophase. Their major shortcoming is that they do not recognize interactions in yield which occur between phenophases because of the additive structure of such models.

(v) Yield = f (water stress in two or more phenophases in a multiplicative model).

The model of Jensen (1968) fits this structure. He defined the degree of water stress operating in each phenophase as the ratio of actual to potential evapotranspiration. The ratio in each phenophase was then modified to accommodate the sensitivity of yield to stress. He then defined relative yield (i.e. the ratio of yield to potential yield) as the product of the above ratios. Multiplicative models of this type reflect changes in the components of yield.

(vi) Yield = f (water stress and other environmental variables in two or more phenophases).

Models of this type introduce further complexity because they recognize yield to be a function of more than one variable and that the effect of each variable is not constant during the crop's life cycle.

Baier (1973) used this approach to predict the yield of wheat at many locations over a large region of Canada. When yield was modelled on minimum temperature, maximum temperature (a synonym for radiation), or the ratio of actual to potential evapotranspiration, he found that the coefficients of determination between predicted and observed yields were only 0.24, 0.30 and 0.34 respectively. However, when these three environmental variables were combined into the one model the coefficient of determination rose to 0.77. Whilst the model used a process approach to estimate the soil water balance, the grain yield model was statistically based. Gradual changes in the effects of each variable on yield were defined as fourth power polynomial functions of biometeorological time.

(vii) Yield = f (accumulation and distribution of dry matter).

Models in this group are process orientated and calculate the growth of plant organs. The grain sorghum model 'SORGF' (Ritchie (1972), Arkin et al. (1976), Vanderlip and Arkin (1977) and Maas and Arkin (1978)), the wheat models of Rickman et al. (1975) and Fisher (1979), and the sunflower model of Hammer and Goyne (1980) are examples. An important feature of models in this group which sets them apart from the models previously discussed, is the dynamic interaction of the soil water balance with plant growth.

Daily calculations of the SORGF model are: (a) progress in phasic development, (b) leaf area development in response to temperature, (c) light interception from calculated leaf area and plant arrangement, (d) potential daytime net photosynthesis from calculated light interception, and (e) reduction of potential photosynthesis due to temperature, moisture stress and night-time respiration. Leaf area, soil moisture and evaporative demand are used to calculate the ratio of actual to potential transpiration. This ratio is then used to calculate moisture stress. An empirical dry matter partitioning sub-model is used to distribute dry matter to leaves, roots, stem, panicle and grain on the basis of phasic development. The model does not consider the components of yield or recognize the process of lodging. Fisher (1979) considers that the division of plant dry matter into its components is an important aspect of modelling yield because this provides the means of establishing whether the supply of photosynthate or the size of the sink is limiting the development of grain yield. The sink refers to the number and potential growth rate of grain.

The above process models merge with more detailed, physiological models such as those described by Fick et al. (1973), Thornley (1977), Goutzamanis and Conner (1977) and Charles-Edwards and Fisher (1980). Such models are aimed toward gaining a better understanding of growth processes rather than the applied nature of objectives in this study.

5.1.6 General Discussion of Grain Yield Models

A considerable range of crop models has evolved, presumably because of the many objectives, data constraints and environmental conditions that prevail. Variables important to yield prediction in one environment were found to be unimportant in others. For example, a multi-variable model was required to predict wheat yields in Canada (Baier 1973), whereas, wheat yields in Israel were predicted with similar accuracy by Lewis and Lomas (1974) using a simple rainfall relationship.

Simulation of phasic development and the soil water balance was central to nearly all of the models reviewed. Models which rely on empirical relationships between water stress and grain yield and those which calculate growth of dry matter from transpiration or evapotranspiration hinge on the classic work of de Wit (1958), as discussed in chapter 3.

Process models of plant growth are appealing because they have general application, but complexity decreases their utility. In comparison to the experimentally-based models of

Nix and Fitzpatrick (1969), Hiler and Clark (1971) and Baier (1973), the process models place greater demand on meteorological and experimental data for development or validation of functional relationships. Computing time for simulation is also greater. No evidence was found to suggest that process models were more accurate in predicting yield.

The following factors suggest that an experimentally-determined grain yield model rather than a process orientated growth model would be most useful in this study: (i) long-term weather data is restricted to daily rainfall, monthly temperature and monthly evaporative demand, (ii) field measurements included soil moisture and the components of grain yield, but did not include leaf area development and total dry matter accumulation, and (iii) yield predictions need to be computationally efficient so that a large number of simulations can be conducted without incurring large computing costs.

Most experimentally based crop yield models use a time step of one day or one week for calculating the soil water balance. The main reason for using a daily time step is usually accuracy in prediction of infiltration, whereas, the main reason for using a weekly time step is usually decreased data management, computing time and cost. This can be important where the model is required for many simulations.

Weekly models have been shown to adequately predict evapotranspiration in weeks that rainfall is nil, or changes in crop management (such as irrigation) do not take place. Therefore, it seems that the advantages of both daily and weekly models could be obtained if a model was developed in which the water balance was only calculated when events such as rainfall, irrigation or changes in crop phenophase occurred. Such an 'event stepping' model would be of most advantage in arid climates.

An experimentally-based model linking environmental influences to the components of grain yield was not found in searching the literature. Use of such a model should be advantageous because the components of yield develop sequentially, and hence environmental influences could be related to each component as it develops. Furthermore, each of the components of yield can be measured at one sampling (i.e. at harvest), and thus resources committed to data collection for development of functional relationships are not great.

It was concluded that the following sub-models would be useful for prediction of grain production in this study: (i) prediction of phasic development from temperature, (ii) prediction of the soil water balance from rainfall, irrigation and evaporative demand, and (iii) prediction of grain yield from its components, using experimentally-derived relationships to estimate the components of yield as functions of weather variables such as temperature, and weather-derived variables such as evapotranspiration.

5.2 Field Experimental Methods

Eleven field experiments to test the effect of irrigation strategy on the water use and yield of grain sorghum were sown on the irrigation-area of RSSRP from February 1970 to April 1975. The experimental site (described in chapter 3) was cropped each year from 1968 to 1975 excepting 1969 and 1974, when the land was bare fallowed.

Land preparation normally involved disc ploughing in October/November to incorporate the previous seasons stubble, followed by a light cultivation to remove weeds promoted by early summer storms. Late planting in Experiments 4, 5, 10 and 11 (to be described later) necessitated additional cultivations before planting.

The first experiment of each season was planted when sufficient rainfall had occurred to produce run-off from the dam's catchment and provide adequate soil moisture for crop establishment. The experiment number, planting date, sowing rate, number of irrigation treatments, number of replications and experimental design for each of the eleven irrigation strategy experiments is shown in table 5.1. This table shows that Experiments 6 and 7 also investigated the effects of plant density on grain production. Irrigation treatments in all experiments were usually 10.5m wide and 200m long.

Nitrogen fertilizer was applied at planting in all experiments at the rate of 35 kg/ha. The hybrid Brolga was used in Experiments 1 and 2 but was replaced with the higher yielding hybrid Dekalb E57 in all subsequent experiments. Irrigation was applied by syphoning water from a head ditch to furrows (see plate III in chapter 1).

Climatic conditions for the experimental period are shown in Appendix A and were discussed in chapter 3.

Table 5.1 Experimental designs of irrigation strategy experiments

Exp. No.	Planting Date	Sowing Rate (seeds/m^2)	No of Irrigation Treatments	No of Replications	Experimental Design
1	10 Feb 70	17	7	3	Randomized block
2	6 Mar 70	17	8	3	Randomized block
3	12 Mar 71	17	1	1	Block
4	6 Apr 71	11	16	2	2^4 Factorial
5	12 Mar 72	22	8	4	2^3 Factorial
6	14 Feb 73	*	5	3	Split plot Ran.block
7	22 Feb 73	*	3	3	Split plot Ran.block
8	4 Jan 75	22	1	4	Block
9	13 Feb 75	22	4	3	Randomized block
10	25 Mar 75	22	1	1	Block
11	23 Apr 75	22	3	3	Randomized block

* Three sowing rates of 13, 20 and 27 seeds/m^2 used in split plots.

Irrigation strategy refers to the frequency and timing of irrigation. Irrigation frequency is the number of irrigations that are applied during the growing season. The terms single, double and triple irrigation are used to describe irrigation frequency.

Irrigation timing is the stage of phasic development at which irrigation is applied. Because the rate of phasic development was different in each experiment it is necessary to normalize the way in which irrigation timing is specified. The standard adopted was for a crop which grows at a constant rate of phasic development and reaches floral initiation, booting, anthesis, dough and physiologic maturity in 30, 50, 60, 80 and 95 days respectively from planting. Thus, if an irrigation was timed to occur 55 standard days after planting then it was applied midway between booting and half bloom. It will be shown later that the standard rate of phasic development given above is equivalent to the average rate of phasic development for crops sown in February.

Table 5.2 shows the irrigation frequency and timing of each treatment used in the irrigation strategy experiments.

A number of factors disrupted the field experiments. They are reported here because the problems experienced are likely to also affect the potential of shallow storage irrigation systems.

A pilot experiment (planted in February 1968) was destroyed at the boot stage by a locust plague (*Locusta migratoria*). No experiments were conducted in 1969 because of drought. Poor and erratic establishment occurred in Experiment 1 (planted 10 February 1970) and hence a section of the experiment was ploughed out so that Experiment 2 could be planted. Experiment 3 (planted 12 March 71) was abandoned after grasshoppers removed 90% of seedlings. It was therefore ploughed out so that Experiment 4 could be planted on 6 April 71. However this experiment was severely damaged by frosts at anthesis. Experiment 5 (planted 10 March 72) was initially designed as a 2^4 factorial with irrigations at 27, 42, 57 and 72 standard days after planting. However, because of erratic establishment the irrigation at 72 days was deleted and replication was doubled. A similar design was proposed for Experiment 6 (planted 14 Feb 73) but the design was disrupted by 196 mm of rain one week before booting.

No experiments were conducted in 1974 because the shallow storage dam was washed away by record floods. The dam was rebuilt in time for the 1975 experiments. Experiments 8 and 9 (planted 4 January 75 and 13 February 75 respectively) were disrupted as irrigation strategy experiments because of continual rainfall with experiment 8 being entirely rain grown.

Table 5.2 Frequency and timing of irrigation treatments

Exp. No.	Treat. No.	Irrigation Strategy*	Treat. No.	Irrigation Strategy*	Treat. No.	Irrigation Strategy*
1	(3)	22	(2)	22/43	(3)	22/52
	(4)	22/60	(5)	22/71	(6)	22/43/60
	(7)	22/52/71				
2	(1)	nil	(2)	39	(3)	49
	(4)	55	(5)	65	(6)	33/49
	(7)	49/65	(8)	39/55		
3	(1)	nil				
4	(1)	nil	(2)	24	(3)	38
	(4)	55	(5)	75	(6)	24/38
	(7)	24/55	(8)	24/75	(9)	38/55
	(10)	38/75	(11)	55/75	(12)	24/38/55
	(13)	24/38/75	(14)	24/55/75	(15)	38/55/75
	(16)	24/38/55/75				
5	(1)	nil	(2)	27	(3)	42
	(4)	57	(5)	27/42	(6)	27/57
	(7)	42/57	(8)	27/42/57		
6	(1)	nil	(2)	32	(3)	60
	(4)	70	(5)	32/70		
7	(1)	52	(2)	61	(3)	70
8	(1)	nil				
9	(1)	nil	(2)	58	(3)	67
	(4)	58/67				
10	(1)	nil				
11	(1)	22	(2)	34	(3)	45

* Timing of irrigation is shown in standard days after planting. The timing of double and triple irrigations are separated by slashes.

The loss of grain to birds was always a difficult problem to control and large areas of Experiments 8 and 9 were destroyed. Galahs (*Eolophus roseicapilla*), little correllas (*Cacatua sanguinea*) and sulphur-crested cockatoos (*C. galerita*) were the main pests, but damage was also caused by quarrions (*Nymphieus hollandicus*) and brolgas (*Grus rubicunda*). Experiment 10 (planted 25 March 75) was abandoned after galahs and little correlas removed more than 95% of seedlings. Experiment 11 (planted 23 April 75) was abandoned after frosts between booting and half bloom had killed most of the leaves and florets.

Loss of yield from weeds, insects (other than grasshoppers) and pathogens was negligible in all experiments and thus no control measures were necessary.

Data Collection Plant density at establishment was measured in all experiments by randomly selecting rows and counting the number of plants in 30 m of row.

Time to half bloom was recorded in Experiments 1 to 9. Because the hybrid Brolga was used in Experiments 1 and 2 the phenology observations for these experiments were made on adjacent areas of Dekalb E57. Leaf appearance was recorded in Experiments 8 and 9.

Gravimetric soil water content was measured in the following number of profiles (each replicated six times) in each experiment: 30 in Exp.1, 31 in Exp.2, 15 in Exp.4, 27 in Exp.5, 34 in Exp.6, 30 in Exp.7, 2 in Exp.8 and 6 in Exp.9. The usual depths of soil sampling were: 0–5, 5–10, 10–15, 15–30, 30–45, 45–60, 60–75 and 75–90 cm. The samples were obtained with a 5cm Jarret hand auger in Experiments 1 to 5 and with an hydraulically driven Veihmeyer tube in Experiments 6 to 9. Gravimetric soil moisture was converted to volumetric soil moisture per unit area using bulk density and the method of Fox (1964) described in chapter 3.

Soil samples to determine the relationship between soil water potential and soil water content were collected in February 1978. The samples, bulked over 3 sites, were taken from 4 depths: 0–10, 10–20, 20–30, 30–90 cm. Two replicates were collected. The soil water content at 1, 5 and 15 bars was measured using the pressure plate method and soil water content at 0.3 bars was measured using the filter paper method.

The following components of grain yield were recorded in Experiments 5 to 8 by hand harvesting sub-plots: plant density, panicle density, grain yield, grain size and proportion of yield lost to lodging (i.e. ratio of panicles lodged to total number of panicles). Sub-plot yields and grain size were recorded in Experiments 1 and 2, and grain size was recorded in Experiment 9. The total number of sub-plots sampled per treatment and the datum area of sub-plots were: .

Experiment No.	1	2	5	6	7	8
No. of sub-plots/treat	3	3	36	36	18	4
Datum area (m^2)	23	23	2.9	3.1	3.1	15

Grain number per unit area was calculated by dividing grain yield per unit area by grain size. Grain number per plant was calculated by dividing grain number per unit area by plant density.

Grain yields were also determined in Experiments 1 to 9 (except 3) by harvesting with a commercial header. The datum area of samples ranged from 400 to 800m^2. Because of the large datum area required by the commercial header, this method was prone to sampling errors caused by irregularities in plant density and patches of bird and pig damage.

5.3 Phasic Development Sub-Model

The objectives of this section are to:

(i) derive from experimental data a relationship based on Rêaumur's heatsum that can be used in simulation experiments to predict the phasic development of the grain sorghum hybrid Dekalb E57, and

(ii) specify phenophases that are to be used in deriving the water balance and grain yield sub-models (sections 5.4 and 5.5 respectively).

Methods Values of Tbase and H (from planting to half bloom) in equation 5.4 were determined from daily minimum and maximum temperature observations and recordings of time to half bloom in Experiments 1, 2, 4, 5, 6, 7, 8 and 9.

This relationship was then used to:

(i) compare the use of daily, mean monthly and long-term mean monthly temperature data for prediction of phasic development,

(ii) determine the effect of sowing date on time to half bloom, and

(iii) specify heatsum values that signify the start and finish of phenophases.

Results and Discussion No differences in time to half bloom were observed among treatments of the same experiment, and hence it was concluded that water stress had little or no effect on phasic development.

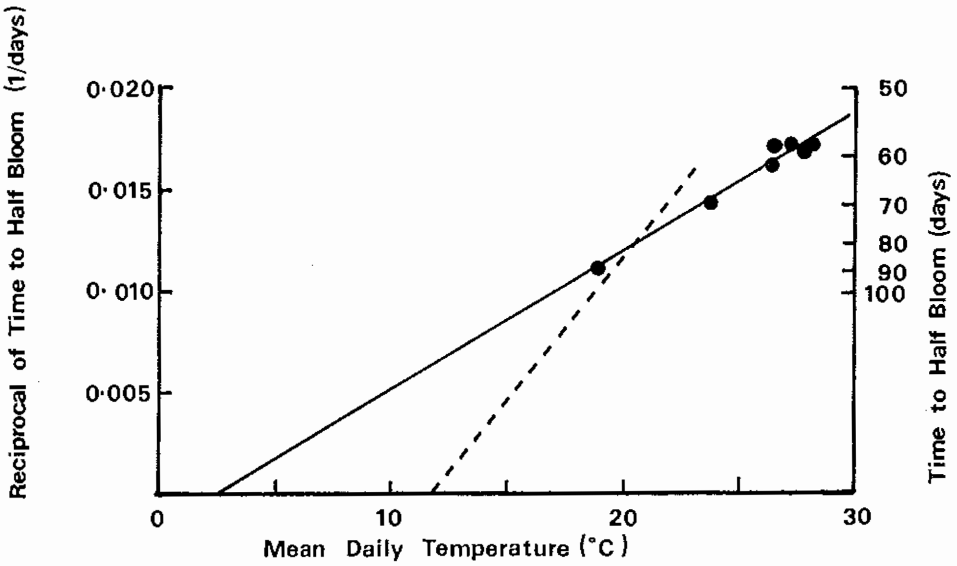


Figure 5.1 Effect of mean daily temperature on the time to half bloom of Dekalb E57 grain sorghum (● observed data, ——— linear regression line, - - - - - line of best fit to the data of Angus (1979, pers. comm.).

The relationship found between the reciprocal of time from planting to half bloom (1/N) and phenophase mean daily temperature (i.e. PMT = $(\sum_1^N (\text{Tmax} + \text{Tmin})/2)/N$) is shown in figure 5.1, and is mathematically given by:

$$1/N = 0.000682\ \text{PMT} - 0.0017 \qquad (5.9)$$

Rearrangement of this equation gives:

$$N(\text{PMT} - 2.5) = 1466 \qquad (5.10)$$

i.e. H = 1466 degree days, and Tbase = 2.5°C.

Although the heatsum relationship of equation 5.9 fits the data very well ($R^2 = 0.97$) the values of H at half bloom and Tbase are uncertain because of the lack of data below 20°C.

In a regime of lower temperatures (15–24°C) J. Angus (pers. comm.) collected phenological data from Dekalb E57 grain sorghum at Lawes, Queensland, and found a heatsum of 715 degree days (approximately) and base temperature of 11°C (approximately). This base temperature is between 1 and 7°C higher than found elsewhere for other sorghum hybrids (Vanderlip and Arkin 1977, Gelroth and Vanderlip 1978, and Schaffer 1980).

Comparison of the results obtained in this study to those of Angus (see figure 5.1) suggest that the relationship between the reciprocal of time to half bloom and temperature is curvilinear. Therefore, little physical meaning can be attached to the estimated base temperature of 2.5°C. However, this does not diminish the value of equation 5.10 for prediction of phasic development where mean daily temperature ranges from 19 to 29°C. There are only two months of the year at Richmond which have a long-term mean temperature outside this range. These months are June and July and they have long-term mean temperatures of 17.6 and 17.3°C respectively. It is therefore concluded that equation 5.5 should give an effective method of predicting the phasic development of Dekalb E57 grain sorghum at Richmond and at other locations on the Mitchell grass plains.

Predictions of time to half bloom using daily, mean monthly and long-term mean monthly temperature records in equation 5.10 are compared in table 5.3. This table also shows the observed times to half bloom that were used to derive equation 5.9.

Table 5.3 Comparison of predicted times to half bloom of Dekalb E57 grain sorghum using daily, mean monthly and long-term mean monthly temperature data.

Exp. No.	Planting Date	Mean daily temperature* (°C)	Time to half bloom			
			Observed	Predicted**		
				(a)	(b)	(c)
8	04 Jan 75	27.6	59	58	58	55
2	11 Feb 70	27.8	60	58	59	59
9	13 Feb 75	26.3	61	61	62	60
6	14 Feb 73	27.2	58	59	59	60
7	25 Feb 73	26.6	59	59	61	63
5	12 Mar 72	23.7	70	68	69	68
4	06 Apr 71	18.8	90	90	89	80

* Daily mean of maximum and minimum temperatures from planting to half bloom.

** Predicted from equation 5.10 using: (a) daily temperature data, (b) mean monthly temperature data, (c) long-term mean monthly temperature data.

Table 5.3 shows that use of long-term mean monthly temperature records led to considerable error in a number of cases. It was concluded that use of such data is unsatisfactory for predictions of phasic development. In contrast, use of mean monthly temperature records led to very little error in prediction of time to half bloom.

Where monthly temperature records are used to predict the time between two growth stages that occur close together (e.g. booting and half bloom), then errors on a proportional basis could be large but the magnitude of the errors will remain small and hence of little agronomic importance. Thus, use of mean monthly records is of acceptable accuracy and preferable to use of daily records in simulation experiments because of the increased efficiency that can be achieved in data management.

The effect of planting date on time to half bloom is shown in figure 5.2. This figure shows that as planting date advances from 1st December to 31st March then time to half bloom increases on average from 54 to 76 calendar days. Thus, the date of half bloom advances on average from 24th January to 15th June. If planting is advanced to 30th April then the average time to half bloom is 87 days and the average date of half bloom is 26th July.

There is a reasonable chance that frosts will occur on the Mitchell grass plains sometime during late June and July. Since grain sorghum is particularly sensitive to frost injury from booting to soft dough, it was concluded that an effective rule for management of grain sorghum crops on the Mitchell grass plains might be to use the 31st March as the last possible date for planting. The severe frost damage to the grain yield of Experiments 4 and 11 (planted on 6 April 71 and 23 April 75 respectively) was mentioned earlier.

Heatsum values at development stages defined by Vanderlip and Reeves (1972) are shown in table 5.4. This table also shows:

(i) the number of days after planting at which each stage of development occurs when the mean daily temperature is constant at 27°C, and

(ii) division of phasic development into five phenophases, each of 400 degree days, and one phenophase (germination) of 200 degree days. These phenophases are used when deriving the water balance and grain yield sub-models. These sub-models also refer to a grain filling phenophase, which is defined here as the period when the heatsum advances from 1400 to 2200 degree days (i.e. the combination of the anthesis and dough phenophases).

The rate of phasic development shown in table 5.4 is used throughout the text as a standard to specify time of irrigation. For example, if irrigation occurs at floral initiation, booting and soft dough then water is applied when the heatsum reaches 733, 1222 and 1710 degree days respectively. This is equivalent to irrigation at 30, 50 and 70 standard days after planting.

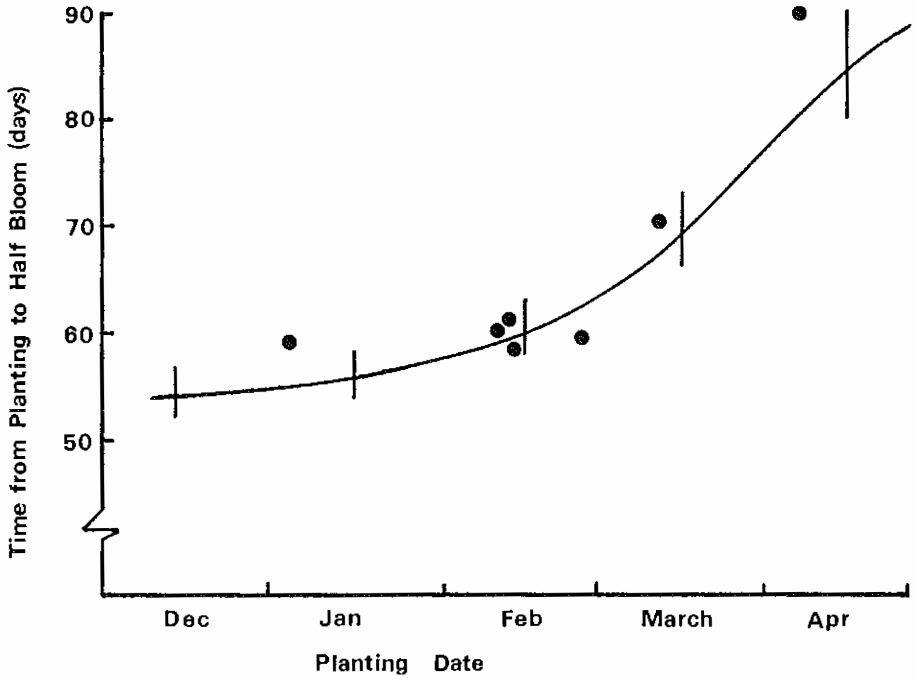


Figure 5.2 Effect of planting data on average time to half bloom of Dekalb E57 grain sorghum. (● observed values, vertical bars are standard deviations about the long-term mean).

Table 5.4 Relationship of development stages and phenophases of Dekalb E57 grain sorghum to heatsum values and time after planting.

Heatsum (°C days)	Time after planting* (days)	Development Stage	Phenophase
0	0	planting	emergence
200	8.3		
513	21	5th leaf	establishment
600	24.6		
733	30	floral initiation	floral initiation
1000	40.9		
1222	50	booting	booting
1400	57.3		
1466	60	half bloom	anthesis
1800	73.7		
1955	80	dough	dough
2200	90		
2321	95	physiologic maturity	ripening
2600	107		

* when temperature is constant at 27°C.

5.4 Irrigation-Area Soil Water Balance Sub-Model

5.4.1 General Considerations

The flow chart in figure 5.3 shows that the water balance sub-model developed for the irrigation-area was very similar to the water balance sub-model developed to predict catchment run-off (shown in figure 3.8). Both sub-models are for the same soil type and both are similarly restricted by the type of meteorological data available for simulation (i.e. daily rainfall and monthly temperature and evaporative demand).

Similarities between the two sub-models are: (i) rainfall received at the soil surface is distributed to surface run-off and three soil moisture stores (a surface store of 0-10 cm soil depth, a sub-surface store of 10-30 cm soil depth and a sub-soil store of 30-90 cm soil depth), (ii) infiltration can occur directly to all soil layers via cracks, (iii) infiltration to the surface and sub-surface layers occurs at an unlimited rate until their capacities are reached, (iv) the rate of infiltration to the sub-soil is dependent on the level of water storage in the sub-soil, (v) overflow from the sub-soil goes to ground water and is lost from the system, and (vi) evapotranspiration is lost from all soil stores.

The irrigation-area water balance sub-model was developed differently from the catchment water balance sub-model in the following ways: (i) irrigation was an input, (ii) infiltration was not modelled as a function of plant biomass because the irrigation-area was normally in bare fallow for most of the summer wet season and because the soil was not covered with litter when a crop was present, and (iii) estimates of crop cover were used to regulate evapotranspiration because of the considerable influence that crop development had on changing the contributions of soil evaporation and plant transpiration to evapotranspiration.

The conservation equation used to represent the daily water balance of the irrigation-area per unit ground area as time progressed from day t_1 (at 9 am) to day t_2 (at 9 am) was:

$$S(t_2) = S(t_1) + \sum_{t_1}^{t_2}(-\,ET + R - Q - G + I) \qquad (5.11)$$

where $S(t_1)$ and $S(t_2)$ = Equivalent ponded depths of soil moisture at times t_1 and t_2 respectively, ET = Rate of evapotranspiration (mm/day), R = Rate of rainfall (mm/day), Q = Rate of run-off (mm/day), G = Rate of deep drainage (mm/day), I = Rate of irrigation (mm/day).

The order of terms in this equation was the order of calculations during simulation. The equivalent ponded depth of irrigation was calculated as the depth of water required to recharge soil moisture in all soil layers to capacity.

The irrigation-area water balance sub-model used event-stepping during simulation. Events which caused calculation of the water balance were rainfall exceeding 3 mm, changes in crop phenophase, planting and irrigation. If conditions satisfied these event stepping requirements then equation 5.11 was contracted to:

$$S(t_2) = S(t_1) - \sum_{t_1}^{t_2} ET \qquad (5.12)$$

where $R \leqslant 3$ mm/day and $Q = G = I = 0$.

Small rainfall events ($R \leqslant 3$) mm/day were modelled by reducing daily evaporative demand by the amount of rainfall occurring. The method of calculating ET over periods of more than one day is given later.

The maximum period between simulation events (i.e. $t_2 - t_1$) during cropping was the duration of one phenophase (i.e. 17 standard days). However, the period between simulation events may extend to months when crops were not present.

5.4.2 Evapotranspiration

Observed Patterns of Soil Moisture Loss Figure 5.4 shows the profile distribution of soil moisture found in Experiment 5, treatments 1 to 4, at successive stages of the drying cycle, and laboratory estimates of soil moisture at 0.3 and 15 bars of soil water tension. While soil water availability cannot be theoretically or practically determined in simple terms of ranges of soil water contents or soil water potentials (Stanhill and Vaadia 1967),

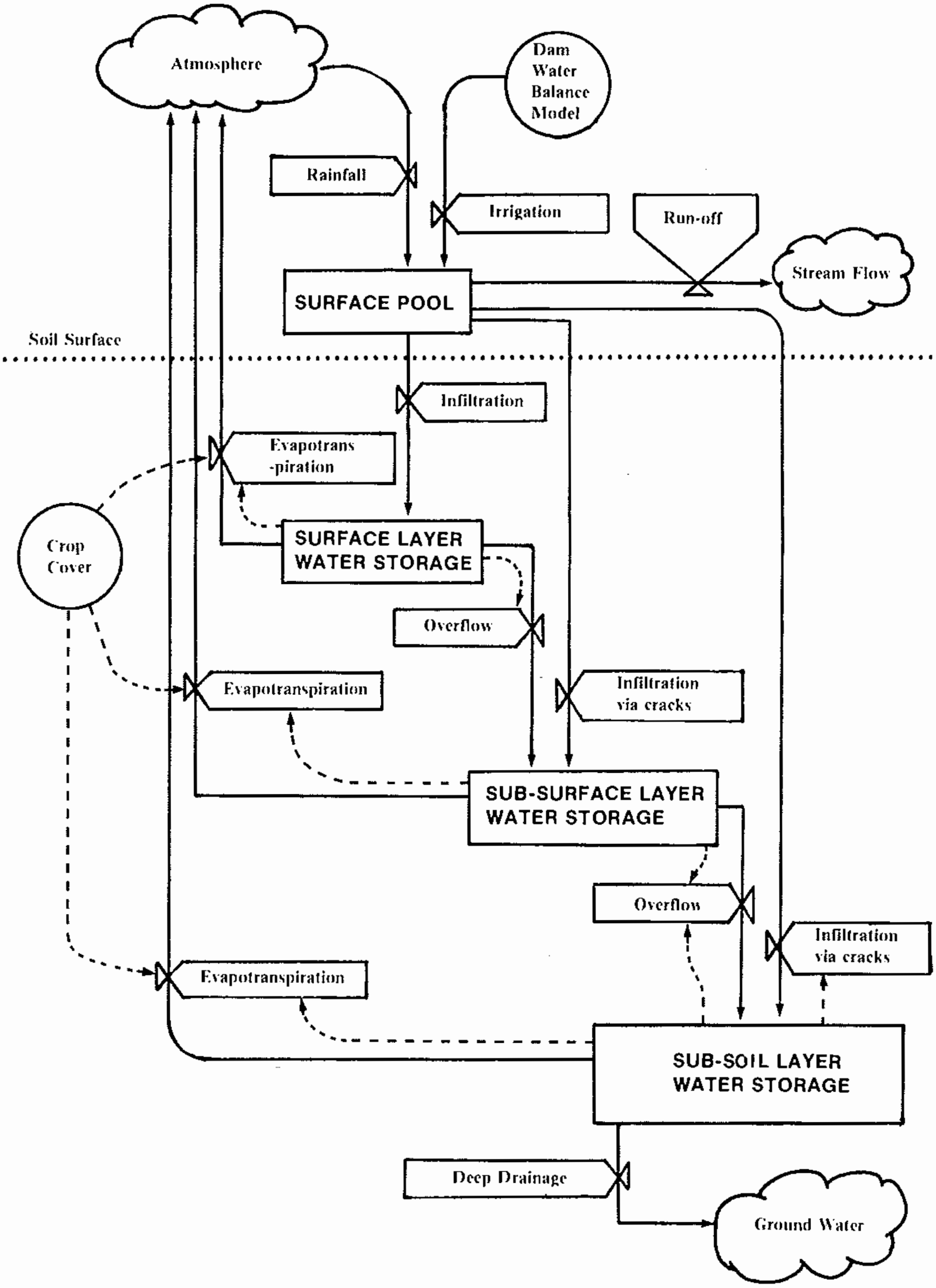


Figure 5.3 Flow–chart of irrigation–area water balance (Forrester (1962) flow chart symbols show: sources and sinks as clouds, level variables as boxes, rate variables as valves, exogenous variables as circles, material flows as solid arrows, and information flows as broken arrows)

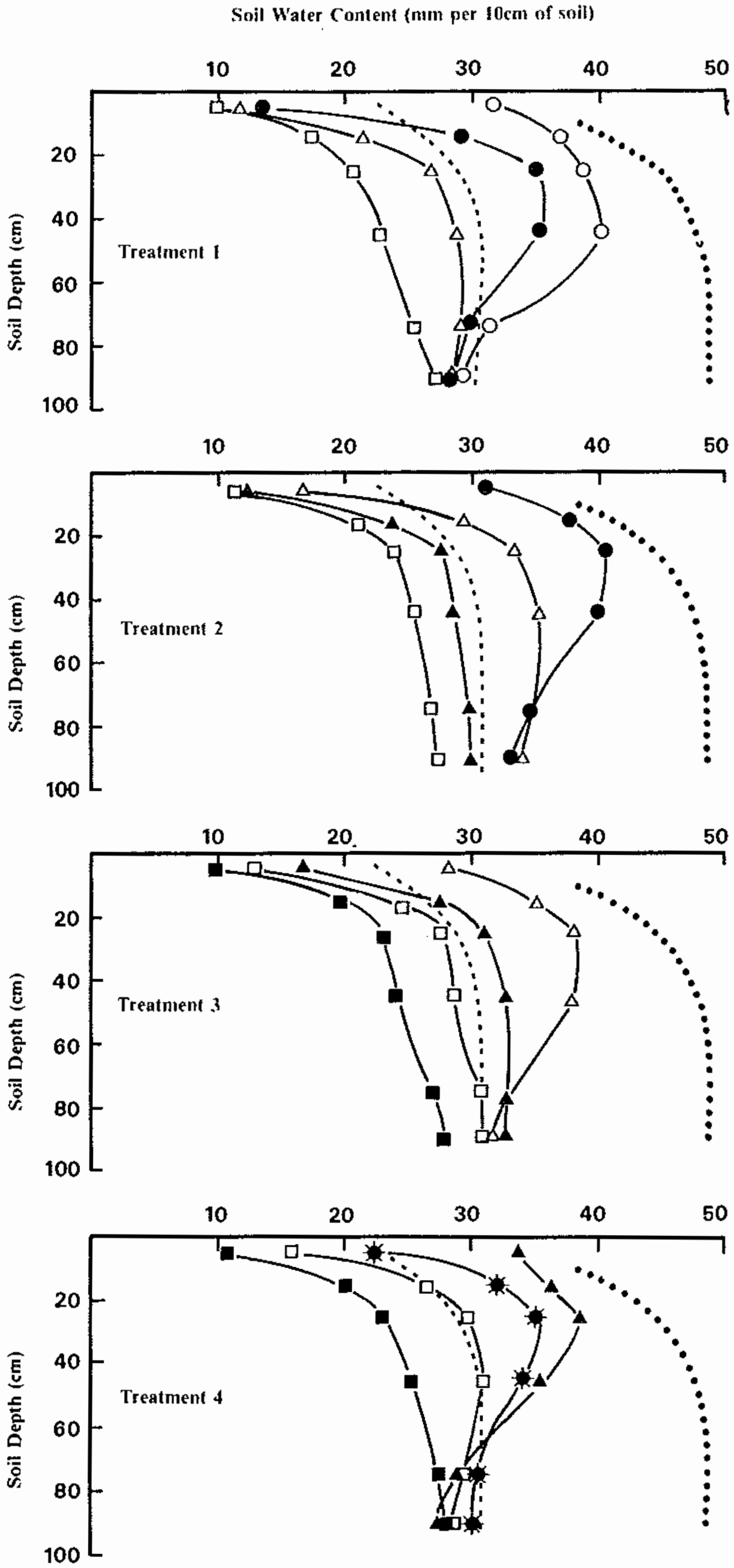


Figure 5.4 Patterns of soil moisture extraction observed in experiment 5. Treatment 1 received no irrigation and treatments 2, 3 and 4 received single irrigations on days 27, 42 and 57 respectively. (Symbol code; ○ = 10 March (2 days before planting), ● = 13 April (day 30), △ = 23 May (day 62), ▲ = 6 June (day 71), □ = 21 June (day 81) ■ = 12 July (day 94), — — — water content at 15 bars, ····· water content at 0.3 bars.

the soil water content at 0.3 and 15 bars is sometimes used to specify field capacity and wilting point (Buchman and Brady 1965).

The data in figure 5.4 suggest that soil moisture was recharged in the surface and sub-surface layers to approximately the laboratory estimate of field capacity (0.3 bars). The data also show very little change in soil moisture content at 90 cm of soil depth, and loss of soil water from well below 15 bars of soil water tension in all soil layers.

Plant vigour and turgidity observations made on Experiment 5 in treatments 1 to 4 on the 21 June 1972 (81 standard days after planting) are of particular significance with respect to wilting point. On this day treatment 2 had exhausted its capacity to maintain transpiration as it was observed to be wilting in the early morning. Wilting was not observed on previous mornings. Treatment 1 was senescing rapidly but treatments 3 and 4 had the appearance of growing vigorously without wilting during the course of the day. The soil moisture profiles of these treatments showed treatments 3 and 4 to be at approximately 15 bars of soil water tension, whereas, treatments 1 and 2 were far below this level.

The contribution of air drying to evapotranspiration from the soil surface and from soil cracks was thought to account for a significant amount of soil water loss, but cannot be determined from the data.

These observations illustrate the difficulties of using laboratory measurements of soil water content and soil water potential to specify the maximum and minimum water storage capacity of soil layers in a water balance model.

Evapotranspiration Relationships A considerable change occurs in the contributions of soil evaporation and plant transpiration to evapotranspiration as the leaf coverage changes during crop growth. However, simple relationships to estimate evapotranspiration (ET) from evaporative demand (Eo), soil moisture (S) and leaf area (COVER) have proven to be reasonably reliable (Fitzpatrick and Nix (1969), Berndt and White 1976, and Rosenthal et al 1976).

The potential rate of evapotranspiration (PET) is the maximum rate at which ET can occur when soil moisture is freely available. The ratio of PET to Eo is dependent on the proportion of ET occurring from the soil and from plants, and thus may be related to the stage of crop growth (Slatyer 1960), or more accurately a function (f) of leaf area (COVER) (Ritchie and Burnett (1972). Thus:

$$PET/Eo = f(COVER) \qquad (5.13)$$

Denmead and Shaw (1962), Ritchie et al (1972) and others have shown that ET reduces soil moisture from its maximum capacity at the potential rate until soil water status is reduced to a critical threshold. Ritchie defined the soil water content at this point as the lower limit to potential evapotranspiration (LLEo). At soil moisture contents greater than LLEo the ratio of ET to PET is equal to one, but at soil moisture contents lower than LLEo the ratio of ET/PET decreases as soil moisture decreases. An exponential decay has been found as one useful way to describe this relationship. Thus:

$$ET/PET = 1 \qquad \text{for } S \geqslant LLEo \qquad (5.14)$$

$$ET/PET = a \exp(kS) \qquad \text{for } S < LLEo \qquad (5.15)$$

Substitution from eq.5.13 gives:

$$ET/Eo = f(COVER) \qquad \text{for } S \geqslant LLEo \qquad (5.16)$$

$$ET/Eo = f(COVER)\ a.\exp(kS) \qquad \text{for } S < LLEo \qquad (5.17)$$

During crop development there are two times at which the crop cover function is a constant. The first is before planting when the land is in bare fallow, continuing until shortly after planting when seedlings do not contribute greatly to soil water loss. The second time is when a full canopy cover has been achieved. Development of leaf cover is usually complete by booting, and, given adequate soil moisture, is maintained during grain filling. Thus equations 5.16 and 5.17 may be rewritten for these two conditions as follows:

$$ET/Eo = m \qquad \text{(for } S \geq LLEo) \qquad (5.18)$$
$$ET/Eo = b\ \exp(kS) \qquad \text{(for } S < LLEo) \qquad (5.19)$$

where m, b and k are constants which have different values for the bare soil and full cover conditions, as does the value of LLEo.

Since ET is proportional to Eo in equation 5.18, values of S at time t can be calculated from:

$$S_t = Smax - m\ SEo \qquad \text{for } S_t \geq LLEo \qquad (5.20)$$

where Smax = Maximum soil moisture storage capacity (mm), and SEo = Cumulative evaporative demand since soil moisture was at capacity (mm).

The form of equation 5.20 when SEo is plotted on a logarithmic scale is illustrated by the dashed curves in figure 5.5. Note that the linear form of equation 5.20 is transformed by the logarithmic scaling.

There is a difficulty in using equation 5.19 to determine b and k from experimental data in which S is measured at intervals separated by longer than a few days. Over such longer intervals, ET will change non-linearly with S, so that use of a mean value of S would lead to error.

A general method of determining the constants b and k in equation 5.19 is presented below which avoids the error referred to above. This general method depends on the experimental observation that soil moisture stored at any time in a profile following saturation becomes linearly related to ln(SEo) as is illustrated in figure 5.5. Hence, for any soil layer, S can be expressed as:

$$S = c - d\ \ln(SEo) \qquad (S < LLEo) \qquad (5.21)$$

The derivative of this equation is:

$$dS/d(SEo) = -\ d/SEo \qquad (5.22)$$

For a time step of one day $dS/d(SEo) = -ET/Eo$ and hence substitution into equation 5.22 gives:

$$ET/Eo = d/SEo \qquad (5.23)$$

Rearrangement of equation 5.21 gives: $SEo = \exp((c-S)/d)$ and hence substitution into equation 5.23 gives:

$$\begin{aligned} ET/Eo &= d/(\exp((c-S)/d) \\ &= d\ \exp(-c/d)\exp(S/d) \qquad (5.24) \end{aligned}$$

This equation now has the same form as equation 5.19, and values of b and k are thus given by:

$$b = d\ \exp(-c/d) \quad \text{, and} \qquad (5.25)$$
$$k = 1/d \qquad (5.26)$$

Since soil moisture is related to cumulative evaporative demand, equations 5.20 and 5.21 may be used in an event stepping model to calculate changes in soil moisture.

Suppose S < LLEo and water input occurs, then it is assumed that S can be calculated using equations 5.20 or 5.21 as appropriate, starting from the new higher water content resulting from this input.

In the above discussion it has been assumed that f(COVER) in equations 5.16 and 5.17 has been a constant appropriate to either bare soil or full cover conditions, for which evapotranspiration rate will be denoted ETbare and ETfull respectively. Partial cover can be described by an index CI, of value 0.0 for bare soil, and 1.0 for full cover.

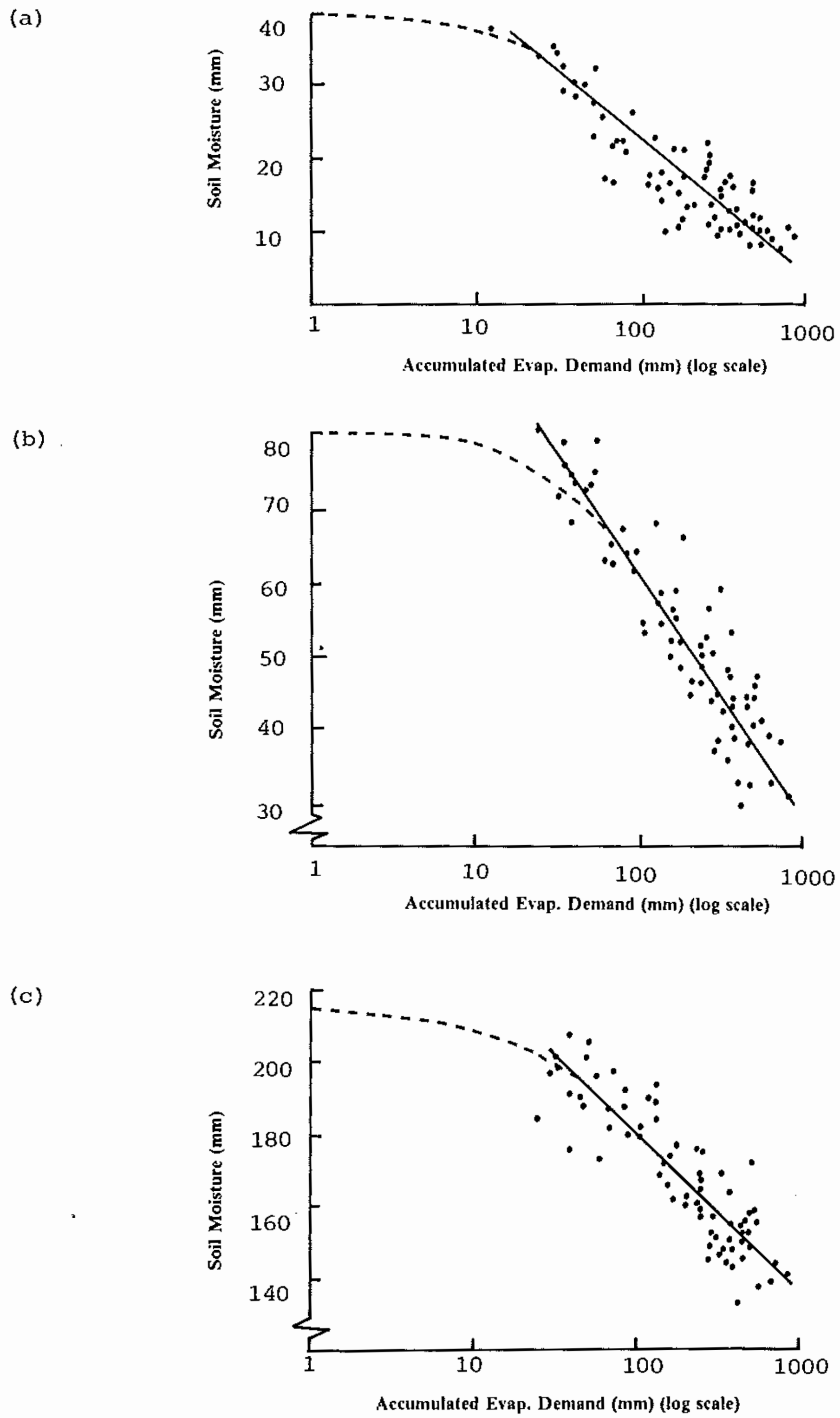


Figure 5.5 Volumetric soil moisture measured under crops with a complete canopy cover versus evaporative demand accumulated since the soil profile was wetted to capacity. (a) Surface soil layer (0–10 cm) (b) Sub-surface layer (10–30 cm), and (c) Sub-soil layer (30–90 cm). (Solid lines are regression lines. The dashed line is explained in the text).

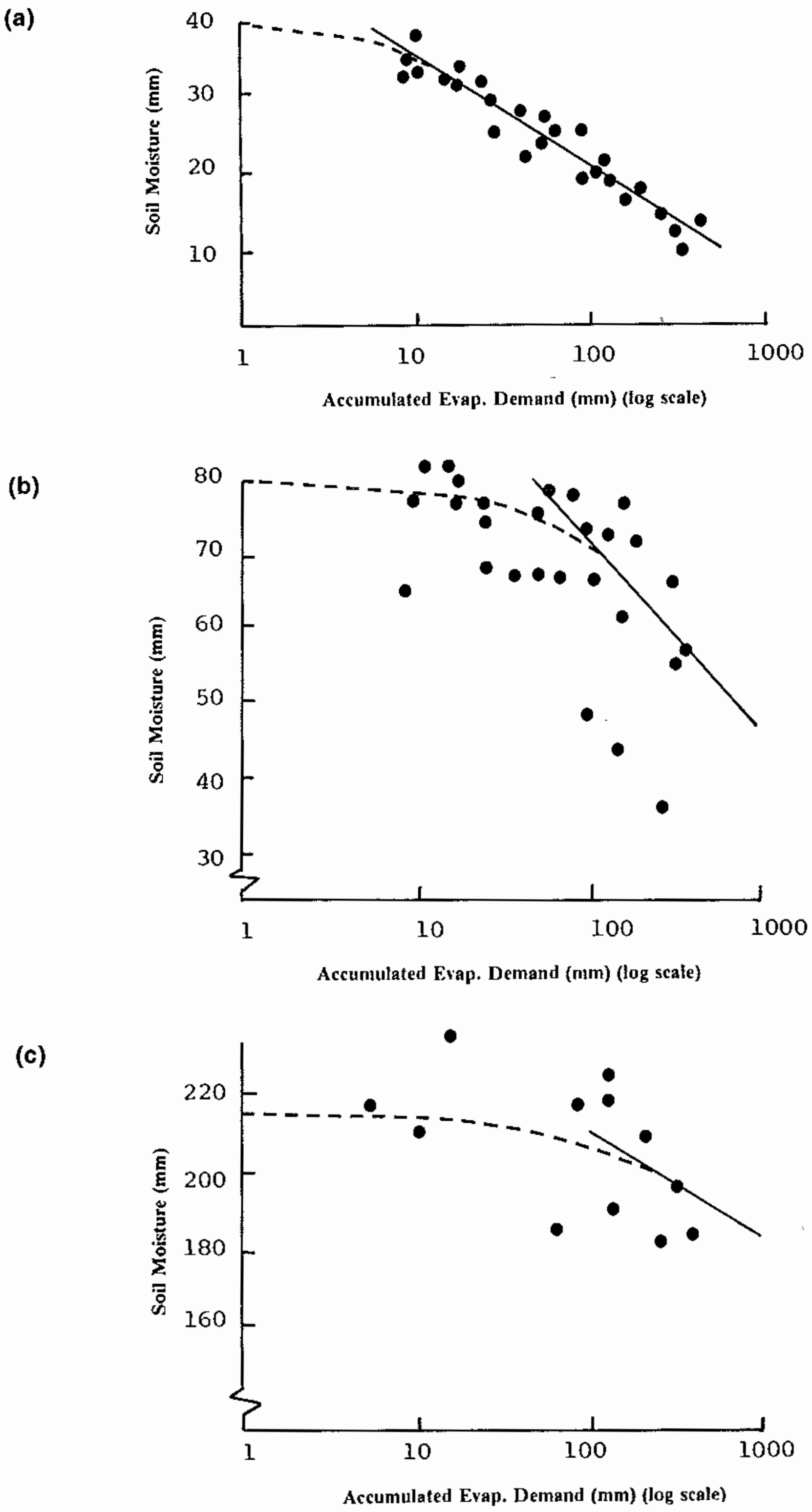


Figure 5.6 Volumetric soil moisture measured from bare soil versus evaporative demand accumulated since the soil profile was wetted to capacity. (a) Surface soil layer (0–10 cm), Sub-surface soil layer (10–30 cm), and (c) Sub-soil layer (30–90 cm). The solid line in (a) was found by regression. The dashed lines and the solid lines in (b) and (c) are explained in the text.

Table 5.5 Linear regressions of soil moisture versus the natural log of evaporative demand accumulated since soil moisture content was at capacity (see equation 5.21 in text).

Soil Layer and Depth	Experiment No.	N	Regression slope	Regression intercept	Std. Error of slope	Std. Error of intercept	Coeff. of Determ.
FULL COVER							
Surface	1	19	-7.602	51.74	.6851	3.266	.879
(0-10cm)	2	18	-7.669	50.88	.6942	3.090	.884
	5	14	-7.689	54.76	.7347	2.424	.901
	6	24	-6.333	49.15	.9393	3.512	.674
	Combined	78	-7.304	51.73	.4362	3.648	.786
Sub-surface	1	19	-14.47	120.4	.8036	3.785	.950
(10-30cm)	2	18	-16.82*	131.1*	1.372	6.108	.904
	5	14	-12.03	114.6	1.429	4.714	.855
	6	24	-12.07	109.3	.9381	3.507	.883
	Combined	78	-13.84	118.5	.6334	5.298	.863
Sub-soil	1	19	-16.86	247.2	2.297	10.80	.760
(30-90cm)	2	18	-22.19*	274.4*	2.201	9.797	.864
	5	8	-16.66	258.6	3.332	10.43	.807
	6	24	-18.64	257.8	1.444	5.397	.883
	Combined	72	-18.61	257.6	1.076	8.918	.811
Whole Profile	1	19	-39.17	419.0	2.531	11.92	.934
(0-90cm)	2	18	-48.20*	464.1*	2.620	11.67	.955
	5	8	-36.66	421.7	4.643	14.54	.912
	6	24	-37.03	416.3	2.524	9.435	.907
	Combined	72	-40.54	430.7	1.517	12.57	.911
BARE SOIL							
Surface (0-10cm)	Combined	26	-6.386	48.0	3661	2.100	.927

* Significantly different from combined regression parameter at P.05

The evapotranspiration from partial cover (ETpart) accumulated over any time period is assumed given by:

$$\sum ETpart = CI \times \sum ETfull + (1-CI) \times \sum ETbare \qquad (5.27)$$

where $\sum$ indicates accumulation.

Changes in soil moisture under crops with partial cover are therefore given by:

$$S_{t_2} = S_{t_1} - \sum ETpart \qquad (5.28)$$

Field Measurements of Evapotranspiration Values of m in equation 5.20 and values of c and d in equation 5.21 for both bare soil and full cover conditions were determined from soil moisture data and Eo estimates in the following way.

Volumetric soil moisture data was divided into three groups according to the amount of plant cover at sampling. The groups were: bare soil, full cover, and remainder. To increase the number of samples in the bare soil group the observations made shortly after planting were also included.

Figures 5.5 and 5.6 show the relationships between S and SEo in each soil layer for both the bare soil and full cover soil moisture groups. The solid lines in figure 5.5 and figure 5.6(a) were found by linear regression (using equation 5.21). Insufficient data were recorded in the 10–30 cm and 30–90 cm layers of the bare soil group to adequately establish a relationship between S and SEo by regression. Therefore the solid lines in figures 5.6(b) and (c) were hand fitted by assuming soil moisture content was: (i) 66 mm in the 10–30 cm layer and 210 mm in the 30–90 cm layer when SEo was 100 mm, and (ii) 46 mm in the 10–30 cm layer and 180 mm in the 30–90 cm layer when SEo was 600 mm.

The dotted line in figures 5.5 and 5.6 represents soil moisture loss when S $\geq$ LLEo (i.e. when ET is proportional to Eo). The method used to calculate the position of these dotted lines is given later.

Table 5.5 shows the results of linear regression of S versus ln(SEo) for: (i) each layer of the full cover group in each experiment, and for all experiments combined, (ii) the whole profile of each experiment and all experiments combined, and (iii) the 0–10 cm layer of all experiments combined in the bare soil group.

Salient points in the data are:

(i) The linear regressions account for a high proportion of the observed changes in soil moisture. Coefficients of determination were more than 0.8 in most cases.

(ii) The relationships found between S and SEo were similar in all experiments for each layer of soil. In each soil layer there are no statistically significant differences (at P.05) among the regression parameters excepting those for Experiment 2 in the 10–30 cm and 30–90 cm soil layer. Soil water loss in Experiment 2 was slightly faster than in other experiments.

(iii) Evapotranspiration from the surface layer of bare soil was very similar to but slightly slower than from the surface soil of crops with full cover.

(iv) Minimum soil water storage at the end of the cropping season in the surface, sub-surface and sub-soil layers was approximately 7.5, 30 and 135 mm respectively (figure 5.5). However, further air drying of the sub-surface and sub-soil layers probably occurred during the dry season, and therefore for the purposes of modelling, the values shown in table 5.6 were adopted as the minimum soil storage capacities. These values are considerably higher than the values found for the catchment area soil water balance sub-model. This difference is supported by the data of Ludlow (1976) who shows that Mitchell grass (Astrebla spp.) can extract soil moisture at much higher levels of soil water tension than Sorghum spp.

The derivatives of equations 5.20 and 5.21 are $-m$ and $-d/SEo$. These derivatives are equal when S = LLEo and hence:

$$m = d/SEo \qquad (S = LLEo) \qquad (5.29)$$

$$\text{and } LLEo = Smax - m\ SEo \qquad \text{(from eq. 5.20)} \qquad (5.30)$$

$$\text{and } LLEo = c - d \ln SEo \qquad \text{(from eq. 5.21)} \qquad (5.31)$$

Table 5.6 Soil moisture storage characteristics used in irrigation-area water balance sub-model.

Soil Layer Depth (cm)	Surface 0–10	Sub surface 10–30	Sub-soil 30–90	Whole Profile 0–90
Max. soil moisture storage				
depth (mm)	40.0	80.0	215.0	335.0
volumetric (%)	40.0	40.0	35.8	37.2
Minimum soil moisture storage				
depth (mm)	7.5	25.0	125.0	157.5
volumetric (%)	7.5	12.5	20.8	17.5
Available soil moisture storage				
depth (mm)	32.5	55.0	90.0	177.5
volumetric (%)	32.5	27.5	15.0	19.7

In these equations there are four unknowns (m, SEo, LLEo and Smax). Therefore it is necessary to approximate one of the unknowns so that the others can be derived from the three equations 5.29–31.

Evaporation from the lower layers of bare soil can be assumed to be negligible when the surface layer is at field capacity. Therefore observations taken a few days after saturation of the profile provide reasonable estimates of the maximum moisture storage in the sub-surface and sub-soil layers. Evaporation from the surface layer of bare soil would proceed at a rate equal to the evaporative demand for only a very short period of time, possibly a few hours, due to the rapid formation of a surface crust.

The values of Smax that were adopted in the water balance sub-model for each soil layer are shown in table 5.6. These values were thought to give reasonable solutions to m and LLEo because the dotted lines in figures 5.5 and 5.6 fit the data satisfactorily. Values of m and LLEo found for each soil layer are shown in figure 5.7 where the ratio of ET/Eo is plotted against percent available soil moisture (i.e. 100(S-Smin)/(Smax-Smin). This figure shows that full cover LLEo occurs in each soil layer when available soil moisture was approximately 75%. By comparison, and from the data and discussion of figure 5.4 given earlier, the permanent wilting point of sorghum occurred at approximately 50% of the available soil moisture range. Therefore, ET was reduced below the potential rate when approximately one third of the soil moisture held between maximum storage and wilting point was used.

The potential rate of full cover ET found for the whole profile was 1.4 times Fitzpatrick's estimate of evaporative demand. This suggests that advected energy from the usually dry native pasture surrounding the moister irrigation-area had a considerable influence on evapotranspiration.

ET Relationships Used in Water Balance Sub-Model The equations derived in the foregoing analysis of field data, and used in the event stepping water balance sub-model to estimate changes in soil moisture due to evapotranspiration from bare soil and full cover were:

(i) Bare soil

0–10 cm layer $S = 40.0 - 0.6712\ SEo$ for $S \geq 33.6$ (5.32)

$S = 47.99 - 6.386 \ln SEo$ for $S < 33.6$ (5.33)

10–30 cm layer $S = 80.0 - 0.137\ SEo$ for $S \geq 68.7$ (5.34)

$S = 118.5 - 11.30 \ln SEo$ for $S < 68.7$ (5.35)

30–90 cm layer $S = 215.0 - 0.082\ SEo$ for $S \geq 198.0$ (5.36)

$S = 288.6 - 16.97 \ln SEo$ for $S < 198.0$ (5.37)

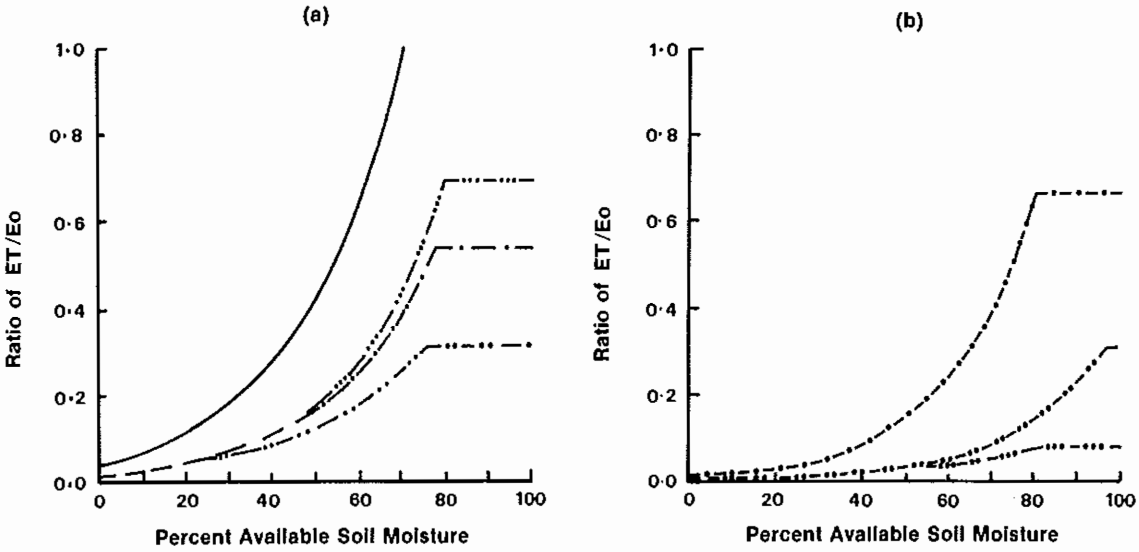


Figure 5.7 Effects of soil moisture on the ratio of actual evapotranspiration (ET) to evaporative demand (Eo) for (a) crops with complete canopy cover, and (b) bare soil. (Solid line is for 0–90 cm soil profile, —·— is for 0–10 cm soil layer, —··— is for 10–30 cm soil layer, and —···— is for 0–90 cm soil layer).

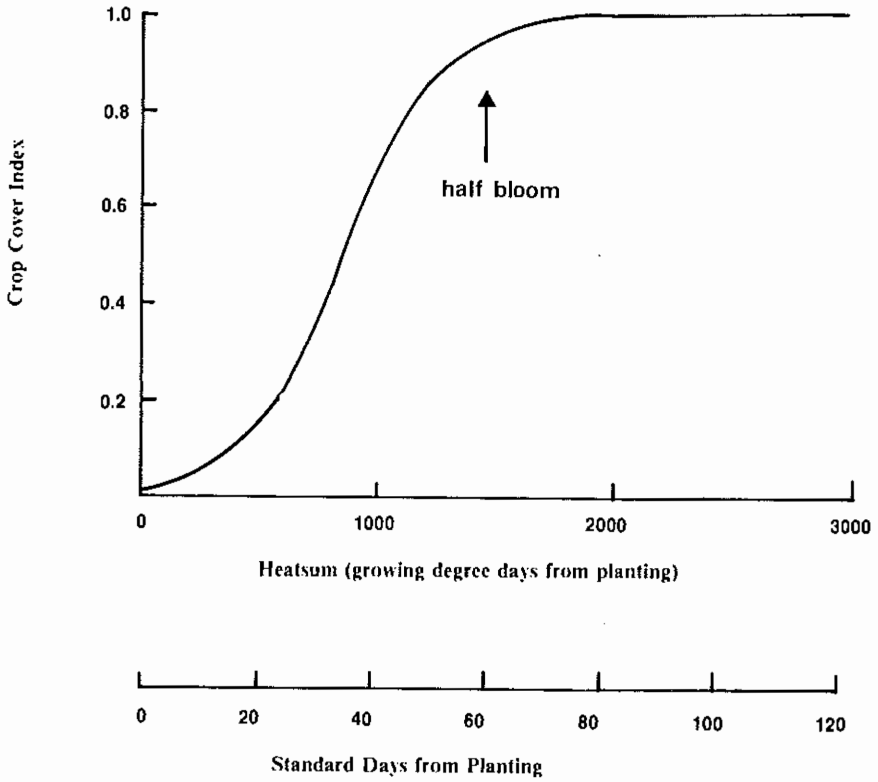


Figure 5.8 Relationship used to define crop cover index as a function of phasic development heatsum.

(ii) Full cover

0–10 cm layer $S = 40.0 - 0.539 \text{ SEo}$ for $S \geq 32.7$ (5.38)

$S = 51.73 - 7.304 \ln \text{SEo}$ for $S < 32.7$ (5.39)

10–30 cm layer $S = 80.0 - 0.315 \text{ SEo}$ for $S \geq 66.2$ (5.40)

$S = 118.5 - 13.84 \ln \text{SEo}$ for $S < 66.2$ (5.41)

30–90 cm layer $S = 215.0 - 0.692 \text{ SEo}$ for $S \geq 196.4$ (5.42)

$S = 257.6 - 18.61 \text{ SEo}$ for $S < 196.4$ (5.43)

Effects of Crop Cover on Evapotranspiration Estimates Because dry matter and leaf area data were not recorded in the field experiments the crop cover index used in equation 5.27 to estimate evapotranspiration from crops with partial cover was calculated as a function of phasic development. The relationship used is shown in figure 5.8 and was adapted from the crop cover versus leaf area relationship used by Rickert and McKeon (1982). It is given by:

$$CI = 1/(1 + 99.0 \exp(-0.00531 H)) \qquad (5.44)$$

where H = Heatsum (growing degree days) as calculated by equation 5.10.

5.4.3 Infiltration

Infiltration processes were modelled with relationships similar to those used in the catchment water balance sub-model with parameters defined by least squares optimization. Parameters of the infiltration equations were optimized using a factorial search technique that minimized the root mean square (RMS) of differences between observed and simulated soil moisture.

Initial values of soil moisture for simulation were set equal to those observed on 25 January 1970. The daily rainfall data recorded at the weather station adjacent to the irrigation-area at RSSRP was used in simulation.

Infiltration via soil cracks was shown to be an important part of the catchment water balance sub-model. Simulations of the irrigation-area water balance without direct infiltration of rainfall to the sub-surface and sub-soil layers showed significant differences between estimated and observed soil moisture. Therefore infiltration via cracks or preferred pathways was represented in the infiltration relationships given below.

Figure 5.3 shows that rainfall was considered to be received by a surface pool and then distributed to infiltration and run-off. The distribution was considered to be instantaneous with no carry over from one day to the next. Thus, run-off (Q) is the difference between rainfall (R) and infiltration (F) (i.e. $Q = R - F$).

Infiltration is the summation of water distributed to the surface, sub-surface and sub-soil layers (F1, F2 and F3 respectively) plus loss of water by deep drainage (G). Thus:

$$F = F1 + F2 + F3 + G \qquad (5.45)$$

The increase in water storage in the surface layer from distribution of infiltration was assumed equal to a proportion p of daily rainfall. However, this increase cannot exceed the water storage deficit of the surface layer (S1max − S1), and hence F1 is given by:

$$F1 = \min(pR, S1max - S1) \qquad (5.46)$$

The value of p in this equation that minimized the root mean square of differences was found to be 0.55. It was assumed that the remaining proportion of rainfall (0.45 R) could be equally distributed to the sub-surface and sub-soil layers via preferred pathways. Therefore, in situations where the surface layer is not filled to capacity, the proportion of rainfall distributed to the sub-surface layer is 0.225 R.

Water uptake by the sub-surface layer was considered similarly to the surface layer, except that the upper limit was set by: (a) 0.225 R plus any excess from the surface layer (i.e. 0.55 R − F1), or (b) the water storage deficit of the sub-surface layer (i.e. S2max − S2). Thus F2 is given by:

$$F2 = \min(0.775 R - F1, S2max - S2) \qquad (5.47)$$

The volume of cracks in the sub-soil was calculated from antecedent soil moisture in the sub-soil (S3) and by assuming soil shrinkage to be three dimensional normal at soil moisture contents below the cracking point (Fox 1964). Field observations showed that the cracking point occurred at approximately 24% gravimetric soil moisture, and hence the soil water content of the subsoil at the cracking point was approximately 173 mm. The equation used to calculate crack volume of the sub-soil (CV3 in units of equivalent ponded depth, mm) was:

$$CV3 = a + b\ (\max\ (0.0,\ 173 - S3)) \qquad (5.48)$$

where a and b are optimized constants, and were found to be a = 5 and b = 0.8.

The amount of rainfall not absorbed by the upper layers is R – F1 – F2. When this excess rainfall was less than computed crack volume then all rainfall was assumed to infiltrate the soil and hence water storage in the sub-soil was incremented by:

$$F3 = R - F1 - F2 \qquad \text{for } CV3 > R - F1 - F2 \qquad (5.49)$$

When the excess rainfall was greater than the computed crack volume then the infiltration rate was considered to be less than the rainfall rate, and hence some run-off was assumed to occur. In this case F3 was calculated from excess rainfall, crack volume and water storage deficit of the sub-soil by a relationship similar to that used in the Boughton model (Boughton 1966). The relationship was:

$$F3 = \min((CV3 + F3max\ \tanh((R-F1-F2-CV3)/F3max)),\ (S3max-S3)) \qquad (5.50)$$

where F3max is an optimized constant and was found to be 15 mm/day.

Loss to deep drainage was calculated as overflow from the sub-soil moisture store.

5.4.4 Evaluation of Water Balance Sub-Model

Figure 5.9 compares simulated and observed soil moisture for a large number of wetting and drying cycles over six years. Differences between simulated and observed soil moisture found in each soil layer are compared statistically in table 5.7.

These results show that the model was reasonably accurate in predicting changes in soil moisture. Coefficients of determination were approximately equal in each layer ($R^2 \approx 0.8$). The mean of the absolute differences between simulated and observed soil moisture were approximately equal in each layer when calculated as a percentage of the

Table 5.7 Comparison of observed soil moisture to soil moisture estimated by irrigation-area water balance sub-model.

Soil layer and depth	Surface (0-10cm)	Sub-Surface (10-30cm)	Sub-Soil (30-90cm)	Profile (0-90cm)
N	97	94	94	92
Mean of absolute diffs (mm)	3.075	5.032	8.248	13.16
Mean difference (mm)	0.192	0.037	-1.998	-1.425
Regression slope	0.902	1.062	1.150	1.105
(std. error)	0.049	0.053	0.058	0.049
Regression intercept	1.437	-3.637	-24.10	-25.10
(std. error)	3.855	6.551	10.29	16.03
Coefficient of Detn.	0.770	0.793	0.821	0.861
Root mean square of differences	3.872	6.533	10.74	16.35

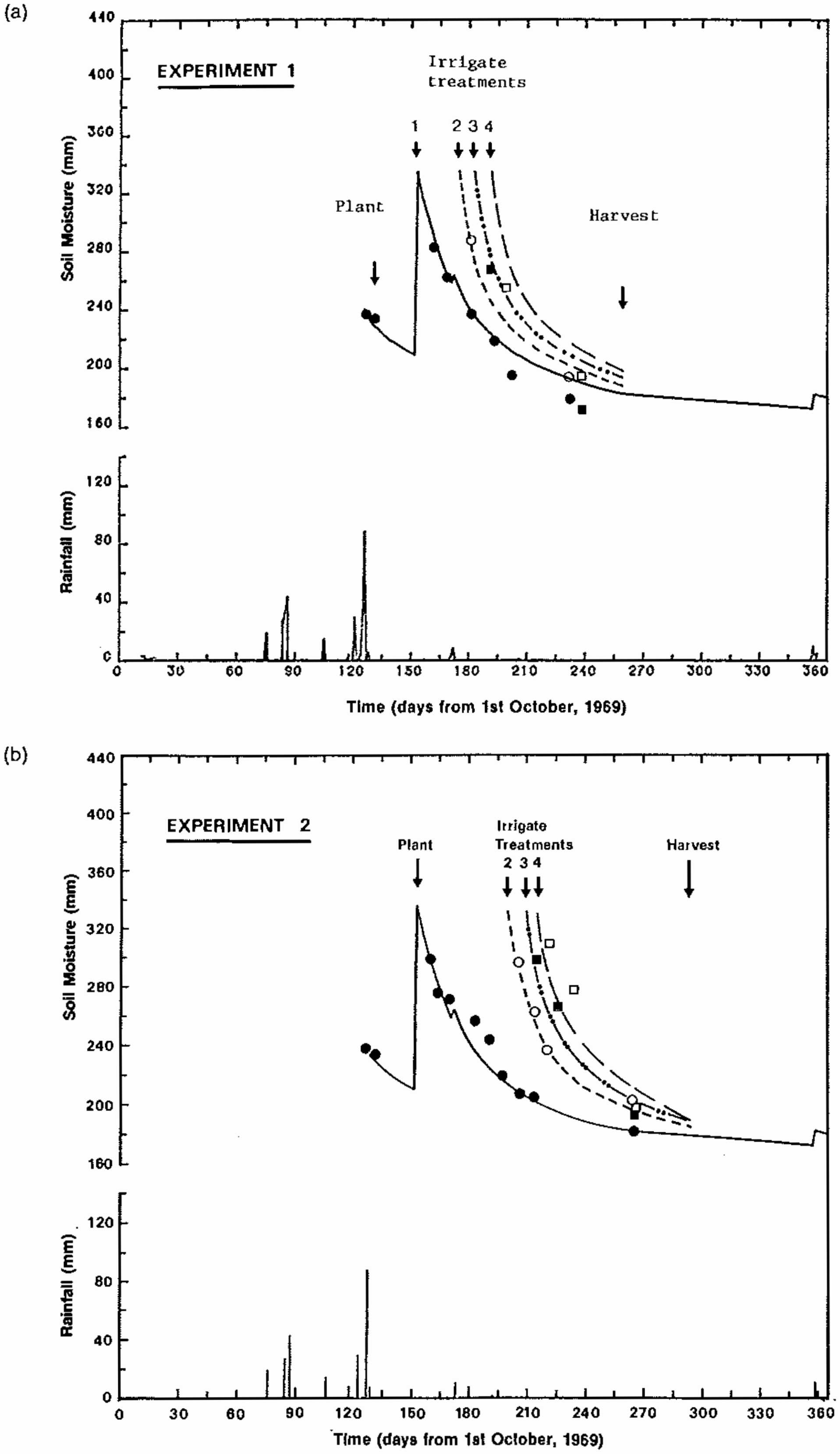
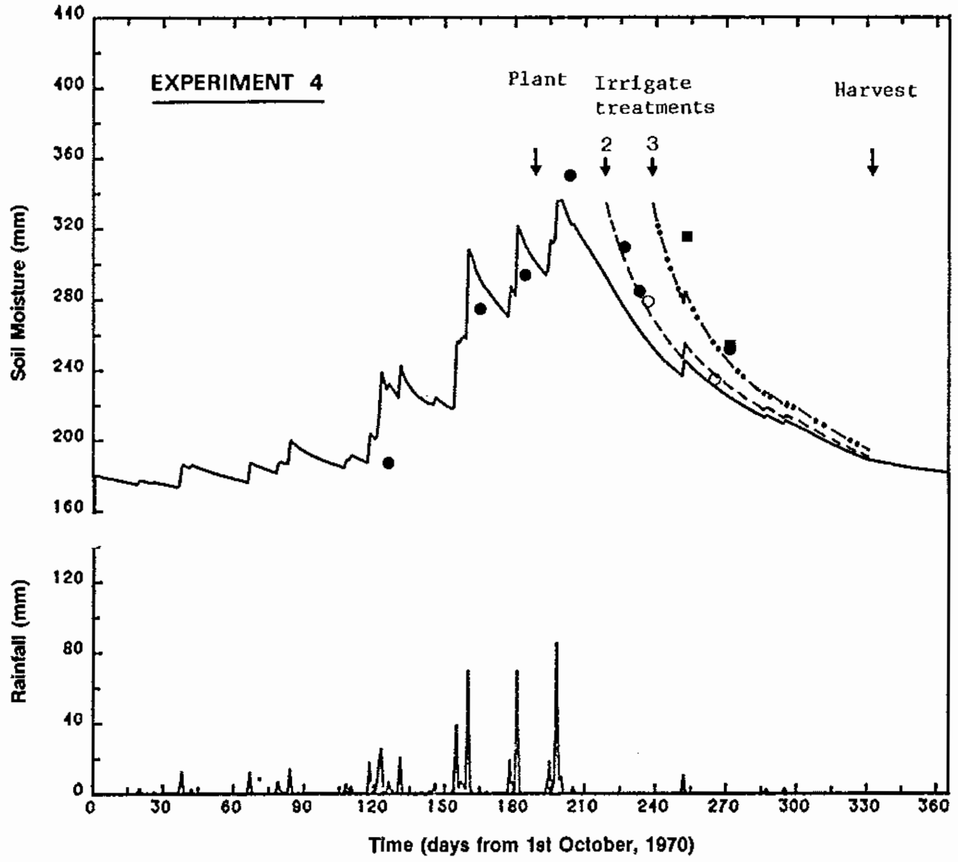


Figure 5.9 Comparisons over time of observed soil moisture in 0–90 cm profile (data points) to simulated soil moisture (lines) for four irrigation strategy treatments in six treatments: (a) Experiment 1, (b) Experiment 2, (c) Experiment 4, (d) Experiment 5, (e) Experiment 6 and (f) Experiment 9. Treatment 1 = ● and ——, Treatment 2 = 0 and - - - , Treatment 3 = ■ and —··— , and Treatment 4 = □ and —— ——).

(c)



(d)

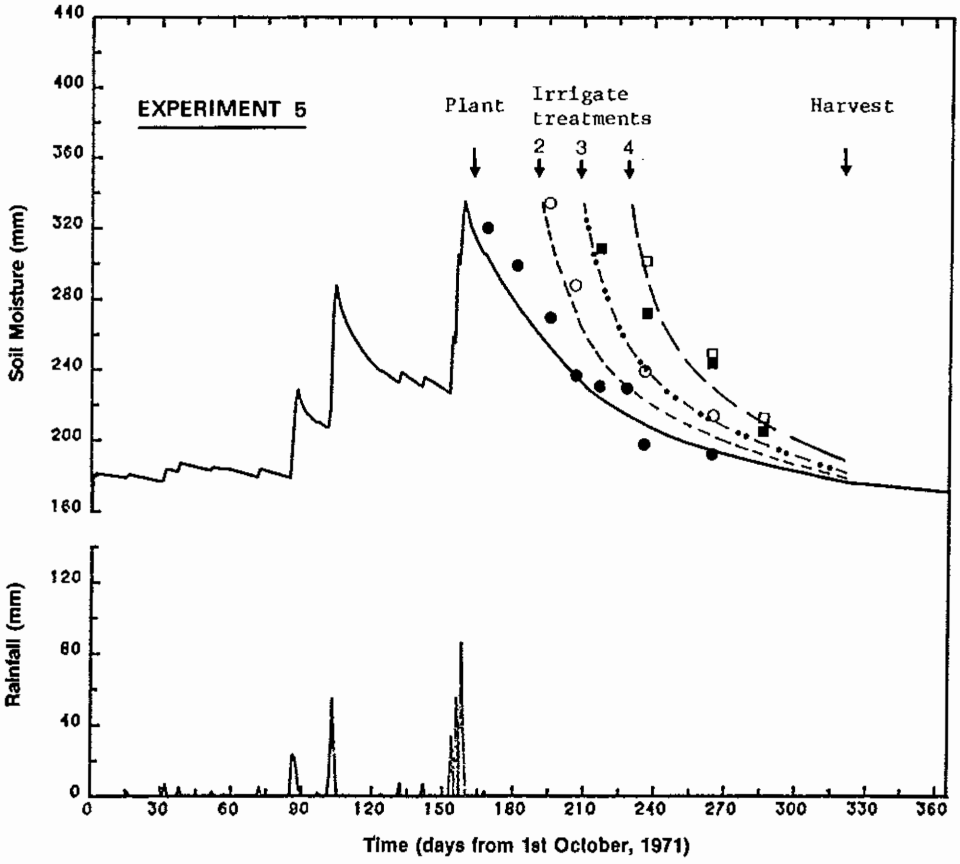
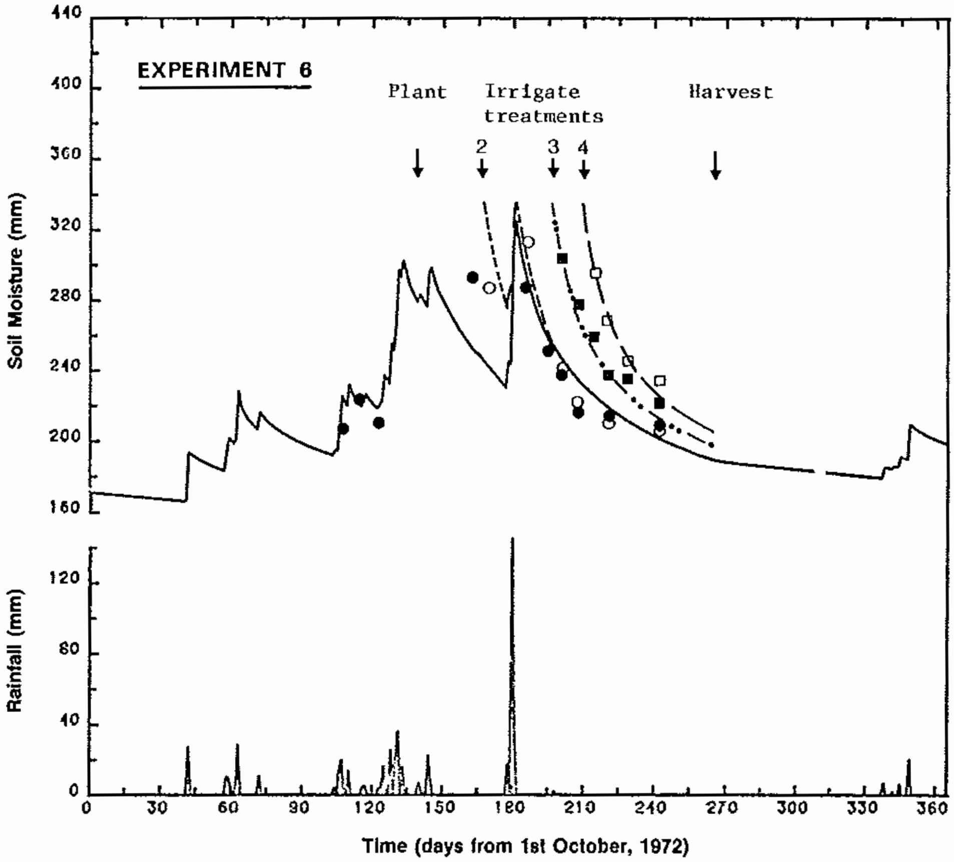


Figure 5.9 (continued)

(e)



(f)

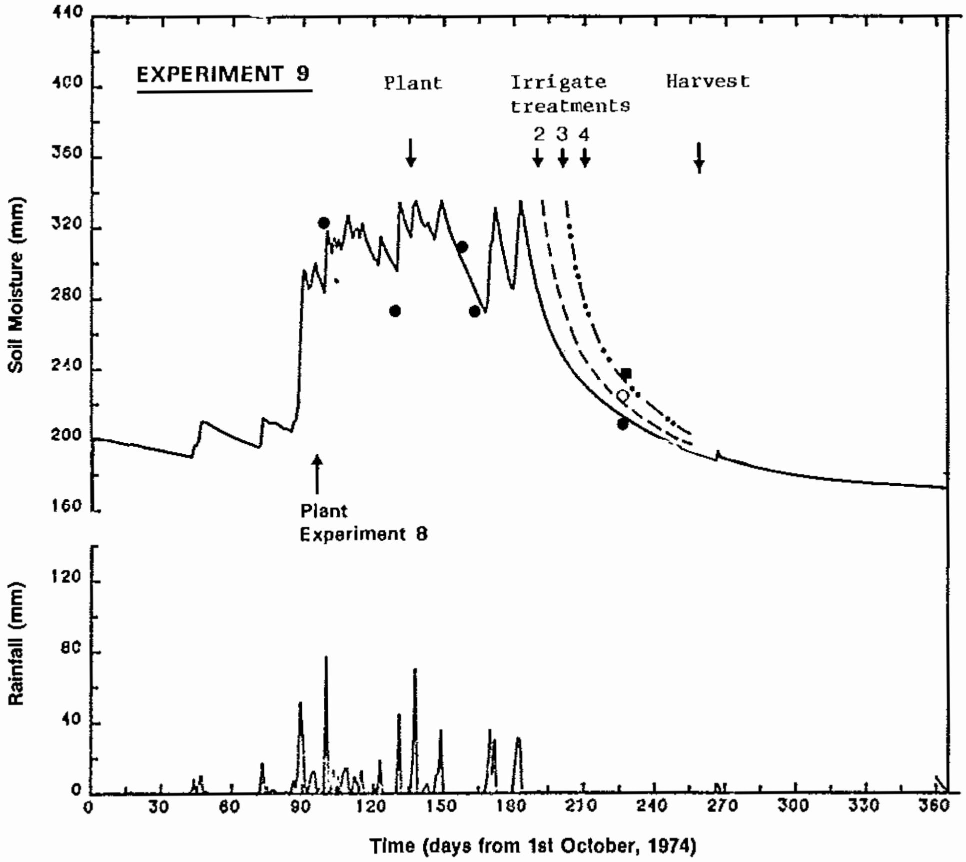


Figure 5.9 (continued)

available soil storage capacity; and were 9.5, 9.1 and 9.2% for the surface, sub-surface and sub-soil layers respectively, and 7.4% for the whole profile. In the surface and sub-surface layers the linear regression coefficients for the slope and intercept of observed versus simulated soil moisture were not significantly different from one and zero. However, in the sub-soil layer the regression slope was significantly greater than 1.0 (at P.05) indicating that the model could be improved. Observed values of sub-soil moisture were on average slightly higher in wet soil conditions and slightly lower in dry soil conditions. Consequently, the model tended to slightly underestimate total evapotranspiration from the sub-soil.

The 95% confidence interval of observed volumetric soil moisture was found to average ± 11.5% of the mean soil moisture. These differences between simulated and observed soil moisture are approximately equal to the spatial variability found in field samples.

It was concluded that the irrigation-area water balance sub-model offered sufficient accuracy for use in developing the grain yield sub-model, and for simulation experiments using long-term climatic records.

5.5 Grain Yield Sub-Model

This section uses field data recorded at RSSRP to derive a set of relationships to predict the components of grain sorghum yield. Yield is estimated from evapotranspiration, the literature review showing this approach to be reliable and theoretically sound in arid climates.

Evapotranspiration from each treatment of the irrigation strategy experiments shown in table 5.2 was calculated using the water balance sub-model described in the previous section. The results are shown in table 5.8 as cumulative totals for each phenophase. These totals are subseqently referred to as phenophase ET.

Table 5.8 shows that the irrigation treatments caused a wide range of phenophase ET values, and it will be shown that this led to large variations in the components of grain yield. Minimum and maximum values of total growing season ET (from planting to the end of the dough phenophase) were 126 and 450 mm respectively. This compares with an average of 551 mm of cumulative evaporative demand over the same period.

5.5.1 Grain Yield Field Observations

Treatment means of the components of grain yield observed in Experiments 1, 2, 5, 6, 7, 8 and 9 are shown in table 5.9. The grain number index shown in this table is discussed later.

Significant points in table 5.9 are as follows.

(i) Variation in plant density between experiments is considerable.

(ii) Grain yields from the nil irrigation treatments were highly variable and ranged from 560 to 3941 kg/ha after deduction of lodging losses. The nil irrigation treatments in Experiments 1, 2 and 5 produced very low yields because rainfall after planting was almost nil (see figures 5.9(b) and (d)). Cumulative evapotranspiration was less than 150 mm (approximately 30% of evaporative demand), and moisture stress was observed from the booting phenophase onwards. The nil irrigation treatment in Experiment 6 also produced very low grain yield, although 196 mm of rain occurred one week before booting. Severe water stress developed during grain fill and this resulted in low grain number, low grain size and high lodging loss. Rainfall was continual from planting to day 91 in Experiment 8 (see figure 5.9(f)) and hence the nil irrigation treatment of this experiment gave a high yield (3941 kg/ha).

(iii) The maximum grain yield under irrigation was 4387 kg/ha. This is very low in comparison to maximum yields recorded in higher latitudes, and thus the data supports the hypothesis of Henzell (1980) and others that yields of grain sorghum hybrids which have a temperate origin are depressed in tropical regions.

(iv) Irrigation timing had large effects on yield, and irrigation was most effective when applied during the anthesis phenophase. For example, the mean effects of irrigation at 27, 42 or 57 days in Experiment 5 was to increase grain yield by 298,

Table 5.8 Effect of irrigation strategy on evapotranspiration accumulated for each phenophase of grain sorghum growth*

Exp. No.	Trt. No.	Irrigation strategy**		Phenophase Evapotranspiration (mm) ***					
		freq.	timing	ETgerm	ETc	ETf	ETb	ETa	ETd
1	1	1	22	10.6	34.8	61.8	35.4	17.8	12.5
1	2	2	22/43	10.6	34.8	61.8	90.5	27.7	16.6
1	3	2	22/52	10.6	34.8	61.8	80.1	46.3	21.1
1	4	2	22/60	10.6	34.8	61.8	35.4	86.9	29.3
1	5	2	22/71	10.6	34.8	61.8	35.4	47.7	63.3
1	6	3	22/43/60	10.6	34.8	61.8	90.5	87.9	29.3
1	7	3	22/52/71	10.6	34.8	61.8	80.1	72.7	63.3
5	1	Nil	-	22.1	31.9	28.7	19.7	14.2	9.5
5	2	1	27	22.1	31.9	75.4	34.2	20.0	13.5
5	3	1	42	22.1	31.9	28.7	83.4	31.4	17.5
5	4	1	57	22.1	31.9	28.7	19.7	89.5	28.1
5	5	2	27/42	22.1	31.9	75.4	84.9	31.4	17.5
5	6	2	27/57	22.1	31.9	75.4	34.2	89.5	28.1
5	7	2	42/57	22.1	31.9	28.7	83.4	89.5	28.1
5	8	3	22/42/57	22.1	31.9	75.4	84.9	89.5	28.1
6	1	Nil	-	23.7	42.9	24.8	80.1	33.3	19.9
6	2	1	32	23.7	42.9	65.9	100.2	35.9	20.6
6	3	1	60	23.7	42.9	24.8	80.1	86.0	32.9
6	4	1	70	23.7	42.9	24.8	80.1	72.0	72.4
6	5	2	32/70	23.7	42.9	65.9	100.2	74.3	72.4
9	1	Nil	-	34.1	56.7	75.7	107.8	39.1	20.8
9	2	1	58	34.1	56.7	75.7	120.8	72.0	26.5
9	3	1	67	34.1	56.7	75.7	107.8	92.4	40.0
9	4	2	58/79	34.1	56.7	75.7	120.8	84.3	82.5
2	1	Nil	-	34.0	44.5	29.9	23.0	14.7	11.7
2	2	1	39	34.0	44.5	41.8	75.3	26.2	17.2
2	3	1	49	34.0	44.5	29.9	78.0	38.2	20.8
2	4	1	55	34.0	44.5	29.9	51.0	63.0	25.7
2	5	1	65	34.0	44.5	29.9	23.0	72.0	42.9
2	6	2	33/49	34.0	44.5	71.3	87.4	38.2	20.8
2	7	2	49/65	34.0	44.5	29.9	78.0	85.8	42.9
2	8	2	39/55	34.0	44.5	41.8	98.0	63.0	25.7
7	1	1	52	18.6	24.6	58.1	77.6	58.1	22.8
7	2	1	61	18.6	24.6	58.1	48.4	86.7	32.5
7	3	1	70	18.6	24.6	58.1	48.4	61.9	57.0
8	1	Nil	-	39.7	87.9	69.4	100.1	58.9	94.4

* Estimated by simulation using irrigation-area water balance sub-model.

** Irrigation timing is shown in standard days after planting.

*** ETgerm = germination ET, ETe = establishment ET, ETf = floral initiation ET, ETb = booting ET, ETa = anthesis ET, ETd = dough ET.

Table 5.9 Treatment means of hand harvest components of grain yield observations.

Treatment	Irrigation Strategy (std.days)	Plant Density (plants/m)	Grain Yield* (kg/ha)	Grain Size (mm)	Grain Number (millions/ha)	Grain Number Index	Lodging Loss** (%)
Experiment 1							
1	22	3.1	699	15.8	44.23	.484	50
2	22/43	3.1	929	15.4	60.30	.660	50
3	22/52	3.1	1453	18.7	77.69	.850	10
4	22/60	3.1	1729	23.3	74.25	.812	5
5	22/43/60	3.1	1947	21.3	91.42	1.000	5
7	22/52/71	3.1	2240	25.5	87.85	.961	5
	LSD+		443	2.1			
Experiment 2							
1	nil	6.5	970	16.6	58.43	.445	50
2	39	6.5	1366	18.5	73.84	.575	30
3	49	6.5	2403	23.4	102.70	.800	20
4	55	6.5	2142	25.4	84.37	.657	5
5	65	6.5	1379	24.2	57.00	.444	5
6	33/45	6.5	2554	23.4	109.14	.850	20
7	49/65	6.5	2550	26.0	98.08	.764	5
8	40/55	6.5	2512	26.4	95.16	.741	5
	LSD+		547	2.2			
Experiment 5							
1	nil	12.7	1174	17.6	66.7	.408	44.9
2	27	12.7	1661	16.4	101.3	.619	12.9
3	42	12.7	2992	20.8	144.0	.881	5.6
4	57	12.7	2998	27.2	123.7	.756	0.8
5	27/42	12.7	2657	20.7	128.3	.782	2.3
6	27/57	12.7	3778	25.4	149.1	.912	0.3
7	42/57	12.7	4127	26.4	156.5	.957	0.1
8	27/42/57	12.7	4387	26.8	163.5	1.000	0.0
	LSD+		576	2.0			
Experiment 6							
1	nil	12.4	1149	14.3	80.4	.491	51.3
2	32	12.4	1029	13.5	76.3	.465	18.9
3	60	12.4	3128	22.0	142.1	.868	6.0
4	70	12.4	3315	25.1	132.1	.806	0.4
5	32/70	12.4	3569	21.8	163.72	1.000	0.1
	LSD+		230	1.8			
Experiment 7							
1	52	9.4	3539	25.5	138.8	0.94	9.2
2	61	9.4	3962	26.9	147.3	1.000	2.1
3	70	9.4	3694	27.0	136.8	0.93	5.3
	LSD+		211	2.9			
Experiment 8							
1	nil	11.0	3941	24.0	164.2	1.00	2.6
Experiment 9							
1	nil	10.4	-	21.7	-	-	-
2	58	10.4	-	24.8	-	-	-
3	67	10.4	-	25.1	-	-	-
4	58/79	10.4	-	25.0	-	-	-
	LSD			2.29			

* Grain yield before lodging losses deducted.

** Lodging losses in experiments 1 and 2 were visually estimated.

\+ LSD = Least significant difference at P.05 between treatment means.

1138 and 1701 kg ha respectively. (Irrigation amounts varied depending on how much was required to fill the profile to capacity as is illustrated in figure 5.9).

(v) Increases in irrigation frequency led to increases in grain yield but each additional irrigation led to smaller increments in grain yield. For example, in Experiment 5 a single irrigation on day 57 increased yield by 1824 kg/ha, two irrigations on days 42 and 57 increased yield a further 1129 kg/ha, and three irrigations on days 27, 42 and 57 increased yield by only a further 260 kg/ha.

(vi) Experiments 1 and 2 had low plant density and low grain yields compared to other experiments, and hence comparison of yields from Experiments 1 and 2 to other experiments requires consideration of plant density.

(vii) Grain number per hectare varied from 44 to 164 million grains per hectare, accounting for four-fold differences in grain yield.

(viii) Grain size varied from 13.5 to 27 mg, thus accounting for two-fold differences in yield.

(ix) All treatments which received irrigation during the grain filling phenophase had a high grain size and a low lodging loss.

(x) Lodging losses exceeded 50% in some treatments and exceeded 10% when grain size was less than 20 mg.

5.5.2 Structure of Grain Yield Sub-Model

One conclusion of the literature review was that a useful way to predict grain yield would be to relate environmental conditions to the components of grain yield. Therefore, the following equations were used to calculate grain yield:

$$GY = GNH \times GS \times (1 - L) \qquad (5.51)$$

where GY = grain yield (kg/ha), GNH = grain number (million grains/ha), GS = grain size (mg), L = proportion of grain lost to lodging.

GNH was calculated by reducing a potential grain number per hectare (PGNH) by a grain number index (GNI) as follows:

$$GNH = PGNH \times GNI \qquad (5.52)$$

where potential grain number is defined as the maximum number of grains that a genotype can produce per unit area for a given plant density when controllable environmental conditions such as water supply and nutrients are at optimum levels; and where grain number index is defined as the ratio of actual to potential grain number, and is thus a measure of environmental stress.

The methods used to estimate PGNH, GNI, GS and L are given in the following sub-sections.

5.5.3 Estimation of Potential Grain Number

The effect of plant density on the yield of grain sorghum is generally and primarily due to changes in grain number rather than grain size (Harper 1977, Thomas 1980, Heslehurst 1982). Therefore, the Reciprocal Yield Law given in the literature review (equation 5.8) is also equally useful for determining relationships between grain number per plant (GNP) and plant density (D). Thus, equations 5.8, 5.6 and 5.7 become:

$$1/GNP = 1/a + bD, \quad \text{and thus} \qquad (5.53)$$

$$GNP = a/(1 + abD), \quad \text{and} \qquad (5.54)$$

$$GNH = aD/(1 + abD), \qquad (5.55)$$

where the constants a and b are differently defined than for grain yield.

The constants a and b in these equations are influenced by environmental conditions such as water stress. If the constants can be determined for environmental conditions which do not restrict growth, then equation 5.55 will define PGNH since PGNH is the upper limit of GNH.

The following sub-sections give results from Experiments 6 and 7 with respect to the effects of plant density and irrigation strategy on tillering, grain number per plant and grain number per hectare. The sub-section on tillering is included because of its influence on grain number per plant.

Tillering Linear regressions of panicle density versus plant density (table 5.10) showed that tillering with production of additional fertile panicles occurred infrequently or not at all in Experiment 6. This was also the case in other experiments excepting those which were damaged by frost. Therefore, the effect of plant density on grain number per plant was restricted to changes in grain number on the primary panicle, and was not complicated by the effects of tillering.

The absence of compensatory increases in panicles per plant found in these experiments at low plant densities contrasts the results of Thomas (1980) and others. High temperatures may have inhibited tillering in the experiments reported here. Downs (1968) found that tillers of grain sorghum were not produced at day/night temperatures of 30/25 and 25/20°C, but that plants tillered well at the lower day/night temperatures of 20/15 and 20/10°C. This data suggests that the day/night temperatures which typically occur in February/March in Richmond (approximately 32/25°C) may be too high for expansion of nodal buds to form fertile tillers.

Table 5.10 Linear regression of panicle density (panicles/m^2) versus plant density (plants/m^2) for each treatment of Experiment 6.

Treatment	Plant Density (plants/m)		Regression Parameters			
	Mean	Range	N	Slope	Intercept	R^2
1	11.9	2 - 25	36	1.03	0.29	0.99
2	12.2	5 - 21	36	1.01	0.53	0.98
3	13.8	5 - 30	36	1.13	-0.54	0.99
4	11.7	3 - 25	36	1.04	0.33	0.98
5	12.3	3 - 24	36	1.08	0.08	0.99

Table 5.11 Regression results of grain number per plant as a function of plant density*.

Exp No.	Treat No.	N	Regression coefficients** 1/a	b	Coeff.of Detn.	Mean Grain No/plant***
6	1	36	.0411 (.0511)	.00913 (.00165)	0.47	727 (a)
	2	36	.0334 (.0374)	.01042 (.00135)	0.64	755 (a)
	3	36	.0184 (.0122)	.00555 (.00039)	0.82	1354 (b,c)
	4	36	.0170 (.0143)	.00620 (.00049)	0.82	1266 (b)
	5	36	.0150 (.0090)	.00490 (.00031)	0.88	1563 (d)
7	1	18	.0277 (.0098)	.00429 (.00084)	0.62	1417 (b,c,d)
	2	18	.0103 (.0086)	.00569 (.00087)	0.78	1487 (c,d)
	3	18	.0326 (.0110)	.00384 (.00092)	0.52	1409 (b,c,d)

* Regression equation was: 1/GNP = 1/a + bD
where GNP = grain number per plant, and D = plant density (plants/m^2).

** Standard errors of regression coefficients are shown in brackets.

*** Mean grain number per plant at a density of 10 plants/m^2 (letters in brackets indicate no significant difference at P.05).

Grain Number per Plant The relationship between grain number per plant and plant density in each treatment of Experiments 6 and 7 was found by linear regression using equation 5.53. Results are shown in table 5.11 and figures 5.10 and 5.11. This set of data shows that a four-fold increase in plant density from 5 to 20 plants/m^2 caused a 3 fold (approximately) decrease in grain number per plant in each treatment. Thus changes in grain number per unit area due to increases in plant density were almost compensated by reductions in grain number per plant.

The data in figures 5.10 and 5.11 also show that the relationship between grain number and plant density was dependent on irrigation strategy. All treatments in Experiment 6 which did not receive an irrigation just after floral initiation (day 32) showed a small reduction of less than 10% in grain number per plant at all plant densities. This may be confirmed by comparing the results for treatment 1 with treatment 2, and treatments 3 and 4 with treatment 5). The effect of irrigation at day 32 in Experiment 6 was probably reduced because 196 mm of rain fell on days 42 to 44 (see figure 5.9). This rain occurred on days 31 to 33 in Experiment 7. Because of this rain, it is probable that grain number was not reduced in any treatment during the boot and early anthesis phenophases of Experiment 6 and during the floral initiation and boot phenophases of Experiment 7.

All treatments in Experiment 6 which did not receive an irrigation during or after the anthesis phenophase showed a two-fold reduction in grain number per plant at all plant densities (compare treatments 1 and 2 to treatments 3, 4 and 5). Differences in the timing of irrigation during the anthesis phenophase had very little effect on grain number per plant in both experiments.

Treatments 1 and 2 in Experiment 6 grew vigorously up to anthesis, however the evapotranspiration estimates in table 5.8 show that water use in these treatments was restricted during grain filling. It was concluded that water stress after anthesis caused the abortion of many grain embryo, and data given later show that it also caused very low grain size of the surviving embryo.

The data in figures 5.10 and 5.11 do not show a significant interaction of irrigation strategy with plant density.

Grain Number per Hectare Figure 5.12 shows the effects of plant density and irrigation strategy on grain number per hectare. Each relationship in this figure was plotted using equation 5.55 and the regression parameters shown in table 5.11. This figure shows that grain number per hectare increased rapidly as plant density increased from zero to 8–10 plants/m^2. However, at plant densities greater than 8–10 plants/m^2, the compensatory changes in grain number per plant were almost equivalent to changes in plant density and thus increases in grain number per hectare were small.

Figure 5.12 also shows that treatment 5 of Experiment 6 maximized grain number per hectare at all plant densities. This treatment was without water stress up to anthesis, and irrigation after anthesis prevented abortion of grain embryo due to water stress. Therefore, the relationship found between grain number per hectare and plant density for treatment 5 was adopted in this study to define potential grain number per hectare. This relationship is:

$$PGNH = aD/(1 + abD) \qquad (5.56)$$

where PGNH = Potential grain number (million grains/ha), D = Plant density (plants/m^2), $1/a = 0.01498$, and $b = 0.00490$.

5.5.4 Estimation of Grain Number Index (GNI)

This section describes the methods used to firstly estimate an observed GNI from recorded grain number per hectare, and secondly predict GNI from environmental conditions.

Observed Grain Number Index In the experimental data given in table 5.9, GNI is calculated by dividing observed GNH by the maximum GNH observed in the experiment. This index normalizes data, and thus facilitates comparison of grain number among experiments that have different plant densities. (The indices for Experiment 2 were further multiplied by 0.85 for reasons discussed below.)

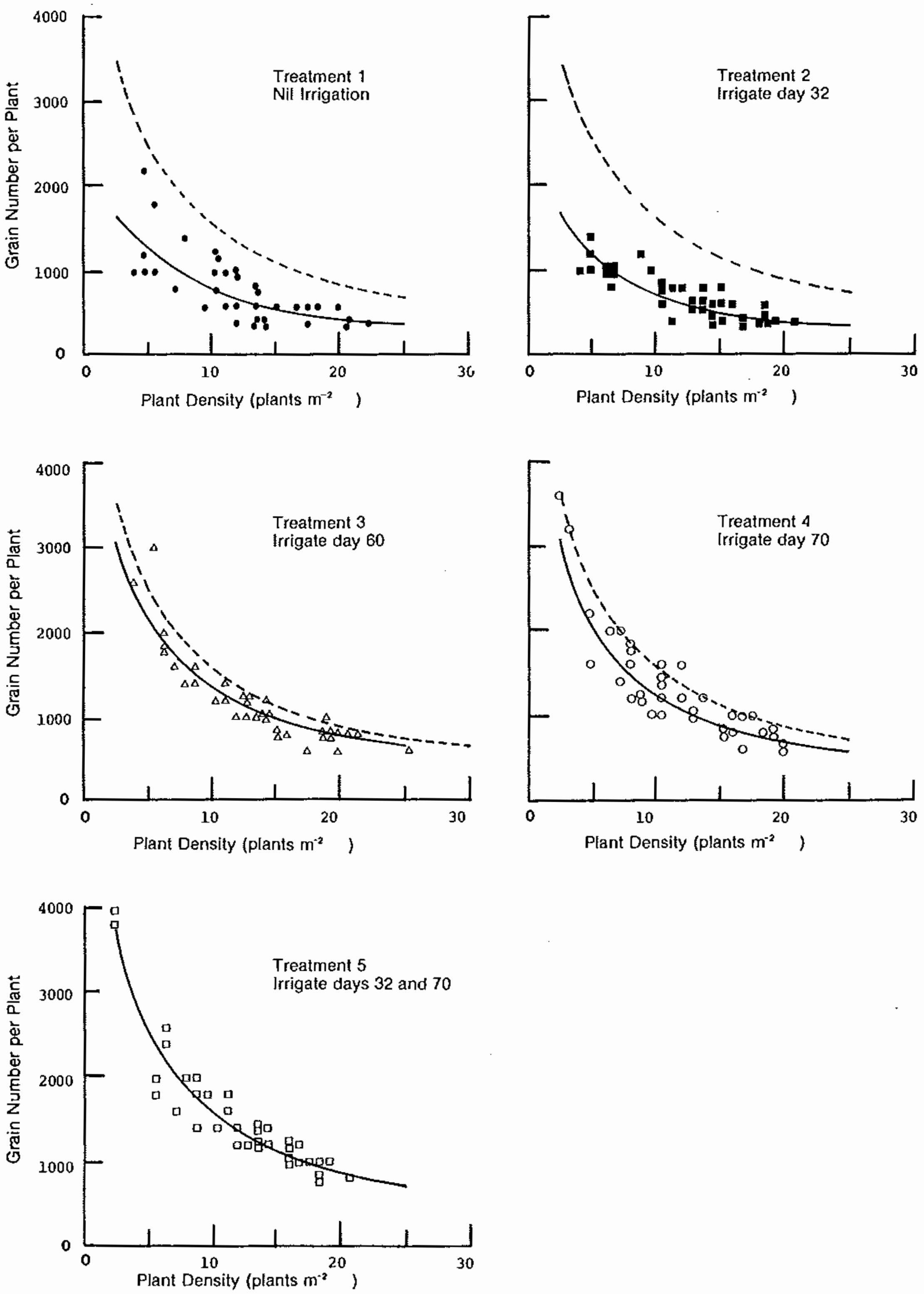


Figure 5.10 Effect of plant density and irrigation strategy on grain number per plant (Results from Experiment 6. The solid lines in each figure were plotted using equation 5.53 and the regression parameters in table 5.11. The dotted line in each figure is the relationship found in treatment 5.)

Use of the normalizing factor GNI has three assumptions: (i) the only differences in grain number between treatments of the same experiment (apart from experimental error) were those due to the effects of irrigation strategy on water stress; (ii) there were no interactive effects of water stress with plant density; and (iii) there was at least one treatment in each experiment in which grain number was not reduced by water stress.

The second assumption is partly substantiated by results from Experiment 6. Grain number indices for each treatment of this experiment at plant densities of 2.5, 5, 10 and 20 plants/m^2 were calculated from the grain number/plant density relationships shown in figure 5.12. The results in table 5.12 show that, in contrast to irrigation strategy, plant density had very little effect on grain number indices.

The third assumption was investigated by comparing the maximum grain number recorded in each experiment to the potential grain number/ plant density relationship of equation 5.56. The results in table 5.13 show these differences to be very small except in

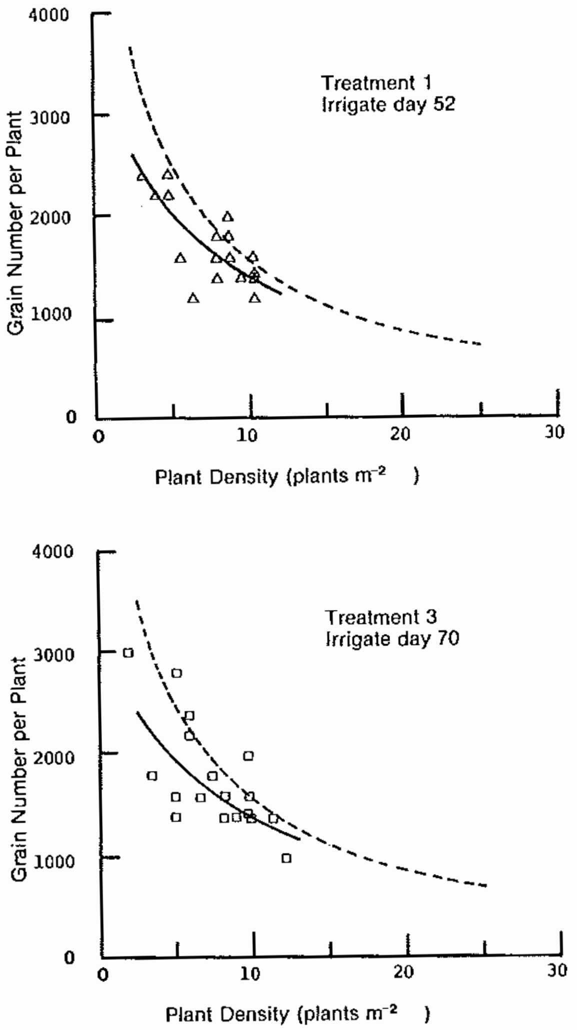


Figure 5.11 Effect of plant density and irrigation strategy on grain number per plant. (Results from experiment 7. The solid lines in each figure were plotted using equation 5.53 and the regression parameters shown in table 5.11. The dotted line in each figure is the relationship found in treatment 5 of Experiment 6.)

Experiment 2 where the observed maximum grain number was substantially less than the predicted grain number. This suggests that grain number in all treatments of Experiment 2 was limited by water stress, but in all other experiments there was at least one treatment that was not limited by water stress. The following procedure was used to normalize the grain number indices of Experiment 2.

The environmental conditions from floral initiation onwards of treatment 6 which produced the most grain in Experiment 2 were very similar to the environmental conditions over the same period of treatment 3 in Experiment 1 (see table 5.8). Experiments 1 and 2 were very similar because they were planted only 3 weeks apart in a season where no rainfall fell after planting; whilst Experiment 1 was planted on a full profile of soil

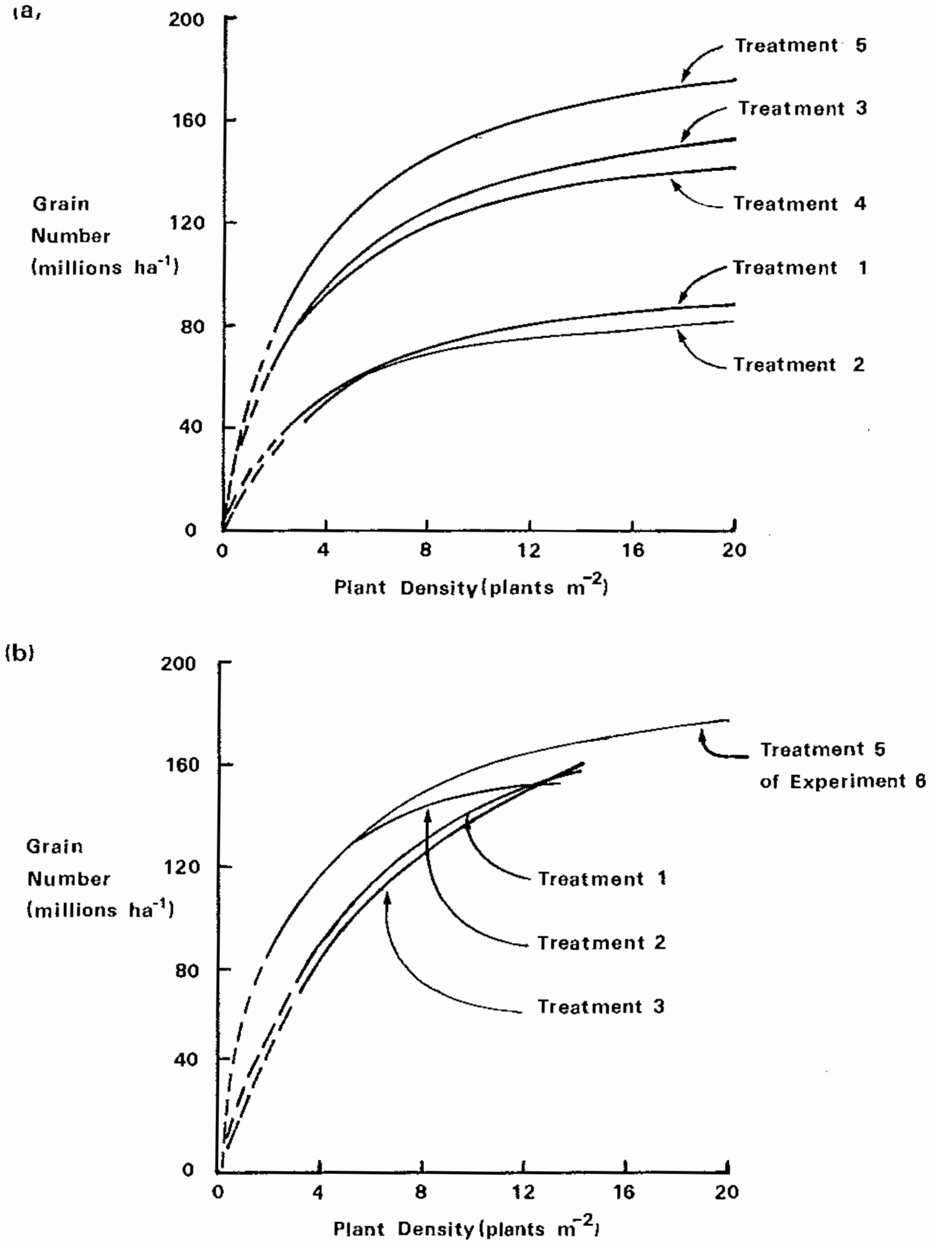


Figure 5.12 . Effect of plant density and irrigation strategy on grain number per hectare. (a) Results from Experiment 6, (b) Results from Experiment 7 and treatment 5 of Experiment 6. (Graphs were plotted using equation 5.55 and the regression parameters shown in table 5.11.) (The irrigation strategy used in each treatment is shown in figures 5.10 and 5.11.)

moisture following heavy rain, germination in Experiment 2 was achieved through irrigation. The irrigation strategies used in both treatments referred to above were similar, and the data in table 5.8 show estimates of evapotranspiration to be very similar. Therefore, the grain number indices of Experiment 2 were weighted so as to be comparable with other experiments by multiplying all the grain number indices of Experiment 2 by the grain number index found for treatment 3 of Experiment 1 (i.e. 0.85).

Prediction of Grain Number Index It is intended to use the estimates of floral initiation, booting and anthesis evapotranspiration (ETf, ETb and ETa respectively) given in table 5.8 as predictors of GNI since both ET and GNI are affected by water stress.

The upper limit of grain number is physiologically determined at anthesis when the florets are fertilized. Water stress before anthesis reduces grain number by limiting the growth of floral organs, whereas water stress after anthesis leads to abortion of grain embryo. Therefore, a multiplicative relationship to estimate GNI from phenophase ET was used because it is conceptually more realistic than an additive approach of multiple regression. However, multiple regression is useful to determine the sensitivity of GNI to phenophase ET, and hence a number of multiple regressions of observed GNI versus various combinations of ETf, ETb and ETa are given first.

Table 5.12 Effect of plant density and irrigation strategy on grain number indices. (GNI values are given under the heading plant density.)

Treatment No.	Irrigation Strategy	Plant Density (plants/m^2)			
		2.5	5	10	20
Experiment 6					
1	nil	.43	.45	.48	.50
2	32	.46	.46	.47	.47
3	60	.84	.85	.86	.87
4	72	.83	.82	.81	.80
5	32/72	1.00	1.00	1.00	1.00
Experiment 7					
1	52	-	.80	.90	-
2	61	-	1.02	.95	-
3	70	-	.76	.90	-

Table 5.13 Comparison of the maximum grain number per hectare observed in each experiment to the estimated potential grain number per hectare*.

Experiment Number	Observed Plant Density (plants m^2)	Grain Number (millions/ha)	
		Maximum Observed	Predicted*
1	3.1	91.4	102.7
2	6.5	109.1	138.8
5	10.1	163.5	156.7
6	12.4	163.7	163.7
7	9.4	147.3	154.0
8	11.0	164.2	159.7

* Potential grain number estimated from plant density using eq. 5.56.

Coefficients of variation found for the above multiple regressions are shown in table 5.14. This table shows that GNI was most sensitive to changes in ETa, however ETa alone accounted for only a small proportion (38%) of the total variation in GNI. ETf and ETb had similar effects on GNI and together they accounted for 37% of variation in GNI.

Agreement between predicted and observed GNI was maximised ($R^2 = 0.65$) when ETf, ETb and ETa were used as independent variables in multiple regression. However, agreement was only slightly better than if ET from these three phenophases was summed to form a single variable. The results also show that the relationship between GNI and ET was essentially linear. Quadratic terms of ET were not significant at P.05 in any of the regressions tested except for $(ETa)^2$ in regression 6, which increased the coefficient of determination by 0.08.

The multiplicative relationship used to predict GNI was as follows. A water stress index of range 0.0 (nil stress) to 1.0 (complete stress) was calculated for each of the floral initiation, booting and anthesis phenophases (WSf, WSb and WSa respectively). Predicted GNI was then calculated from:

$$GNI = (1 - WSf) \times (1 - WSb) \times (1 - WSa) \qquad (5.57)$$

Each water stress index in this equation was calculated from phenophase ET using the relationship:

$$WS_k = \max(0.0,(c - m\ ET_k)) \qquad (5.58)$$

where c and m are constants, and the sub-script k refers alternately to the floral initiation, booting or anthesis phenophase.

Table 5.14 Coefficients of determination found for regressions of observed grain number index versus floral initiation, booting and anthesis phenophase evapotranspiration (ETf, ETb and ETa respectively).

Regression Number	Independent Regression Variable(s)*	Coefficient of Determination
1	f	.22
2	f, f^2	.22
3	b	.28
4	b	.28
5	a	.38
6	a, a^2	.46
7	b, a	.57
8	b, b^2, a, a^2	.59
9	f, b, a	.65
10	f, f^2, b, b^2, a, a^2	.69
11	(f + b)	.37
12	(f + b), $(f + b)^2$	.39
13	(b + a)	.56
14	(b + a), $(b + a)^2$	.57
15	(f + b + a)	.62
16	(f + b + a), $(f + b + a)^2$	.64
17	(f + b), a	.64
18	(f + b), $(f + b)^2$, a, a^2	.68

* The mnemonics ETf, ETb and ETa have been abbreviated to f, b and a in this table. Brackets indicate that ET has been summed over two or more phenophases to form a single variable.

The values of c and m in this equation for each phenophase were found by minimizing the root mean square of differences between predicted and observed values of GNI using a factorial search technique (Cochran and Cox 1966). The optimum values so found were:

(i) floral initiation phenophase
$c = 0.31$, $m = .00534$ (i.e. $WSf = 0.0$ when $ETf = 58$ mm)

(ii) booting phenophase
$c = 0.43$, $m = .00741$ (i.e. $WSb = 0.0$ when $ETb = 58$ mm)

(iii) anthesis phenophase
$c = 0.46$, $m = .00613$ (i.e. $WSa = 0.0$ when $ETa = 75$ mm)

Calculation of GNI using the multiplicative water stress relationships of equations 5.57 and 5.58 gave slightly closer agreement ($R^2 = 0.69$) between observed and predicted GNI than was previously found ($R^2 = 0.65$) using multiple regression. Equations 5.57 and 5.58 were therefore adopted as the method of predicting GNI in the grain yield sub-model.

The relationship found between observed and predicted grain number per hectare was:

$$OGNH = 1.095\ PGNH - 12.5 \qquad (5.59)$$

where OGNH = Observed grain number (millions/ha), PGNH = Predicted grain number (millions/ha), Standard error of regression slope = 0.107, and Coefficient of determination = 0.78

Although the regression slope and intercept of this relationship are not significantly different from 1.0 and zero, the scatter of points about the regression (see figure 5.13) clearly indicate the limitations of the relationship. The two data points which contributed most to the error variance were the values from treatment 3 of Experiment 5 (observed = 144, predicted = 102) and treatment 2 of Experiment 6 (observed = 76, predicted = 124). These two treatments received no rainfall or irrigation after booting and were therefore stressed during grain fill. However, cooler temperatures favoured development of grain size in Experiment 5 and so loss of grain in threshing was not as high as in Experiment 6. The very low grain size and adherence of grain to the glumes made separation of grain from chaff very difficult in treatment 2 of Experiment 6.

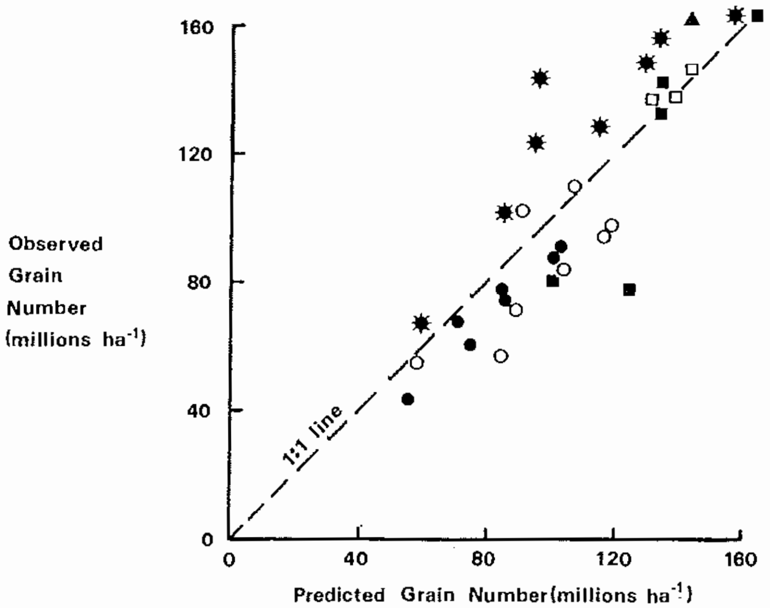


Figure 5.13 Comparison of observed to predicted grain number per hectare. (Experiment symbol code ● = Exp.1, ○ = Exp.2, ✱ = Exp.5, ■ = Exp.6, □ = Exp.7, ▲= Exp.8)

Two other points are of significance in figure 5.13. Firstly, predicted GNH was greater than observed GNH in 13 of the 15 treatments in Experiments 1 and 2. This difference may have been caused by use of the lower yielding hybrid 'Brolga' in Experiments 1 and 2 rather than the hybrid Dekalb E57 that was used in the other experiments. Secondly, observed GNH was consistently greater than predicted GNH in Experiment 5. This may have been caused by lower temperatures during floral development. Mean daily temperature from floral initiation to anthesis in Experiment 5 was 22°C, whereas the mean daily temperature for the same period in other experiments was 25 to 28°.

5.5.5 Estimation of Grain Size

This section investigates the effects of evapotranspiration, temperature and grain number on grain size.

Evapotranspiration Effects of cumulative ET during the anthesis and dough phenophases on grain size were found to be very similar. Thus results are given with respect to cumulative ET for the grain filling phenophase, denoted ETg, where ETg = ETa + ETd.

The mean grain size found in each treatment is plotted against ETg in figure 5.14.

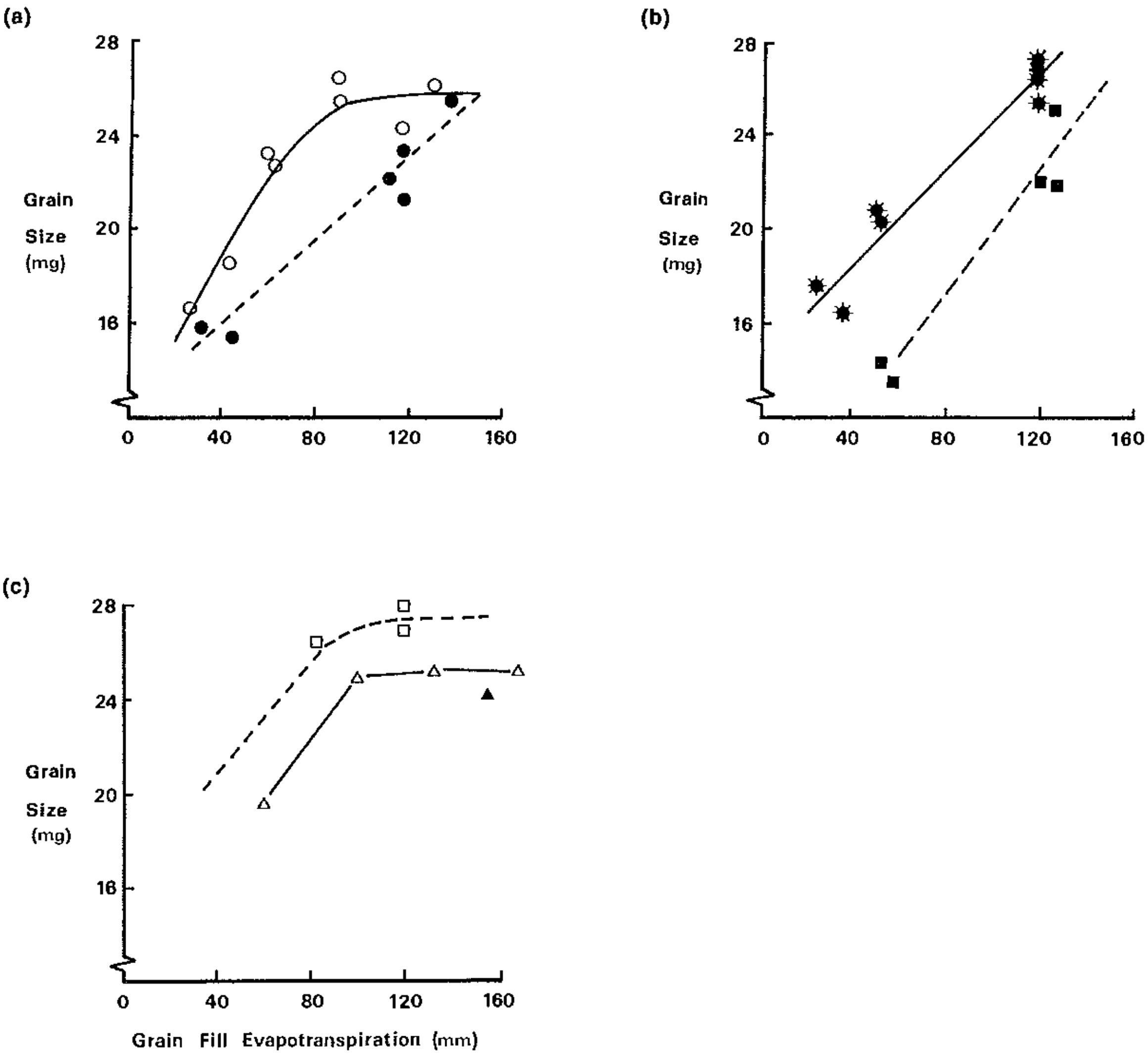


Figure 5.14 Relationships found between observed grain size and cumulative grain fill evapotranspiration (ETg) for: (a) Exp. 1 (●) and Exp. 2 (○), (b) Exp.5 (✱) and Exp.6 (■), and (c) Exp.7 (□), Exp.8 (△) and Exp.9 (▲).

This figure shows that:

(i) Grain size increased in all experiments as ETg increased.

(ii) The relationship was linear in Experiments 2, 5 and 6 but curvilinear in Experiments 3 and 9. (The data for Experiments 3, 7 and 9 suggest that ETg had little effect on grain size when ETg exceeded 80 mm).

(iii) Considerable differences occurred in the relationship of grain size to ETg between experiments. Significant differences at P.05 were found among the mean grain sizes determined for each experiment when the data was analysed by analysis of covariance using ETg and $(ETg)^2$ as the covariates. Therefore the effects of other variables (temperature and grain number) on grain size were investigated.

Temperature The effect of mean daily temperature during the grain filling phenophase (Tg) on grain size is shown in figure 5.15. The only grain size observations shown in this figure are those in which ETg exceeded 80 mm so that grain size was relatively independent of ETg.

The most important feature in figure 5.15 is that grain size decreased as Tg increased. This decrease is opposite to the relationship between *Sorghum* growth and temperature that was discussed in the literature review. However, the observed changes in grain size may be more related to changes in solar radiation or evaporative demand than temperature because these factors are strongly interrelated. Increased grain size at lower temperature may have been due to increased growth per unit of water transpired because of lower evaporative demand. Alternatively, the longer duration of the grain filling phenophase at lower temperature may have resulted in increased light interception and increased net assimilation.

The results of multiple regression of all grain size observations versus ETg, $(ETg)^2$ and Tg are shown in table 5.15. This table shows that use of Tg in the regressions led to a considerable improvement in the agreement between predicted and observed grain size.

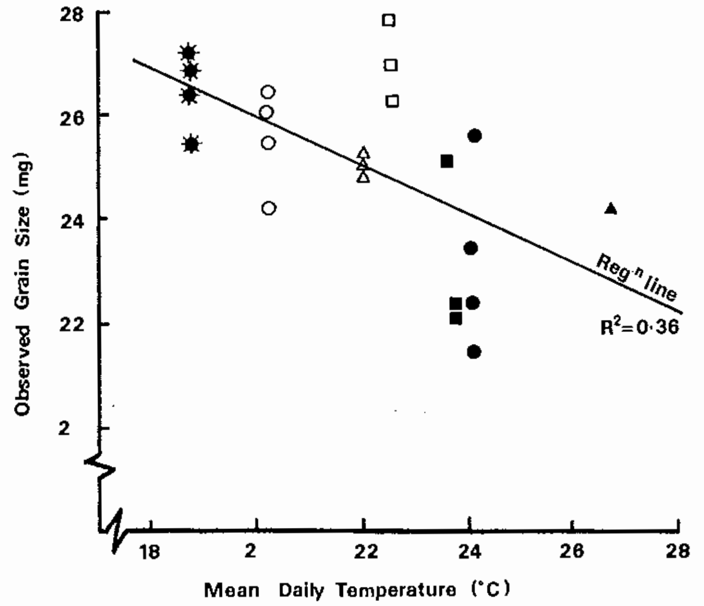


Figure 5.15 Effect of mean daily temperature during the grain filling phenophase on grain size. (Exp.1 = ● , Exp.2 = ○ , Exp.5 = ✸ , Exp.6 = ■ , Exp.7 = □ , Exp.8 = △ , Exp.9 = ▲)

Table 5.15 Multiple regression of grain size (GS) versus grain fill evapotranspiration (ETg, mm) and mean daily temperature (Tg, °C) during the grain fill phenophase.

	Regression (standard errors are in brackets)	Coeff. of determination
1.	$GS = .0767\ ETg + 15.42$ $(.0118)\quad(2.77)$	.55
2.	$GS = .2231\ ETg - .0008349\ (ETg)^2 + 10.28$ $(.05657)\quad(.0003165)\quad(2.55)$	.63
3.	$GS = .0889\ ETg - .7794\ Tg + 30.37$	.71
4.	$GS = .2187\ ETg - .0007436\ (ETg)^2 - .7408\ Tg + 25.88$ $(.0448)\quad(.0002514)\quad(.1631)\quad(2.022)$	.78

Effect of Grain Number on Grain Size The possible presence of compensating increases in grain size due to reduction in grain number by water stress before anthesis was investigated. Treatments from the same experiment were paired on the basis of having similar water use after anthesis (i.e. similar values of ETg), but different levels of water use before anthesis (i.e. different values of ETf and ETb). Thirteen treatment pairs were formed. Table 5.16 shows for each pair: (i) estimates for ETf + ETb and ETg, and (ii) observed grain number, grain size and difference in grain size. Compensating gains in grain size were calculated for each treatment pair by subtracting the grain size of the treatment with the higher grain number from the treatment with the lower grain number.

Table 5.16 shows that lower pre-anthesis ET led to lower grain number per hectare in all cases except the last case. However, compensating increases in grain size were found in only 8 of the 13 cases, and the increase exceeded 1 mg in only 4 cases. The mean increase in grain size was 0.53 mg or only 4% of the observed variation in grain size. There was no significant correlation between pre-anthesis ET and the residual distribution of grain size after the effects of ETg and Tg on grain size were removed.

It was concluded that the effects of grain number on grain size could be ignored in prediction of grain size.

Grain Size Relationship Adopted The relationship used in the grain yield sub-model to estimate grain size was the same as regression number 4 in table 5.15, but the following limits were imposed: (i) ETg was limited to 147.5 mm so that the quadratic term of ETg would not cause grain size to decrease when ETg exceeded 147.5 mm, (ii) the effect of temperature was limited to the minimum and maximum values of Tg observed in the experiments (i.e. 19.0 and 25.6 °C), and (iii) a minimum grain size of 13.5 mg was specified, since grains smaller than 13.5 mg (approximately) could not be separated from chaff when threshing.

The relationship adopted to estimate grain size was:

$$GS = \max(13.5,\ 0.2187ET - 0.0007436ET^2 - 0.7408T + 25.88)) \qquad (5.60)$$

where GS = grain size (mg), ET = min (147.5, ETg), ETg = cumulative evapotranspiration during grain fill phenophase (mm), T = min (25.6, max (19.0, Tg)), and Tg = mean daily temperature of grain fill phenophase (°C).

The relationship between predicted and observed grain size is shown in figure 5.16.

Table 5.16 Compensatory gains in grain size caused by changes in water stress*.

Exp. No.	Trt. No.	Irrigation Strategy	ETf+ETb (mm)	ETg (mm)	Grain Number (millions /ha)	Grain Size (mg)	Compensatory Gain in Grain Size (mg)
Water stress absent during grain fill							
1	4	60	97.2	116.2	74.3	23.3	+ 2.0
	6	43/60	152.3	116.2	91.4	21.3	
2	4	55	80.9	88.7	84.4	25.4	- 1.0
	8	39/55	139.8	88.7	95.2	26.4	
2	5	65	52.9	114.9	57.0	24	- 2.0
	7	49/65	107.9	114.9	98.1	26	
5	4	57	48.4	117.6	123.7	27.2	+ 1.8
	6	27/57	109.6	117.6	149.1	25.4	
5	4	57	48.4	117.6	123.7	27.2	+ 0.8
	7	42/57	112.1	117.6	156.5	26.4	
5	4	57	48.4	117.6	123.7	27.2	+ 0.4
	8	27/42/57	160.3	117.6	163.5	26.8	
6	4	70	104.5	144.4	132.1	25.1	+ 3.3
	5	32/70	166.1	146.4	163.7	21.8	
Water stress medium to severe during grain fill							
1	1	22	97.2	30.3	44.2	15.8	+ 0.4
	2	22/43	152.3	43.3	60.3	15.4	
2	1	Nil	52.9	26.4	58.4	16.6	- 1.9
	2	39	117.1	43.4	73.8	18.5	
2	3	49	107.9	59.0	102.7	23.4	0.0
	6	33/49	158.7	59.0	109.1	23.4	
5	1	Nil	48.4	23.7	66.7	17.6	+ 1.2
	2	27	108.6	33.5	101.3	16.4	
5	3	42	112.1	48.9	144.0	20.8	+ 0.1
	5	27/42	160.3	48.9	128.3	20.7	
6	1	Nil	104.9	53.2	80.4	14.3	- 0.8
	2	32	166.1	56.5	76.3	13.5	

* Treatments have been paired. In each pair the same level of water stress occurred after anthesis (i.e. similar values of ETg), however, the upper case of each pair received greater stress before anthesis as shown by the differences in ETf and ETb.

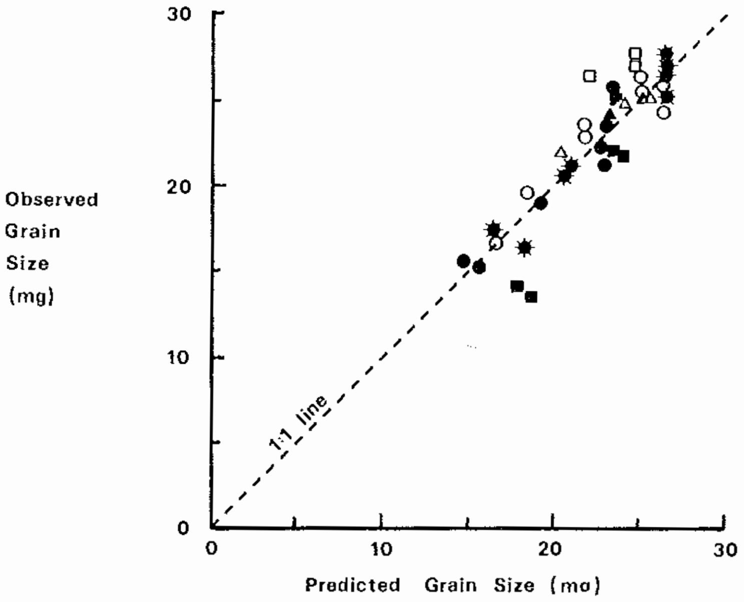


Figure 5.16 Comparison of observed to predicted grain size
(● = Exp.1, ○ = Exp.2, ✱ = Exp.5, ■ = Exp.6, □ = Exp.7,
△ = Exp.8, ▲ = Exp.9).

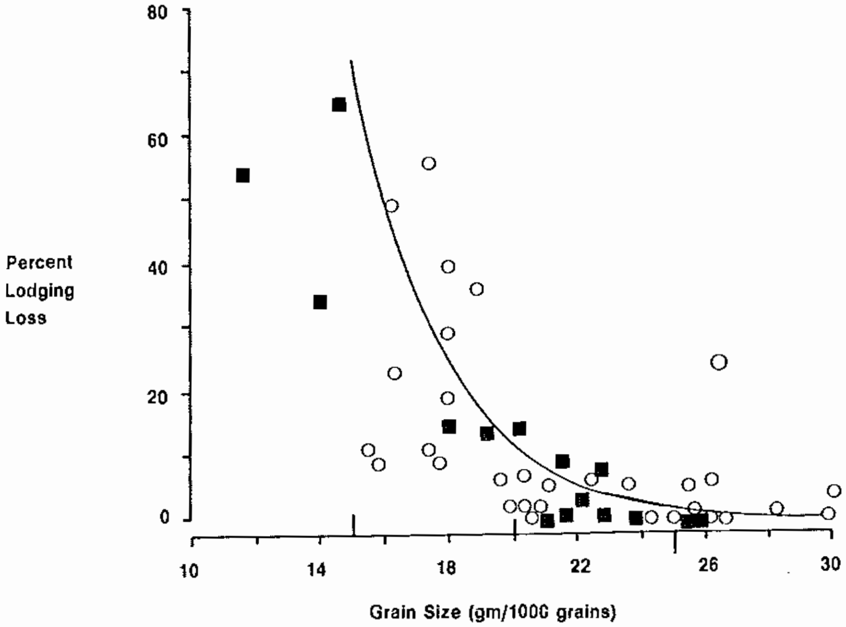


Figure 5.17 Relationship found between the proportion of grain yield lost to lodging and grain size. (○ = data from Experiment 5, ■ = data from Experiment 6).

5.5.6 Estimation of Lodging Losses

It was concluded in the literature review that stem strength was an important determinate of lodging. It was also concluded that lodging could be related to grain size, because stem strength and grain size were both dependent on moisture stress.

Figure 5.17 shows the relationship found in Experiments 5 and 6 between the proportion of grain yield lost to lodging and grain size. This figure shows that lodging losses were minimal when grain size was greater than 20 mg but was high and variable at grain sizes of less than 20 mg. The high level of variance in lodging at grain sizes less than 20 mg was attributed to the effects of other factors such as windiness and mutual support on the rate of lodging.

The relationship adopted to estimate the proportion of grain yield lost to lodging (L), shown by the solid line in figure 5.17, is:

$$L = \min\{0.80,\ 0.721\ \exp(-0.3665(GS-15.0))\} \qquad (5.61)$$

This equation was determined by hand fitting to the data, and was deliberately chosen to overestimate L at low grain sizes so that estimates of yield would be conservative in situations where lodging losses were high.

5.5.7 Evaluation of Grain Yield Sub-Model

Comparison of Observed and Simulated Grain Yields Observed hand-harvested grain yields before and after deduction of lodging losses are compared to predicted grain yields in figure 5.18(a) and 5.18(b) respectively. Yields after lodging in figure 5.18(b) do not include data from Experiments 1 and 2 because lodging losses were not measured in these two experiments. The regression slope and intercept are not significantly different from one and zero in both figures, and the coefficients of determination show the grain yield sub-model to have reasonable accuracy.

Grain yields recorded in each experiment by harvesting with a commercial header are compared to predicted grain yields in figure 5.19. The main outliers in this figure are from Experiments 4 and 9, and this is attributed to frost damage at anthesis in Experiment 4, and bird damage in Experiment 9. Birds showed a marked preference for treatments that were irrigated so that the nil irrigation treatment was only slightly damaged by birds and showed good agreement with predicted yield.

Frosts in Experiment 4 caused prolific tillering, especially in those treatments which received irrigation at anthesis or during grain filling. The tillering delayed harvest by two months, and almost all of the grain yield came from the tillers.

From these comparisons it was concluded that the components of yield sub-model was satisfactory for predicting grain yield in simulation experiments, provided a crop management strategy was used to restrict time of planting so that the chance of frost damage was unlikely.

Occurrences of loss in yield from birds and locusts have been reported as causing serious loss in some commercial crops in the region. These losses may be very important in determining the viability of commercial grain cropping. However, no data are available to estimate the probability of such losses, and hence it is not possible to include them in computations. It is an implicit qualifier on yield predictions.

General Comments on Grain Yield Sub-Model It was shown that plant density had a considerable effect on grain number per hectare at plant densities of less than 8-10 plants/m^2, but factors determining changes in plant density were not reported. It is therefore necessary to assume a plant density in the simulation experiments of chapter 8. Poor germination and establishment are common characteristics of commercial sorghum crops (Skerman 1978, Radford 1983) and thus models which are used to simulate commercial yields should incorporate factors governing plant density.

Relationships of the grain yield sub-model are likely to be specific to the Mitchell grass plains environment, particularly the relationships of evapotranspiration with grain number and grain size, and the plant density relationship used to define potential grain number per hectare. The maximum grain number observed in the experiments was 177 million grains/ha, whereas, Heslehurst (1982) reports grain numbers of up to 500 million grains/ha in more temperate environments. In contrast to this large difference in grain number, recorded grain sizes were similar to those reported from temperate environments (Bielorai et al. 1964, Plaut et al. 1969, Langlet 1973).

Wright (1982) showed that grain sorghum grown on a clay soil during the winter dry season of tropical Australia gave a twenty percent higher yield when spray irrigated than when furrow irrigated. It was proposed that spray irrigation improved soil nutrient availability. Thus, it is possible that the low grain number observed in the experiments at RSSRP may have been due in part to the crop husbandry methods employed. However, it is also possible that grain number was depressed by the effects of high temperature and consequent rapid rate of phasic development as discussed in the literature review.

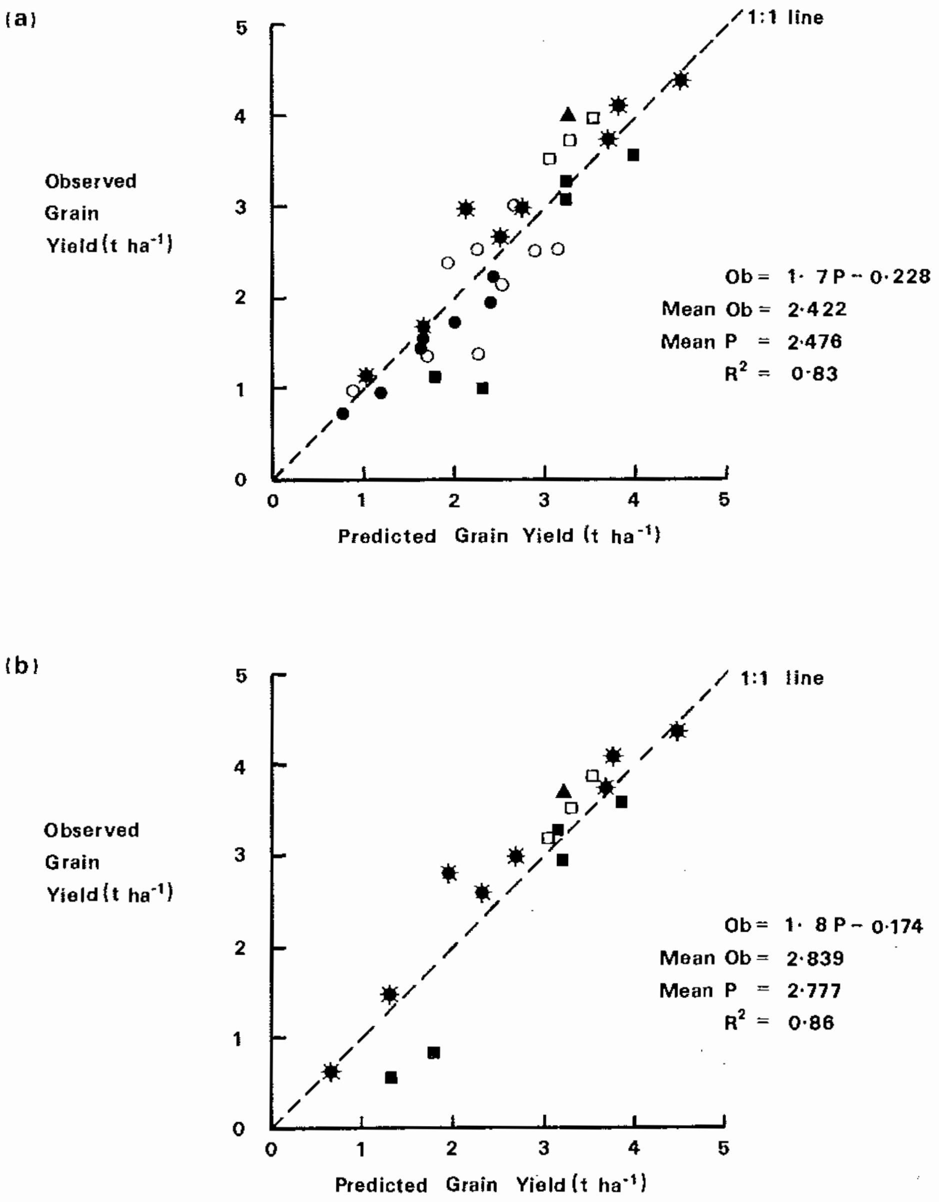


Figure 5.18 Comparison of observed (Ob) hand harvest grain yields to predicted (P) grain yields (a) before lodging losses are deducted, (b) after lodging losses are deducted (● = Exp.1, ○ = Exp.2, ✱ = Exp.5, ■ = Exp.6, □ = Exp.7, △ = Exp.8).

While improvements in grain yield may occur through advances in crop husbandry methods and development of tropically adapted genotypes, it was concluded that the grain yields obtained in the experiments at RSSRP should exemplify yields that are likely to be obtained by commercial enterprises on the Mitchell grass plains using current technology.

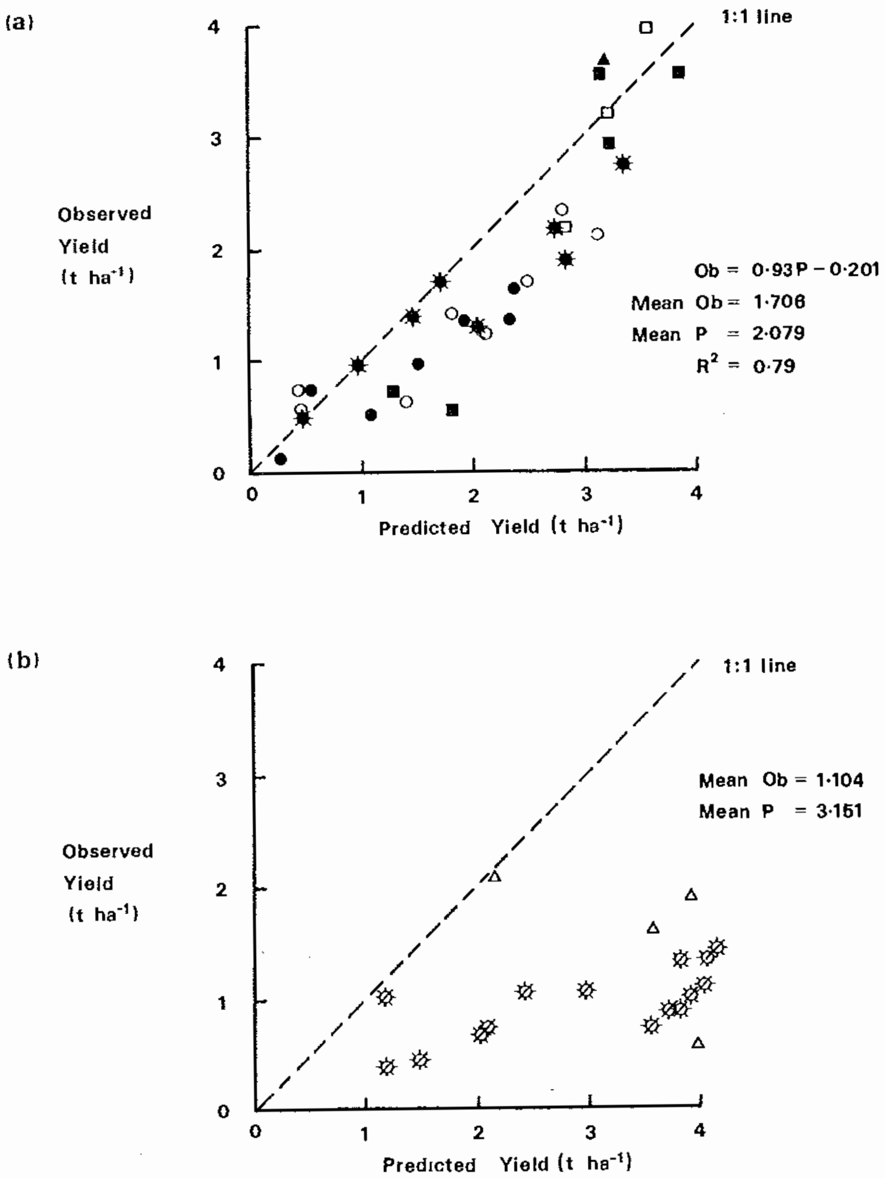


Figure 5.19 Comparison of observed (Ob) header harvest grain yields to predicted (P) grain yields: (a) data from experiments 1,2,5,6,7 and 8, (b) data from experiments 4 and 9 (Symbols are: ● = Exp.1, ○ = Exp.2, ☼ = Exp.4, ✹ = Exp.5, ■ = Exp.6, □ = Exp.7, △ = Exp.8, ▲ = Exp.9).

CHAPTER 6

PONDED-AREA FORAGE SORGHUM PRODUCTION MODEL

6.1 Introduction and Literature Review

The ponded-area of a shallow storage dam is normally planted over a period of time as evaporation and irrigation reduce the level of water in the dam. Planting may take place once every two weeks, and on each occasion planting takes place around the water's edge once the ground has dried sufficiently. Eventually the whole ponded-area is planted with contour shaped strips of crop of differing age. The yield per unit area of each strip may be different because of exposure to different weather conditions. This chapter derives and discusses the model used to predict the production of forage sorghum grown on the ponded-area.

If the ponded-area is divided into n strips on the basis of time of planting, and if ASi and FYi are the area and forage yield respectively of strip i, then the total forage production (FP) of the ponded area is given by:

$$FP = \sum_1^n ASi \times FYi \tag{6.1}$$

The area of each strip depends on rates of evaporation and irrigation, and on the design of the shallow storage dam. The total area of crop planted in each year depends on the area of land inundated by the dam, and thus on seasonal variation in run-off from the catchment as well as the design of the dam. In some years the dam may be only half filled or not filled at all. Forage production is nil in years that run-off does not occur.

The following reasons lead to the conclusion a much simpler model for estimating forage yields from the ponded-area is adequate in comparison to that used to estimate grain yield on the irrigation-area:

(i) Flooding saturates the ponded-area soil, and thus soil moisture at planting can be assumed to be constant.

(ii) The weather is relatively stable during autumn and winter when ponded-area cropping is usually in progress. Variation in temperature from season to season is not great, and rainfall seldom occurs. The probability of rainfall exceeding 100 mm within ten weeks of crops planted at the beginning of April, May and June is only 15, 10 and 6 percent respectively (Clewett 1969).

(iii) The effects of water stress on forage yield are not coupled to the stage of phasic development as is the case in development of grain yield. The water use efficiency for forage growth (i.e. growth per millimetre of water evapotranspired) is independent of phasic development but depends on factors such as leaf area development, temperature and soil fertility as discussed in earlier chapters.

Temporary inundation of the ponded-area creates a very good seed-bed. The previous season's stubble is completely decomposed during flooding so that cultivation before planting is unnecessary. By the time planting occurs a dry surface crust (some 5 mm thick) has formed, but soil moisture under this crust is plentiful for germination of seed. Adequate establishment of crops is not a problem.

Inundation of the ponded-area has the disadvantage of creating anaerobic conditions in the soil. Under water-logged conditions the concentration of some nutrients in the soil solution are increased but others are decreased. Both chemical and microbial reactions are involved. Flooding reduces the soil redox potential so that concentrations of ammonium, phosphorous, iron and manganese increase. However, nitrate ions are reduced to gaseous nitrogen by bacterial denitrification, and sulphate ions are reduced to toxic hydrogen sulphide (Clark and Kemper 1967, Viets 1967).

Aeration of the soil surface occurs at planting, but this layer of soil dries rapidly so that it is not exploited by roots unless rainfall occurs. Hence roots must penetrate the anaerobic, saturated soil below. The ammonium compounds in the saturated soil have only limited availability to plant roots and must be mineralized to nitrate ions after aeration before effective root uptake can take place (Viets 1967). If rainfall occurs after the soil has been dried by evapotranspiration, then a considerable release of accumulated ammonium compounds to nitrate ions could occur.

The next section of this chapter discusses the methods and results of ponded-area field experiments at RSSRP. The following section derives sub-models for estimation of: (i) time and area of planting, (ii) soil water balance, and (iii) forage yield per unit area.

6.2 Field Experiments

The objective of field experiments on the ponded-area of the dam at RSSRP was to determine the potential for crop production from a range of species, and to investigate agronomic methods that could possibly increase yield. The methods and results of experiments that are relevant to this thesis are summarized below. Further details are given elsewhere (Clewett and Weston 1980).

6.2.1 Time of Planting

The effect of time of planting on the dry matter yield of forage sorghum was investigated in the following way. Contour strips of Sudax (*Sorghum* hybrid spp cv. Sudax SX-11A) were planted on the ponded-area on 37 occasions from March 1968 to September 1975. The strips were normally planted in 75 cm rows at 8 kg/ha, and no fertilizer was applied. Dry matter yields at flowering (9 to 12 weeks after planting) were determined by measuring the fresh weight from 3 to 6 sub-plots of 30 m (approximately) by 1.1 m, and then sub-sampling the fresh material for oven drying and determination of dry matter content. The results in table 6.1 have been separated on the basis of year of planting, month of planting and whether or not significant rainfall (greater than 25 mm) occurred between planting and harvest.

Important points in table 6.1 with respect to crops that did not receive significant rainfall after planting are as follows.

(i) Highest yields were recorded in the first year of cropping. The ponded-area was flooded for the first time in February 1968 following construction of the dam in 1967. Substantial decreases in yield were measured in subsequent years.

(ii) Yields were relatively stable during the last three years of cropping, but were on average only 25% of the yields recorded in 1968, and appeared to be deficient in both nitrogen and water.

Table 6.1 Effect of time of planting and rainfall on dry matter yields of ponded-area forage sorghum.

Time of Planting	Dry Matter Yield (kg/ha)					
month/year	1968	1970	1971	1972	1973	1975
March	12455**	–	–	–	–	–
April	9151**	5403*	–	1812*	–	–
May	7143**	5610*	3560*	1781*	2563*	1920*
June	6266*	4963*	2119*	–	1218*	1437*
July	6947*	–	2031*	1143*	2127*	–
August	6634*	–	1445*	–	–	6898**
September	–	–	1550*	–	5874**	4021**
October	–	–	–	–	5983**	–
Mean***	6818	5325	2141	1579	1969	1679

* Cumulative rainfall between planting and harvest was less than 25 mm.

** Cumulative rainfall between planting and harvest was greater than 25 mm (monthly rainfall records are shown in appendix I).

*** Mean for crops receiving less than 25 mm of rain between planting and harvest.

Measurements of soil moisture under crops which did not receive additional rainfall showed that approximately 120 mm of soil moisture were evapotranspired between planting and half bloom. The average water use efficiency from planting to half bloom for crops sown in 1970 was approximately 45 kg/ha of growth per mm of water evapotranspired. Water use efficiency was reduced to approximately 15 kg/ha/mm in 1972, 1973 and 1975.

Monthly means of mean daily temperature in June, July and August ranged from 16.0 to 21.6°C (see appendix A). These temperatures are below the optimum for growth and thus yields were probably restricted during winter, though the data in table 6.1 do not show any clear relationship between yield and month of planting.

Table 6.1 also shows that crops received benefit from rainfall when planted during the spring in 1973 and 1975. Yields were increased 3 to 4 fold, and estimated water use efficiency was increased to approximately 30 kg/ha of growth per mm of water evapotranspired between planting and half bloom.

6.2.2 Fertilizer Experiments

The use of fertilizer to increase forage sorghum yield was investigated in four experiments. Experiment 1 investigated the consequence of deep drilling ammonium nitrate (at 80 kg/ha of N) into the soil before the ponded-area was inundated. Planting occurred as soon as possible after flooding and took place 3 months after placement of the fertilizer. Yield measurements at flowering showed no difference between the fertilized and unfertilized plots. The nitrogen fertilizer was probably lost by denitrification processes during flooding.

Experiment 2 investigated the effect of nitrogen fertilizer on the yield of Sudax forage sorghum under irrigated and non irrigated conditions. The object of irrigation was to supply sufficient water to increase the availability of nutrients without greatly increasing the amount of water available for transpiration. The nitrogen treatments were 0, 100 and 300 kg/ha of N applied at planting on 11 May 1973. Half of the plots were given one spray irrigation (of approximately 25 mm depth) 31 days after planting. No other irrigations were applied and no rain fell from planting to harvest. All treatments were replicated four times in a factorial randomized block design.

The dry matter yields that were recorded 83 days after planting at half bloom are shown in table 6.2. The most important aspect of the data in this table is that nitrogen fertilizer did not increase yield unless irrigation was applied. Irrigation alone did not increase yield. All treatments appeared water stressed at harvest.

The type of investigation described for Experiment 2 was repeated in Experiment 3 and similar results were observed.

It was concluded that fertilizer applied at planting remains unavailable to plant roots in the dry surface layer of soil unless rainfall or irrigation occur.

Table 6.2 Effect of nitrogen fertilizer and irrigation on dry matter yields of forage sorghum in experiment 2.

Treatment		Dry Matter Yield
Nitrogen (kg/ha)	Depth of Irrigation (mm)	* (kg/ha)
0	0	2563
100	0	2275
300	0	2675
0	25	2663
100	25	3686
300	25	4025

* Least significant difference at P.05 = 1012 kg/ha.

Experiment 4 investigated the effect of the following fertilizers on the yield of forage sorghum in a 2^4 factorial design with two replicates: nitrogen at 150 kg/ha of N, phosphorous at 50 kg/ha of P, sulphur at 40 kg/ha of S and a group of micro-nutrients (15 kg/ha of Mn, 15 kg/ha of Cu, 15 kg/ha of Zn and 4 kg/ha of B). The experiment was sown on 17 September 1975. Nutrient availability was insured by 68 mm of rainfall 4 weeks after planting, and an irrigation of 50 mm applied 8 weeks after planting. Dry matter yield, nitrogen percent and phosphorous percent were measured during late anthesis (78 days after planting).

The mean yield of the control treatment (i.e. nil fertilizer) was 6025 kg/ha. The mean effect of each of the fertilizer treatments on yield, nitrogen percent and phosphorous percent are shown in table 6.3. This table shows that the micro-nutrient and sulphur treatments had no effect on yield, but that nitrogen and phosphorous increased yield by 979 and 649 kg/ha respectively. The effects of nitrogen and phosphorous on yield were additive. Application of nitrogen increased the quality of forage by increasing nitrogen percent, whereas phosphorous application decreased nitrogen percent. Phosphorous percent was not altered by any treatment.

The yield of the control treatment in this experiment was approximately three times the expected yield of ponded-area crops not receiving rainfall or irrigation. The control treatment grew vigorously, was dark green in colour and appeared to be without symptoms of nutrient deficiency. It is possible that all treatments benefited from substantial mineralization of accumulated ammonium nitrogen to nitrate nitrogen following rainfall and irrigation. This effect would mask any yield response in the plus nitrogen treatments.

6.2.3 Other Ponded-Area Experiments

Comparison of ponded-area soils to those outside the ponded-area showed that annual flooding by the dam had a slight leaching, and thus beneficial effect on salt levels. However, an 8% increase in aggregate bulk density from 1.67 to 1.81 g/cc was found after the ponded-area had been flooded and cropped for five years (Denning and Bell 1974). This increase would decrease the range of soil moisture available to plants, and would increase soil resistance to penetration by plant roots.

Table 6.3 Factorial effects of fertilizer treatments on the yield, nitrogen content and phosphorous content of forage sorghum observed in experiment 4.

Treatment	Dry Matter Yield (kg/ha)	Nitrogen* (% DM)	Phosphorous* (% DM)
minus nitrogen	6330	1.07	.14
plus nitrogen	7309	1.55	.14
minus phosphorous	6494	1.36	.14
plus phosphorous	7143	1.26	.14
minus sulphur	6691	1.28	.14
plus sulphur	6946	1.34	.14
minus micro-nutrients	6971	1.32	.14
plus micro-nutrients	6666	1.30	.14
Least significant difference at P.05	671	0.10	0.01

* Nitrogen and phosphorous contents given as percent of dry matter.

The growth of Pearl millet (*Pennisetum typhoides* cv. Katherine Pearl) and Sudax forage sorghum were compared in an experiment in 1972. In the case of millet a dense mat of roots was observed at the base of the cultivation layer with very few roots penetrating lower layers. It appeared incapable of exploiting the soil moisture reserves of lower layers. Forage sorghum did not appear to have this problem, but detailed observations on fine roots were not made, and it is possible that sorghum roots were also restricted. The dry matter yields of millet and forage sorghum in this experiment were 685 and 1660 kg/ha respectively.

6.2.4 Conclusions

It was concluded that the major factor affecting the growth of ponded-area crops was limited availability of soil moisture. Nitrogen deficiency was identified as a factor restricting yield but its correction with fertilizer is difficult because rainfall to mobilize fertilizer placed in the surface soil is highly unlikely. Use of irrigation water to mobilize nitrogen would be possible but perhaps less preferable than its use on the irrigation-area.

Compaction of ponded-area soils may have contributed to the observed decline in forage yields between 1968 and 1972, partly by decreasing the range of available moisture, partly by increasing soil resistance to root penetration and partly by restricting aeration after flooding.

No agronomic practices (apart from irrigation) were found that would restore yields to the high levels observed in the first two years of cropping. Thus, the lower yields observed in 1972, 73 and 75 are thought to exemplify the long-term productivity of the ponded-area.

6.3 Time and Area of Planting Sub-Model

The water storage model in chapter 4 described the surface area of water stored in a shallow storage dam as half an ellipse, and the volume of water storage as half an inverted elliptical cone. Thus, the surface area of water was proportional to the square of the height of water in the dam (equation 4.2).

Because the length and width of shallow storage dams are very large in comparison to their height the assumption was made that the area of land flooded was equal to the surface area of water storage.

The area of land flooded by a shallow storage dam varies from year to year depending on catchment run-off. The area of land flooded in any year is given from equation 4.2 by:

$$AF = 3p\ Hmax^2/10000 \qquad (6.2)$$

where AF = Area of land flooded (ha), and Hmax = Maximum height of water in dam during year (m).

The perimeter of the ponded-area at RSSRP was found to be unsuitable for cropping because weeds proliferated where the depth of flooding was very shallow. Conditions required for planting on the ponded-area were not created unless the depth of flooding exceeded 15 cm approximately. Because of this requirement, the total area of land planted on the ponded-area was less than AF.

Planting on the ponded-area was simulated to begin in each season when evaporation and irrigation had reduced the water level in the dam by more than 15 cm below Hmax. The area of the first strip of crop planted was calculated from:

$$AS_i = (3p(Hmax-0.15)^2 - 3p\ H_1^2)/10000 \qquad (6.3)$$

where AS_i = Area of strip 1 (ha), and H_1 = Height of dam (m) when planting of strip 1 is simulated.

The planting of subsequent strips was simulated when the water level in the dam fell by a further 15 cm. Thus the area of strip i was calculated by:

$$AS_i = 3p(H_{i-1}^2 - H_i^2)/10000 \qquad (6.4)$$

where H_i and H_{i-1} = Height of water in dam at planting of strips i and i-1 respectively.

Conditions for planting were checked at the end of each fortnight during simulation. If the simulated level of water in the dam rose because of catchment run-off so that ponded-area crops were flooded, then the area of cropping was reduced by the area of land affected. This land was replanted as evaporation and irrigation subsequently reduced the dam's water level.

6.4 Soil Water Balance Sub-Model

The soil water balance for each strip of crop grown on the ponded-area was estimated independently. The flow chart in figure 6.1 shows that the soil water balance of each strip was simplified to a single soil store, with rainfall and infiltration of water from the dam as inputs, and with losses from evapotranspiration and run-off.

Infiltration of water from the dam was considered to recharge soil moisture to capacity, and to occur only when the soil surface was flooded by the dam. No lateral movement of water below the soil surface was considered. Infiltration from rainfall was considered to occur instantaneously until the soil store was recharged to capacity. Deep drainage was considered not to occur, and thus all rainfall in excess of the amount required to recharge the soil store to capacity was disposed as run-off. This run-off, which will go to the dam, is a negligably small component of the water balance of the dam, and was thus neglected. The rate of evapotranspiration was estimated as a function of soil moisture storage, evaporative demand and crop cover.

The following water balance equation was used to estimate changes in the depth of soil water storage as time (t) progressed from day t_1 to day t_2.

$$S_{t_2} = S_{t_1} + \sum_{t_1}^{t_2}(-ET + ID + R - Q) \qquad (6.5)$$

where S_{t_1} = Equivalent ponded depth of soil moisture (mm) at 9 am on day t_1, S_{t_2} = Equivalent ponded depth of soil moisture (mm) at 9 am on day t_2, ET = Rate of evapotranspiration (mm/day), ID = Rate of infiltration from dam (mm /day), R = Rate of rainfall (mm/day), and Q = Rate of run-off (mm/day).

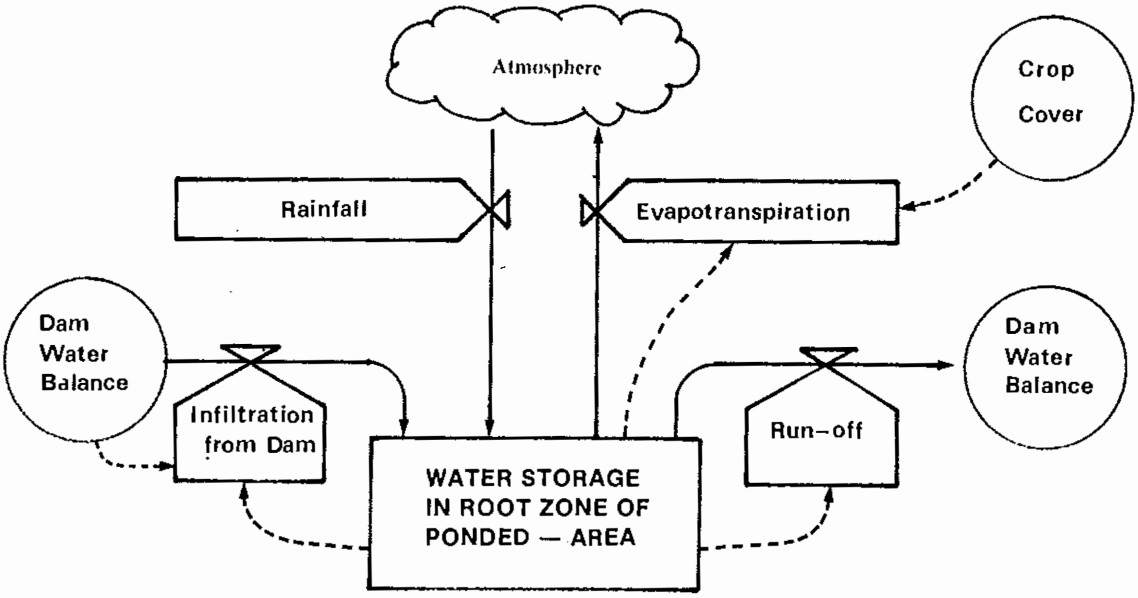


Figure 6.1 Flow chart of ponded-area soil water balance. Forrester (1962) flow chart symbols show: sources and sinks as clouds, level variables as boxes, rate variables as valves, exogenous variables as circles, material flows as solid arrows and information flows as broken arrows.

Change in soil water storage was estimated on a daily basis if daily rainfall exceeded 3 mm, otherwise it was calculated at the end of each fortnight. The event stepping procedures given in chapter 5 were used to estimate evapotranspiration.

A single soil moisture store was used to simulate changes in soil moisture from the soil surface to a depth of 150 cm. The minimum and maximum water storage capacity of the soil to 150 cm were estimated to be 283 and 520 mm respectively. The store was set at 15 mm less than capacity at planting to account for water loss between the cessation of flooding and planting.

The equations used in the event stepping procedures to estimate soil moisture at time t from cumulative evaporative demand for bare soil and full cover conditions as in equations 5.20 and 5.21 were:

(i) for bare soil:

$$S = 520 - 0.541\ \mathrm{SEo} \qquad (S \geq 490.7\ \mathrm{mm}) \qquad (6.6)$$

$$S = 607.6 - 29.28\ \ln(\mathrm{SEo}) \qquad (S < 490.7\ \mathrm{mm}) \qquad (6.7)$$

(ii) for full cover:

$$S = 520 - 1.408\ \mathrm{SEo} \qquad (S \geq 461.6\ \mathrm{mm}) \qquad (6.8)$$

$$S = 675.9 - 58.45\ \ln(\mathrm{SEo}) \qquad (S < 461.6\ \mathrm{mm}) \qquad (6.9)$$

These equations were derived by assuming: (i) the rate of bare soil evaporation on the ponded-area was equivalent to the rate found for the irrigation-area, (ii) the maximum rate of evapotranspiration from crops with full cover was the same as found for the irrigation-area, and (iii) the value of SEo found to reduce soil water storage on the irrigation-area to its minimum value also applies to the ponded-area.

Changes in the crop cover index (CI) used in equation 5.27 were estimated as a function of time as follows:

$$\mathrm{CI} = \exp((\min(t,8)-8)^2(-30.44)) \qquad (6.10)$$

where t = time (weeks after planting).

6.5 Forage Yield Sub-Model

Changes in dry matter yield per unit area of each strip of forage grown on the ponded-area were calculated at the end of each fortnight by:

$$(\mathrm{FY}_i)_f = (\mathrm{FY}_i)_{f-1} + (\mathrm{G}_i)_f \qquad (6.11)$$

where $(\mathrm{FY}_i)_f$ = Forage dry matter yield (kg/ha) of strip i at the end of fortnight f, and $(\mathrm{G}_i)_f$ = Growth (kg/ha) of strip i during fortnight f.

The subscripts i and f are implied in the following discussion but are not shown for simplicity.

Growth during each fortnight was calculated from cumulative evapotranspiration (estimated by the water balance sub-model) and water use efficiency as follows:

$$\mathrm{G} = \mathrm{WUE} \times \sum \mathrm{ET} \qquad (6.12)$$

where WUE = Water use efficiency (kg/ha/mm), and $\sum$ET = Cumulative evapotranspiration (mm) for fortnight f.

The maximum value of water use efficiency was estimated from the field experiments to be approximately 50 kg/ha/mm. This value was therefore used in equation 6.12 but was reduced by indices for crop cover (CI), temperature (TI) and nitrogen availability (NI) when these were below optimum levels. The range of these indices was 0.0 (complete limitation to growth) to 1.0 (no limitation to growth). The equation used to calculate WUE was based on the hypothesis that each variable in the environment may limit growth independently of other variables and was taken to be as follows:

$$\mathrm{WUE} = 50 \times \mathrm{CI} \times \mathrm{TI} \times \mathrm{NI} \quad (\mathrm{kg/ha/mm}) \qquad (6.13)$$

The crop cover index was calculated by equation 6.10 given in the water balance sub-model.

The temperature index was calculated from mean daily temperature as follows:

$$TI = \exp(-(\min(T,27)-27)^2/100) \quad (6.14)$$

where T = Mean daily temperature (°C) = (Tmax+Tmin)/2, Tmax = Monthly mean of maximum daily temperature at screen height (°C), and Tmin = Monthly mean of minimum daily temperature at screen height (°C).

This function is very similar to relationship used in the sorghum model of Arkin et al. (1976) to regulate leaf expansion and net photosynthesis.

The field experiments showed that growth of forage sorghum on the ponded-area was limited by nitrogen availability, but that nitrogen fertilizer applied at planting would not increase yield unless subsequent rainfall or irrigation occurred. It was hypothesized that rainfall after planting led to mineralization of native soil nitrogen and that this increased water use efficiency. This regime was modelled by setting the nitrogen index (NI) to 0.6 at planting and increasing the index by 0.004 per millimetre of rainfall after planting up to a maximum of 50 mm. These values gave good agreement between simulated dry matter yields after 10 weeks growth and the experimental data recorded at flowering in the years 1972, 1973 and 1975 (see figure 6.2). Therefore the model was adopted for use in the simulation experiments described in chapter 8.

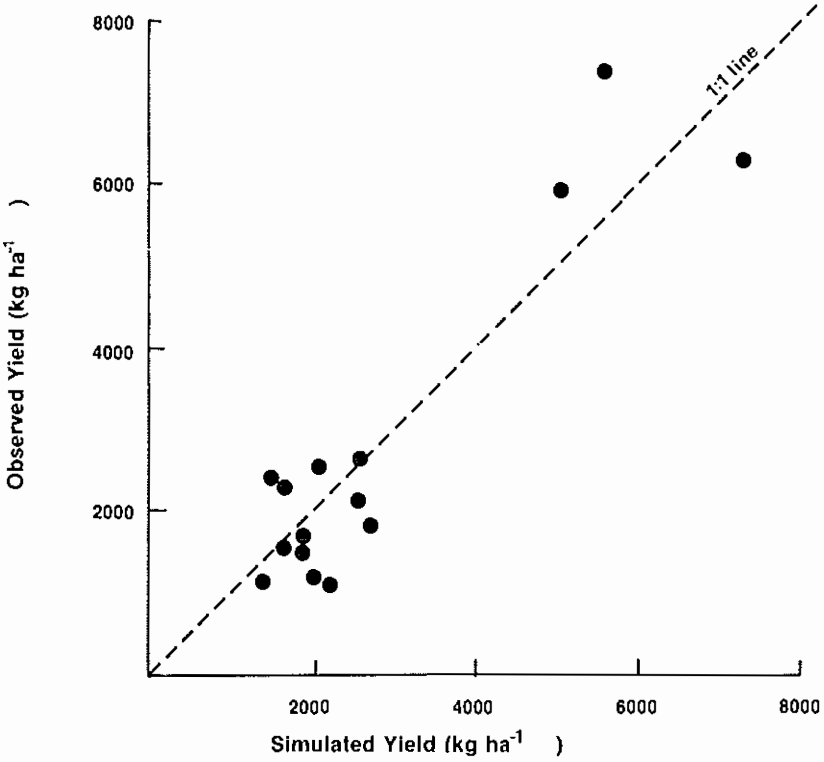


Figure 6.2 Comparison of dry matter yields of ponded-area forage sorghum observed at flowering to yields predicted by simulation after 10 weeks growth.

CHAPTER 7

ECONOMIC MODEL

Introduction

The aim of the economic model was to provide criteria upon which shallow storage designs and management strategies which could be ranked in order of economic efficiency.

The economic model partitions costs of shallow storage irrigation into fixed and operating costs. The fixed costs were those which apply to the design of the system and were charged annually irrespective of farm management. Operating costs accrue from implementation of farm management operations such as planting, irrigation and harvesting.

Annual profit was calculated by subtracting costs from income. Income was calculated on the total tonnage of crop production with grain valued at \$80/t and forage at \$65/t.

7.1 Water Storage and Irrigation Fixed Costs

The annual fixed costs for interest, depreciation, repairs and maintenance charged to the irrigation-area for water storage construction and irrigation-area development are shown in table 7.1. Crop production from the ponded-area was regarded as a bonus to the system, and therefore the only fixed cost charged to ponded-area crop production was the cost of fencing.

The cost of constructing the dam wall was calculated by multiplying the unit cost of earth moving by the volume of earth in the dam wall (given by equation 4.7 in chapter 4), and then adding the cost of a drop-inlet. A drop-inlet is a necessary item, as it serves to reduce bywash erosion (Clewett and Weston 1980) and release water for use in irrigation.

The fixed costs for development of the irrigation-area were: (i) construction of irrigation supply and head ditch channels, (ii) purchase of polythene piping for syphons, and (iii) erection of fencing.

7.2 Farm Machinery Fixed Costs

Ownership sharing arrangements, contract farming, price fluctuations and availability of new, second-hand and existing equipment create many alternatives in farm machinery cost accounting. The alternative adopted here assumed purchase of a tractor, disc-plough, chisel-plough and combine with harrows, and with harvesting equipment hired as required.

Table 7.1 Water storage and irrigation-area fixed costs

Item	Capital Cost (\$)	Annual Fixed Costs (% capital cost)		
		Interest	Depreciation	Maintenance
Dam Wall (per m^3)	0.60	12	3	2
Drop-inlet	2000	12	3	2
Irrigation channels*	7.50	12	5	**
Irrigation syphons*	4.18	12	2	3
Fencing (per km)	400	12	3	2

* Calculated per hectare of the irrigation-area.

** Irrigation channel maintenance was calculated as an operating cost.

Planting must occur rapidly after rain, and therefore purchase of equipment for this operation is essential. Since there is considerable time to plan the harvesting operation, and because harvesting equipment is expensive, the hiring of equipment for harvest is a satisfactory alternative.

Tractor size was calculated on the minimum engine power required to completely plant the irrigation-area in 60 hours. It was assumed, after Blomfield (1978), that the rate of planting was 0.56 ha/hr per metre of combine, and that 16 KW of tractor engine power was required per metre of combine. Minimum tractor power was 40 KW. A limit of 60 hours was placed on the planting operation because data from RSSRP showed the need to plant rapidly after rain to avoid poor germination and establishment (Clewett and Weston 1980). Tractor power requirements for tillage and planting shown in table 7.2 were used to establish the width of equipment for these operations. It was assumed that a continuous range of machinery was available for purchase.

Values for ownership and operating costs of farm machinery used in the model were those published by the Economic Services Branch of the Queensland Department of Primary Industries based on average prices in 1977 (Blomfield 1978). Interest on farm implements was charged as a fixed cost (see table 7.2).

7.3 Operating Costs

Because a tractor can be used for many purposes on a farm (fencing, maintenance of stock water supplies, drought feeding) the cost accounting for the tractor was based on hourly operation. This charge included fuel, oil, repairs, maintenance, depreciation, interest and labour. The data of Blomfield (1978) was used to derive a linear relationship between hourly tractor operating costs (TOC, \$/hr) and engine power (KW, in kilowatts)

$$TOC = 0.0921 \times KW + 3.375 \qquad (7.1)$$

Other operating costs used in the model were:

(i) depreciation, repairs and maintenance on farm implements per hour of usage (see table 7.2),

Table 7.2 Farm machinery work rates, tractor power requirements, life expectancy and costs.

	Disc Plough	Sweep Plough	Combine with Harrows
Work rate (ha/hr/m)*	0.60	0.64	0.56
Tractor power required (engine KW/m)*	25	16	16
Expected life (hr)	2500	2500	1200
Capital cost (\$/m)*	1512	1131	1506
Life-time repairs and maintenance (% of capital cost)	120	120	100
Fixed Costs			
Annual interest at 12% of capital cost (\$/m)*	181.4	135.7	180.7
Operating Costs			
Repairs and Maintenance (\$/hr/m)*	.727	.543	1.255
Depreciation (\$/h/m)*	.544	.407	1.130

* Values are shown per meter width of implement. Source: Blomfield (1978)

(ii) contract grain and forage harvesting (see table 7.3),
(iii) grain sorghum seed (5 kg/ha at $1.25/kg),
(iv) forage sorghum seed (8 kg/ha at $0.88/kg),
(v) application of irrigation water at $3.87/ha per irrigation for labour and transport, and
(vi) maintenance of irrigation channels at $4/ha.

The economic model was combined with the four models describing the physical components of the system to calculate the net profit from grain and forage sorghum production.

Table 7.3 Contract Harvesting Costs.

Self propelled grain harvester	29.80	$/ha
Carting and storing grain	2.50	$/t
Mower conditioner	8.82	$/ha
Hay baler	1.20	$/t
Carting and storing hay	4.00	$/t
Forage harvesting	10.92	$/ha

CHAPTER 8

SIMULATION EXPERIMENTS

Introduction

Expected levels of crop production from shallow storage systems were investigated through a number of computer simulation experiments. This involved integration of the component models described in previous chapters to form a single mathematical model of the system. The system was driven during simulation by a long period (60 years) of meteorological records.

The experiments were conducted to investigate the effects of climatic variability, irrigation strategy, planting strategy and shallow storage design on catchment run-off, water supply, irrigated grain sorghum production, ponded-area forage sorghum production and the economics of production.

The effect of climatic variability on the performance of shallow storage systems was investigated in Experiment 1 by simulating the physical characteristics of the water storage at RSSRP with a set of management decision rules that were recommended prior to this study.

The effects of irrigation strategy on grain production from the irrigation-area were investigated in Experiments 2, 3 and 4. The term 'irrigation strategy' is used in these experiments not only to specify a schedule for the timing and frequency of irrigation, but also a set of decision rules which alter the timing, frequency and fraction of the irrigation-area that is watered in response to climatic conditions and simulated water supply and soil moisture status.

The term 'planting strategy' is used to specify a set of management decision rules based on environmental conditions to determine time of planting on the irrigation-area. Experiment 5 investigates antecedent soil moisture conditions on the irrigation-area and catchment run-off conditions as criteria effecting the decision rules for planting strategy.

The effects of shallow storage design on attributes of crop production were investigated in Experiment 6 by changing four parameters of the design. They were catchment area of the water storage, stream gradient at the dam site, water storage capacity and size of the irrigation-area.

8.1 Experiment 1: Effects of Climatic Variability on Water Supplies and Crop Production.

8.1.1 Introduction

The first objective of this experiment was to define the effect of climatic variability, as indicated by long-term climatic records, upon the performance of a shallow storage system. The second objective was to form a base from which subsequent experiments could be designed.

The shallow storage design parameters chosen for this experiment were defined by the physical characteristics of the dam at RSSRP, and the management strategies were those recommended by Weston (1972) and used by Weggoner and Weston (1973) in their preliminary economic analysis of shallow storage irrigation. These management strategies were adopted because they form the basis of current recommendations to farmers. Weston recommended that grain sorghum should not be planted on the irrigation-area before catchment run-off filled or partially filled the water storage, so that the risk of crop failure was minimized. His recommendation for irrigation was to apply one irrigation shortly before half bloom.

8.1.2 Simulation Methods

Most of the detail describing simulation methods given in this sub-section will also be applicable to subsequent experiments, and will not be repeated.

Historic meteorological data from the Richmond Post Office were used to drive the mathematical model through the sixty year period from 1 October 1918 to 30 September 1978. The records of daily rainfall, monthly maximum temperature and monthly minimum temperature, together with monthly estimates of evaporative demand calculated by the method of Fitzpatrick (1968) are given in Appendix A.

Initial Values. Values of soil water status and water storage required to initiate the simulation were established by running the model over the 60 year simulation period, and then calculating mean values at the end of each climatic year (30 September) in those years that were climatically similar to 1918. This method is justified because monthly rainfall data prior to October 1918 shows that 1918 was climatically typical of the region with 746 mm of rain in the preceding wet season, and no rain for the period May to September. Initial values of soil moisture found by this method were 6.2, 20.9 and 109.3 mm for the surface, sub-surface and sub-soil layers of the catchment water balance sub-model, and 7.5, 25.0 and 125.0 mm for the same layers in the irrigation-area water balance sub-model. The water storage in the dam was zero at this time.

Initial values used for grass and litter yields in the catchment pasture biomass sub-model were 1040 and 330 kg/ha respectively. These values were estimated using the catchment water balance and pasture biomass sub-models with monthly data for the four years preceding October 1918.

Design Parameters. The shallow storage design parameters were: catchment area of water storage = 1660 ha, water storage capacity = 400 ML, stream gradient of dam site = 1 : 977, and size of irrigation-area = 40 ha.

Some design parameters calculated from these parameters by the water storage model were: maximum depth of water storage = 2.0 m, maximum length of dam = 1954 m, maximum width of dam = 391 m, maximum surface area of dam = 60 ha, and maximum size of ponded-area = 51 ha.

Some economic parameters calculated by the economic model from the above set of design parameters were: annual fixed costs for water storage and irrigation = $30.65/ha, annual fixed costs for farm machinery and fencing = $31.80/ha.

Planting Strategy. The following set of decision rules were applied in each year of simulation to determine time of planting of grain sorghum on the irrigation-area:

(i) Planting was delayed until the third day without rain following the first run-off event from the catchment which exceeded 4 mm.

(ii) Planting was postponed until further rainfall occurred if the above run-off condition occurred prior to the month of December.

(iii) Planting was abandoned for the season if the above run-off condition did not occur before the 1st April. This condition was applied because experiments reported in chapter 5 showed that grain sorghum planted after March had very slow growth rates and that the risk of frost damage was high.

This set of rules requires land to be prepared for planting in every year because ploughing must be done before the wet season. The estimated cost of this operation (two ploughings) was $15.50/ha per annum.

Since the grain sorghum yield model does not calculate establishment rates, a plant density of 100 000 plants/ha was assumed in all experiments. This density assumes a reasonable level of farming efficiency and gives a potential grain number of 156 million grains/ha and a maximum yield of 4267 kg/ha.

In all experiments the strategy used to simulate planting of forage sorghum on the ponded-area was as described in chapter 6.

Irrigation Strategy. The following set of decision rules were used to schedule irrigation.

(i) A single irrigation strategy of one irrigation was scheduled midway between booting and half bloom (i.e. 55 standard days after planting at the heading stage of crop development).

(ii) Irrigation was delayed if estimates of soil moisture in the 0-90 cm soil profile of the irrigation-area exceeded 60% of the available soil moisture range.

(iii) Irrigation was delayed if estimates of water storage in the dam were less than 5 ML, and cancelled if irrigation had not been applied by the end of grain filling (84 standard days after planting).

(iv) If water storage in the dam was less than that required to irrigate all of the irrigation-area, then the area of irrigation was reduced in accordance with the availability of water.

It is important to note the different sense in which the terms 'irrigation-area' and 'area of irrigation' are used. The area of irrigation varies from year to year depending on seasonal conditions. If the volume of water in the dam is less than that required to irrigate all of the irrigation-area, then the area of irrigation must obviously be less than the size of the irrigation-area. However, if water storage is greater than that required to irrigate all of the irrigation-area, then the area of irrigation can be equal to, but not greater than the size of the irrigation-area.

In order to isolate the effects of climatic variability from that of irrigation on grain yield, a second simulation (denoted treatment 2) of sixty years was conducted without irrigation.

Computing. A Digital PDP-10 computer was used for calculations with the source program written in FORTRAN. This program is shown in Appendix B. Computing time for each simulation of sixty years was approximately 16 seconds (CPU time) and cost $1.93 (approximately). The event stepping procedures used for the irrigation-area and ponded-area water balance sub-models were found to reduce computing costs by a factor of 5.

8.1.3 Simulation Results

The results of simulation are given in the following sequence: catchment run-off, frequency of cropping, water supply, irrigated grain sorghum yield, irrigated grain sorghum production, ponded-area forage sorghum production, and economics of production. While a computer printout of simulation results is shown in Appendix C, the results are also given below in the more easily assimilated form of figures and tables.

Catchment Run-off. Appendix C table C2 shows the depth of daily run-off for the period 1 October 1918 to 30 September 1978 for each day that run-off was estimated to have exceeded 0.5 mm; table 8.1 shows cumulative run-off for each month and year during this period. The characteristics of catchment run-off given below were calculated from this data.

Run-off was a relatively rare event, and did not occur in 32% of years during the 60 year simulation. Run-off occurred on more than 3 days per year in 20% of years, and on more than 5 days per year in 7% of years. Consecutive years without run-off occurred 4 times. The longest period without run-off was estimated to be almost four years from 10 January 1957 to 27th December 1960.

Fifty percent of daily run-off events were equal to or less than 7 mm, and ten percent of run-off events equalled or exceeded 38 mm. The maximum daily run-off was estimated to be 89 mm.

Eighty four percent of run-off events were found to occur in the months January to March, and February was found to have the highest expectancy of run-off (see table 8.1). Run-off was estimated to have occurred on only one occasion in the months June to October (1 mm on 5 July 1936).

Mean annual run-off was 35.1 mm, however, this depth of run-off was exceeded in only 30% of years. The median annual run-off was 5 mm. When cumulative percent frequency of annual run-off was plotted against the log of annual run-off the relationship was found to be linear (see figure 8.1). The relationship was:

$$FQ = 29.6 + 29.65 \log Qa \quad \text{for } Qa > 1 \text{ mm} \qquad (8.1)$$

where FQ = Cumulative percent frequency of annual run-off (%), and Qa = Estimated annual run-off (mm).

This finding was used to divide annual run-off into 7 frequency classes. The upper bounds of classes 2 to 6 were increased logarithmically as follows: 4, 10, 25, 62 and 156 mm. Class 1 included all years in which run-off was zero and class 7 included all years in which run-off exceeded 156 mm. Classes 1 and 2 included all years in which run-off was inadequate as a source of water for irrigated cropping as defined by the planting strategy decision rules. The upper limit of class 4 (i.e. 25 mm) is equal to the depth of run-off required to fill the dam at RSSRP.

Table 8.1 Estimated monthly run-off (mm) from Mitchell grass catchment, October 1918 to September 1978

Year	O	N	D	J	F	M	A	M	J	J	A	S	Total	Days
1919	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1920	-	-	-	1	-	-	-	6	-	-	-	-	7	2
1921	-	-	-	-	-	-	3	-	-	-	-	-	3	1
1922	-	-	-	-	5	-	-	-	-	-	-	-	5	1
1923	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1924	-	-	-	-	34	30	-	-	-	-	-	-	64	4
1925	-	-	-	-	-	3	-	-	-	-	-	-	3	1
1926	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1927	-	-	-	-	55	4	-	-	-	-	-	-	59	5
1928	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1929	-	-	-	2	-	-	-	-	-	-	-	-	2	1
1930	-	-	-	-	1	-	-	1	-	-	-	-	2	2
1931	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1932	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1933	-	-	-	-	6	-	-	-	-	-	-	-	6	3
1934	-	-	-	-	14	-	-	-	-	-	-	-	14	2
1935	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1936	-	-	-	-	-	6	-	-	-	1	-	-	7	2
1937	-	-	-	-	-	4	-	-	-	-	-	-	4	1
1938	-	-	-	-	6	-	-	-	-	-	-	-	6	1
1939	-	-	-	-	2	-	-	-	-	-	-	-	2	1
1940	-	-	-	-	136	19	-	-	-	-	-	-	155	8
1941	-	-	-	44	55	-	-	-	-	-	-	-	99	5
1942	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1943	-	-	2	-	-	-	-	-	-	-	-	-	2	1
1944	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1945	-	-	-	-	-	22	-	-	-	-	-	-	22	2
1946	-	-	-	3	2	-	-	-	-	-	-	-	5	3
1947	-	-	-	-	-	1	-	-	-	-	-	-	1	1
1948	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1949	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1950	-	-	-	-	41	62	65	-	-	-	-	-	168	13
1951	-	-	5	97	-	-	-	-	-	-	-	-	102	4
1952	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1953	-	-	-	-	48	-	-	-	-	-	-	-	48	3
1954	-	-	-	-	45	87	-	-	-	-	-	-	132	5
1955	-	-	-	-	18	26	-	35	-	-	-	-	79	6
1956	-	-	-	-	41	-	-	-	-	-	-	-	41	2
1957	-	-	97	9	-	-	-	-	-	-	-	-	106	4
1958	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1959	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1960	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1961	-	-	11	34	-	-	-	-	-	-	-	-	45	3
1962	-	-	-	3	-	-	-	-	-	-	-	-	3	1
1963	-	-	-	-	-	9	12	-	-	-	-	-	21	4
1964	-	-	-	-	5	-	-	-	-	-	-	-	5	2
1965	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1966	-	-	-	14	-	-	-	-	-	-	-	-	14	3
1967	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1968	-	-	-	-	32	-	-	-	-	-	-	-	32	1
1969	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	-	-	20	-	-	-	-	-	-	-	20	1
1971	-	-	-	-	-	94	90	-	-	-	-	-	174	6
1972	-	-	-	1	-	60	-	-	-	-	-	-	61	4
1973	-	-	-	-	1	73	-	-	-	-	-	-	74	3
1974	-	2	-	333	36	-	-	-	-	-	-	-	371	20
1975	-	-	-	18	26	-	-	-	-	-	-	-	44	3
1976	-	-	-	-	41	-	-	-	-	-	-	-	41	4
1977	-	-	15	-	-	-	-	-	-	-	-	-	15	1
1978	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mean	0	0	2	9	11	8	3	1	0	0	0	0	35.1	2.4

The frequency of annual run-off in each of the above frequency classes is shown in table 8.2 for each of the six decades from 1 October 1918 to 30 September 1978. This table shows: (i) years of zero run-off were evenly distributed among the decades, and (ii) the frequency of run-off in classes 2 to 6 were approximately equal when summed over the six decades. However, very large differences occurred between decades. In the first three decades the estimated annual run-off would have not been sufficient for irrigation in 60% of years, and in one decade the depth of annual run-off would have not been sufficient to fill the dam at RSSRP in any year. In contrast, annual run-off in two of the last three decades exceeded the depth of run-off required to fill the dam at RSSRP in 60% of years, and in one decade run-off exceeded two and a half times storage capacity in 50% of years.

Frequency of Cropping. Grain production from the irrigation-area was simulated to occur in only 29 years of the 60 year simulation period (48% of years), planting conditions not being satisfied in the remaining 31 years. Run-off occurred too late in three cases and did not exceed 4 mm in 28 cases. The 95% confidence interval for percent frequency of cropping from 60 years of data is equal to 29 x 100/60 ± 13 (i.e. 35 to 61% of years).

Ponded-area cropping was simulated in 32 years of the simulation period. The three years that run-off occurred too late for irrigated grain production were suitable for forage cropping on the ponded area.

Time of Planting. The most frequent month of planting on the irrigation-area was February. In the 60 years of simulation, three crops were planted in December and January, 19 crops in February, and four crops in March (see Appendix C table C2). Whilst the mean percent frequency for cropping in any year was 48%, the relative frequencies for planting before and after February were only 10 and 7% respectively.

Planting on the ponded-area usually commenced in March or April and normally occurred on 2 or 3 occasions over a period of six weeks.

Water Supply. In years of cropping the volume of water stored in the dam at the time of irrigation exceeded the requirement of crops on the irrigation-area in 79% of years. While the average demand of the 40 ha irrigation-area was 41 ML the average supply available at the time of irrigation was 187 ML or sufficient to irrigate 107 ha. Thus, expansion of the irrigation-area should lead to a considerable increase in water use efficiency.

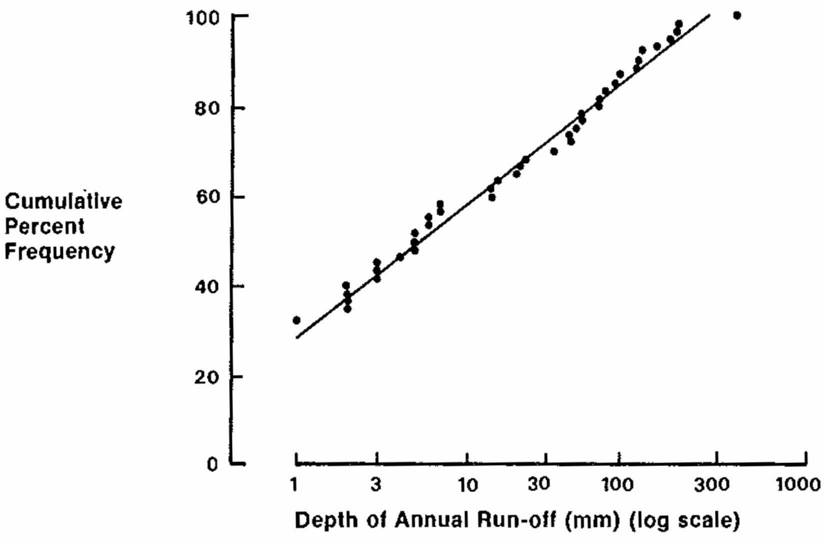


Figure 8.1 Cumulative percent frequency of estimated annual run-off from Mitchell grass catchment (Run-off was estimated to be zero in 32% of years).

Table 8.2 Mean annual run-off and frequency distributions of annual run-off from the Mitchell grass catchment in the six decades from October 1918 to September 1978.

		Decade						Sixty years Oct.1918 to Sep.1978
		Oct.1918 to Sep.1928	Oct.1928 to Sep.1938	Oct.1938 to Sep.1948	Oct.1948 to Sep.1958	Oct.1958 to Sep.1968	Oct.1968 to Sep.1978	
Mean Annual Run-off(mm)		14.1	4.2	28.6	67.6	12.0	80.0	35.1
Frequency of Annual Run-off (number)								
Class	Bounds(mm)							
1	0	4	3	3	3	4	2	19
2	1-4	2	3	3	0	1	0	9
3	5-10	2	3	1	0	1	0	7
4	11-25	0	1	1	0	2	2	6
5	26-62	2	0	0	2	2	3	8
6	63-156	0	0	2	4	0	1	8
7	156	0	0	0	1	0	2	3

The cumulative percent frequency distribution of water supply in figure 8.2 shows that the volume of water storage at the time of irrigation was less than the volume required to irrigate all of the 40 ha irrigation-area in 6 out of the 29 years of cropping. In these years the irrigation strategy rules reduced the area of irrigation so that only a portion of the irrigation-area was simulated to have been irrigated. The remaining portion was simulated as a dryland crop. This suggests that management of the water supply for irrigation needs to be quite flexible if the efficiency of water use is to be optimized.

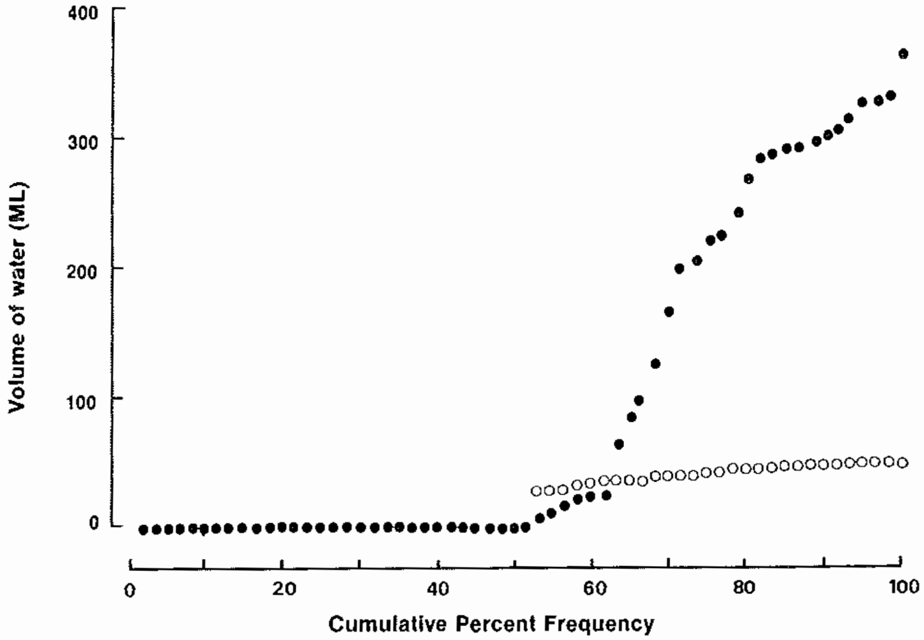


Figure 8.2 Cumulative percent frequency distributions for entire 60 year simulation period of: (a) water supply (●) (i.e. volume of water held in storage at the time of irrigation), and (b) water demand (○) (i.e. volume of water required to irrigate the 40 ha irrigation-area at the time of irrigation).

Irrigated Grain Sorghum Yield. The cumulative percent frequency distributions of grain yield determined from the irrigated and dryland (i.e. nil irrigation) treatments of this experiment are shown in figure 8.3. This figure shows the distribution of irrigated grain yield to be almost linear over its range (2225 to 4068 kg/ha). The mean and median yields were 3153 and 3019 kg/ha respectively. In contrast the distribution of dryland grain yield was curvilinear and had a median of only 839 kg/ha. Increases in yield due to irrigation ranged from 826 to 2757 kg/ha and exceeded 2238 kg/ha in 50% of years. The above distributions are approximated by:

$$\text{Irrigated Yield} = 2250 + 17.88\ \text{FY} \tag{8.2}$$
$$\text{Dryland Yield} = 147.3\ \exp(0.03178\ \text{FY}) \tag{8.3}$$

where FY = cumulative percent frequency of yield, and yields are in kg/ha.

Rainfall was not disruptive to irrigation scheduling as irrigation was delayed by high levels of soil moisture in only two years. Irrigation was delayed by one day in 1950, and by seven days in 1975. Therefore the simulation was effective in demonstrating the effect of irrigation at heading on grain yield.

Irrigation increased mean grain number by 59% from 84 to 134 million grains/ha, and mean grain size by 35% from 18 to 24 mg. The largest effect of irrigation was to reduce the proportion of grain lost to lodging from 40% to 3%.

Comparison of the mean irrigated yield in this experiment (3153 kg/ha) to the maximum yield predicted by the model (4267 kg/ha) shows there is potential to further increase yield by 35% with additional irrigation. Possible increases in grain number and grain size with additional irrigation are approximately equal, being 16% and 14% respectively. However, the potential to further reduce lodging loss is very small (2%).

Irrigated Grain Sorghum Production. The mean production of irrigated grain sorghum in the 29 years of possible cropping was 115 tonnes (2864 kg/ha), which is equivalent to 55 tonnes per annum (1385 kg/ha) when averaged over all 60 years. Hereafter the mean results from the 60 years of simulation are referred to as the long-term mean.

Considerable variation was found in both the level and continuity of grain production. The cumulative percent frequency distribution of irrigated annual grain production in figure 8.4(a) shows three distinct segments. The first segment of zero production was the most frequent outcome, as it occurred in all years of the simulation that run-off did not satisfy planting conditions (i.e. 52% of years). The second segment was a rapid increase in

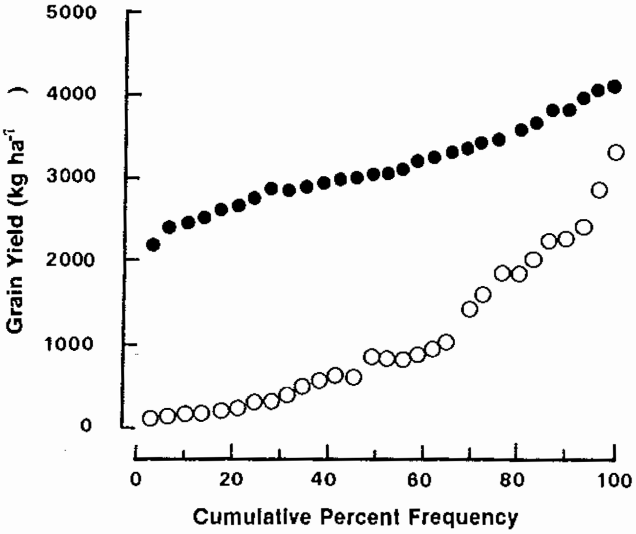


Figure 8.3 Cumulative percent frequency distributions of irrigated grain yield (●) and dry-land grain yield (○) in years of cropping.

production from zero to 106 tonnes as cumulative percent frequency increased from 53 to 67%. In this segment there was only sufficient water stored in the dam to irrigate a portion of the 40 ha irrigation-area, and thus the remaining portion of the irrigation-area was forced into dryland cropping. The mean yield of the irrigated portion was 2675 kg/ha compared to 292 kg/ha on the portion of the irrigation-area which could not be irrigated. In the third segment of the relationship in figure 8.4(a), production increased at a slower rate from 106 to 163 tonnes as cumulative percent frequency increased from 68 to 100%. In this segment the supply of water exceeded demand in all cases and hence there was sufficient water to apply a single irrigation at heading to all of the 40 ha irrigation-area. Increases in production were primarily due to the effect of rainfall on grain yield. The mean yield of the third segment was 3278 kg/ha.

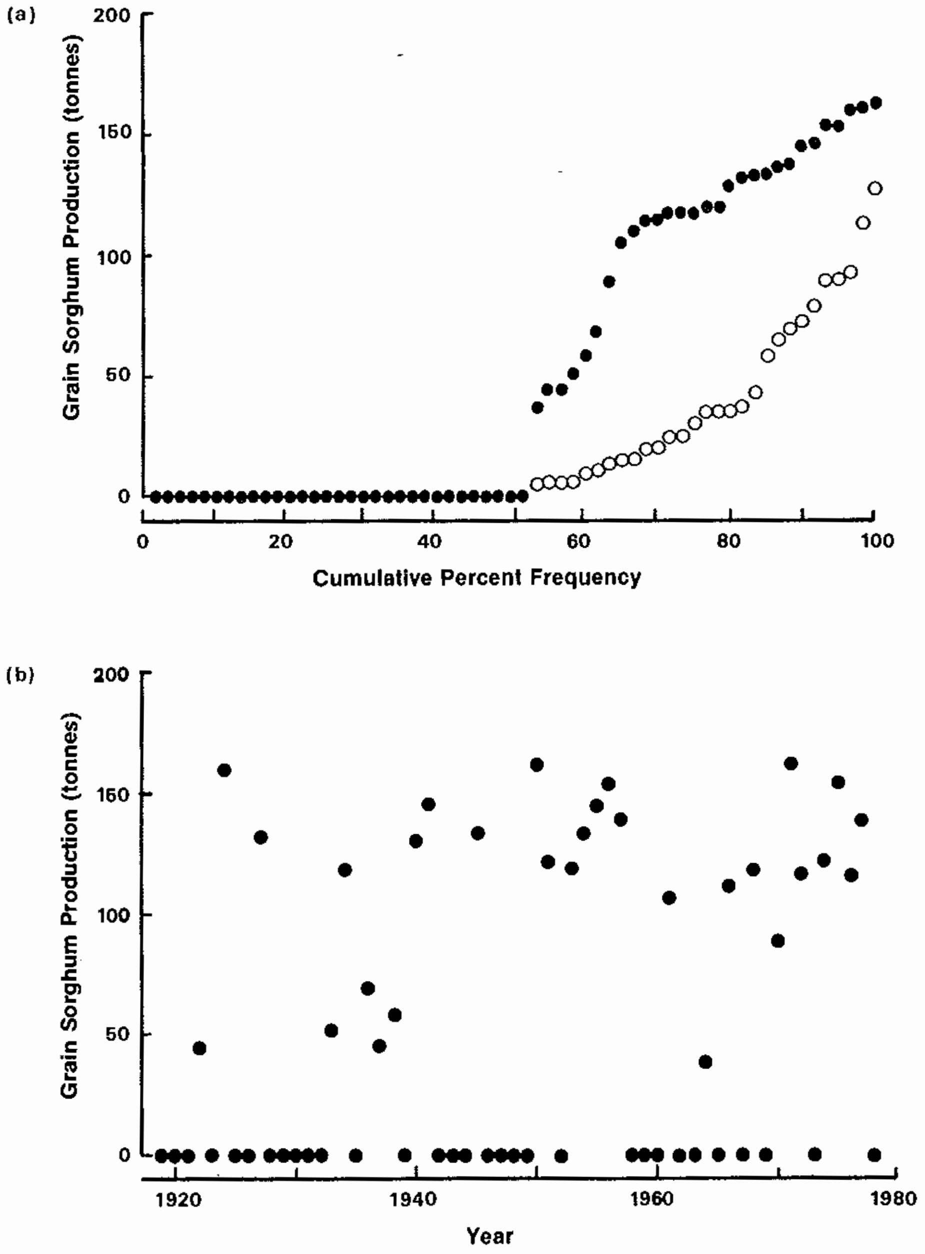


Figure 8.4 Variation in simulated production of grain sorghum from the 40 ha irrigation-area for the entire 60 year simulation period for (a) cumulate frequency distributions of grain production from treatment 1 (● irrigated) and treatment 2 (○ dryland), and (b) time series distribution of grain production of treatment 1 (● irrigated).

The time series of annual grain production from treatment 1 in figure 8.4(b) shows long periods of zero production in the 1920's, 30's, 40's and 60's and periods of persistent production in the 1950's and 70's. Average production in the first half of the 60 year simulation was substantially lower than average production in the second half (36 t/yr cf 75 t/yr). This major shift in production casts some doubt on the adequacy of using only 60 years of data to establish long-term probability levels.

Figure 8.4(b) shows that years of zero production were not evenly distributed through the 60 year simulation. However, the estimated frequency of zero production in 1, 2, 3, 4 and 5 consecutive years closely followed the expected frequency of these events if years of zero production were independently distributed in a statistical sense throughout the 60 year simulation (see table 8.3).

The high frequency of zero production in consecutive years caused a large variation in short-term production. Mean five year production ranged from zero to 138 t/yr, and mean ten year production ranged from 29 to 97 t/yr. This provides a salutory warning on reliance of short term experiments to obtain estimates of the long-term mean.

Ponded-Area Forage Production. Estimates of mean yield, total area of cropping and total forage production for each of the 32 years that ponded-area forage sorghum cropping was simulated are shown in table 8.4. This table shows:

(i) that the ponded-area was fully planted (51 ha) in only 19 of the 32 years of cropping (run-off was not sufficient to completely inundate the ponded-area in the remaining 13 years of cropping, and was not sufficient for cropping to occur at all in the remaining 28 years of the 60 year simulation),

(ii) that the mean annual dry matter yield of forage was 1634 kg/ha and that little variation in yield occurred from year to year (yield was less than 1350 kg/ha or greater than 2000 kg/ha in only 6 cases), and

(iii) that variation in forage production was mainly caused by variation in area of cropping.

Mean annual forage production in years of cropping was estimated to be 65.9 tonnes, which is equivalent to 35 tonnes per annum when averaged over all 60 years of the simulation.

Economics of Production In the 31 years of the simulation that crops were not planted on the irrigation-area the mean annual cost for capital and ploughing was $78/ha. In the 29 years of grain cropping the mean annual cost of grain production was $141/ha. While the mean cost per tonne of grain production in years of cropping was $49/t, the long-term mean was substantially higher because of the fixed costs incurred in non-cropping years and was $77/t. (The long-term mean was calculated by dividing total costs of production over 60 years by total production from the 29 years of cropping). Since grain was valued at $80/t the profits in years of cropping were just sufficient to meet costs in non-cropping years. The mean annual operating cost of ponded-area forage production was $18/t. Fixed costs were not charged to the ponded-area.

Table 8.3 Frequencies of zero production in consecutive years.

Number of consecutive years of zero production	Frequency observed in simulation results	Expected frequency of an independent distribution
1	0.52	0.52
2	0.25	0.27
3	0.13	0.14
4	0.03	0.07
5	0.02	0.04

In the 29 years of irrigated cropping there were six years that irrigation supplies were not sufficient to meet the irrigation demand of one watering at flowering. In these years, costs of production exceeded income and a mean net loss of $25/t occurred.

The time series of profits in figure 8.5 shows that short term profitability (5 years) is highly dependent on the year in which the cropping system was implemented and that the risk of economic failure in the short term is high.

Table 8.4 Simulated dry matter yields of forage sorghum, area of cropping and forage production from the ponded-area

Year	Forage Yield (kg/ha)	Area of Cropping (ha)	Forage Production (t)
1919-20	1630	19	31
1921-22	1380	13	18
1923-24	1470	51	75
1926-27	1650	51	84
1932-33	1940	16	31
1933-34	1480	30	44
1935-36	2930	15	44
1936-37	1360	11	15
1937-38	1330	15	20
1939-40	1310	51	67
1940-41	1780	51	91
1944-45	1840	44	81
1949-50	1590	51	81
1950-51	1440	51	73
1952-53	1420	51	72
1953-54	1520	51	77
1954-55	1690	51	86
1955-56	2060	51	105
1956-57	1820	51	93
1960-61	1530	51	78
1962-63	1640	47	77
1963-64	1910	11	21
1965-66	1500	29	44
1967-68	1850	51	94
1969-70	1390	39	54
1970-71	1820	51	93
1971-72	1290	51	66
1972-73	1630	51	83
1973-74	1560	51	80
1974-75	1500	51	77
1975-76	1390	51	71
1976-77	2560	32	82
Mean	1634	39.5	65.9

8.1.4 Discussion and Conclusions.

Climatic variability was shown to have large effects on cropping frequency, crop production and the economics of crop production.

Simulation of dry land grain sorghum cropping showed yields to exceed the minimum economic level for successful cropping (approximately 1800 kg/ha) in only 12% of years. In contrast, all years in the 29 years of simulated cropping were shown to exceed 2000 kg/ha when one irrigation was applied. Therefore the first concdusion of this study is that grain cropping on the Mitchell grass plains cannot be successful without irrigation. This agrees with earlier works (Weston 1971; and Clewett 1969) and supports the management strategy recommended by Weston (1972) that planting should not proceed until run-off has filled or partially filled the water storage.

The two main factors which led to the large variation in crop production were the low frequency of cropping and the unreliability of water supplies for irrigation. Because catchment run-off determined cropping frequency, irrigation supply and the maximum area of cropping on the ponded-area, the main effect of climatic variability on crop production was through its effect on catchment run-off. Direct effects of climatic changes on grain and forage yields were much less important.

Catchment run-off was shown to be much less frequent and more variable than previous estimates by Weston (1972), Morwood (1976) and the Australian Water Resources Council (1976) discussed in the literature review in chapter 1. While catchment run-off was shown to be adequate for successful cropping in some decades of the simulation, the limitations that catchment run-off impose on the long-term use of shallow storage irrigation are greater than previously recognized.

Variation in short-term estimates of productivity are important in analysis of cropping systems because farm planning horizons are generally no longer than ten years, and are often only five years. A key point found in analysis of the simulation results was the large variation found in mean values when calculated over short time periods. For example,

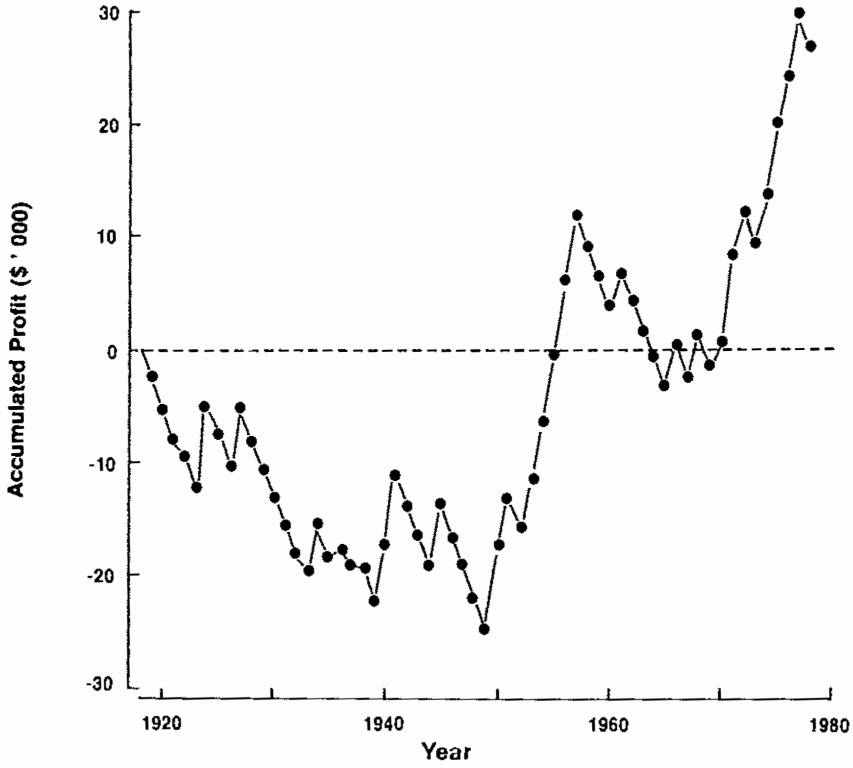


Figure 8.5 Simulated time series of annual profits from irrigated grain sorghum production.

the minimum and maximum values of the ten year moving average of the following variables were:

mean annual catchment run-off = 3.5 and 80 mm/yr,
frequency of irrigated cropping = 20 and 80 % of years,
mean irrigated grain production = 29.3 and 101 t/yr, and
mean cost of irrigated grain = $51 and $129/t.

The time series of profits showed persistent periods of substantial economic losses and gains. Therefore in commercial development of a shallow storage irrigation scheme, the timeliness of development is important because cash flow and interest payments in the first years are critical to economic viability. This result emphasizes the importance of dynamic models in economic analysis.

The planting and irrigation strategies used in this experiment had some undesirable consequences. There were a number of years in the simulation period that were not cropped, but in which rainfall may have been sufficient for establishment and growth of dry-land crops. Therefore the condition that catchment run-off must exceed 5 mm before planting occurs may have unnecessarily reduced cropping frequency. In contrast, there were six years in the simulation period in which grain production was low and unprofitable because irrigation supplies were only sufficient to irrigate a small portion of the irrigation-area. Increasing the amount of run-off required to satisfy planting conditions would reduce this risk. The consequence of using alternative planting strategies is investigated in experiment 5.

The irrigation strategy used in this experiment (i.e. a single irrigation at heading) was shown to substantially increase the yield of grain sorghum. However, this irrigation strategy did not increase yield to the maximum predicted by the model (4267 kg/ha) in any year. Since an excess of irrigation supply occurred in 23 of the 29 years of cropping, there was considerable potential to further increase grain yield and production by increasing either or both the frequency of irrigation and the size of the irrigation-area. The consequences of altering irrigation strategy are investigated in experiments 2, 3 and 4.

An alternative method of increasing the efficiency of water use is by altering the shallow storage design. This is investigated in experiment 6.

8.2 Experiment 2: Effects of Irrigation Timing on Grain Sorghum Production.

8.2.1 Introduction

The results of the irrigation strategy field experiments in chapter 5 showed irrigation timing to have substantial effects on grain sorghum yield. Irrigation timing also effects the area of land that can be irrigated because the volume of water stored in the dam decreases with time due to evaporation losses, and because the soil moisture deficit of the irrigation-area increases with time.

This experiment investigates changes in grain sorghum production that are caused by the effects of irrigation timing on: (i) grain yield, (ii) volume of water storage, (iii) depth of irrigation required to recharge soil moisture to capacity, and (iv) the area of land that can be irrigated.

8.2.2 Methods

The effect of irrigation timing on grain production was determined by repeating one year of simulation with the time of irrigation delayed by one day in each simulation. The same set of meteorological data were used in each simulation.

To remove the effects of climatic variability on grain production, it was assumed that run-off filled the water storage on 15 February, that planting occurred three days later, that rainfall and run-off after planting did not occur and that evaporative demand was equal to the long-term mean. To remove the effect and restriction that size of the irrigation-area has on grain production, it was further assumed that the size of the irrigation-area in each simulation was equal to the area of land that could be irrigated with the water available in the storage.

8.2.3 Results and Discussion

Grain Yield. The effect of irrigation timing on grain number per hectare, grain size, lodging losses and grain yield per hectare are shown in figure 8.6. When irrigation was applied at planting then moisture stress was severe during the boot, flowering and grain filling phenophases and consequently predicted grain yield was very low (543 kg/ha).

Grain yield increased (figure 8.6(d)) as time of irrigation was delayed and reached a maximum of 2943 kg/ha when irrigation was applied at heading (day 56). Irrigation at this time minimized the effects of moisture stress on the product of grain number, grain size and lodging losses. Grain number per hectare and grain size were greatest when irrigation was delayed to days 56 and 58 respectively.

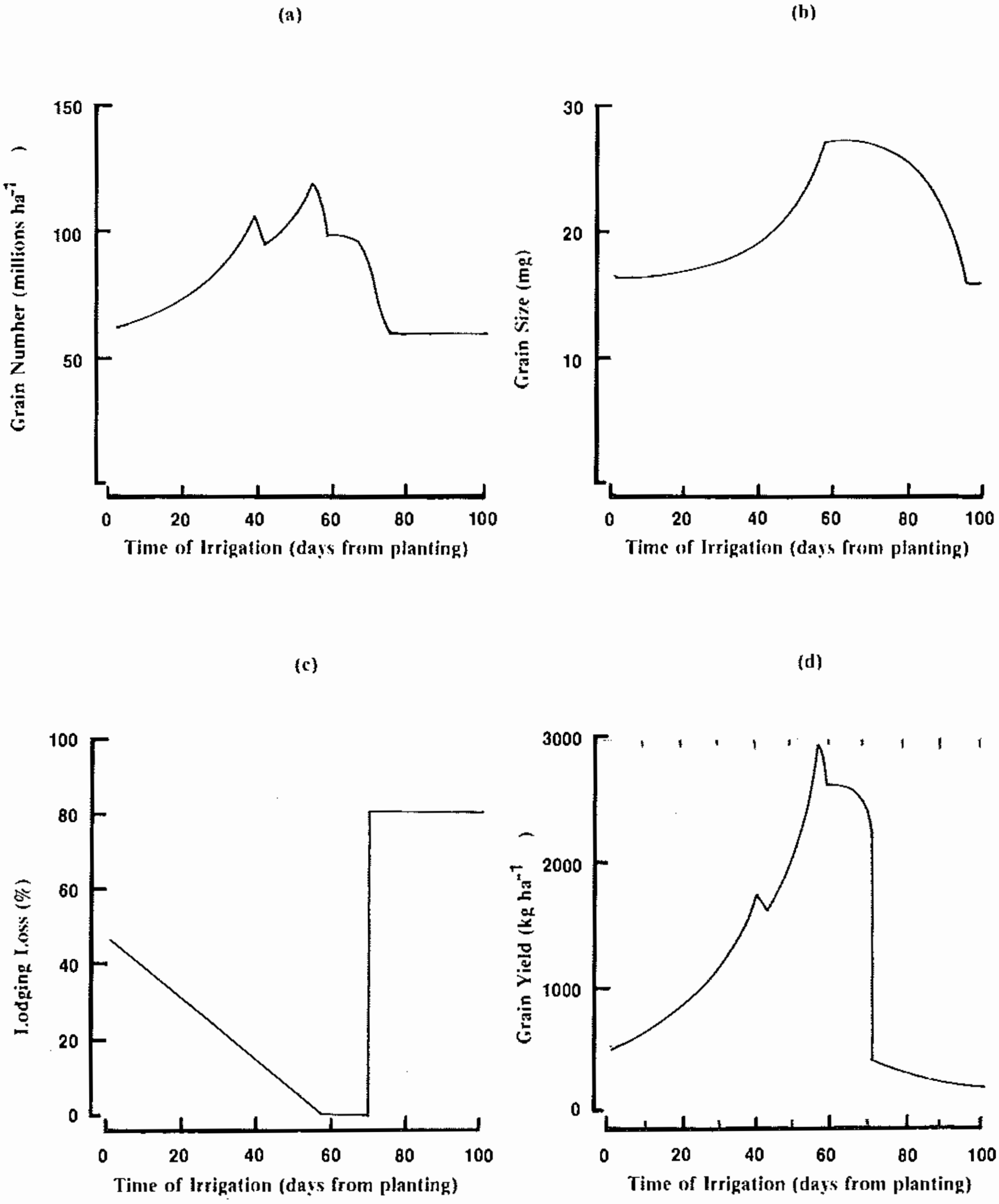


Figure 8.6 Effect of time of irrigation on (a) grain number per hectare, (b) grain size, (c) lodging loss, and (d) grain yield per hectare.

Irrigation at day 56 gave a grain number of 118 million grains/ha which is 76% of the potential grain number (156 million grains/ha). The maximum water stress simulated in the floral initiation, booting and anthesis phenophases reduced grain number below that achieved by irrigation at day 56 by 15%, 28% and 40% respectively.

The small discontinuities in the grain yield response curve in figure 8.6(d) at the end of the floral initiation and booting phenophases resulted from conceptual simplifications in the grain yield sub-model. They were caused by multiplication of the water stress indices for the floral initiation, booting and anthesis phenophases when calculating the reduction in potential grain number per hectare.

If irrigation was delayed until after day 70 then very low grain yields of approximately 400 kg/ha were predicted. This occurred because water stress during the booting and anthesis phenophases was severe and most grains in the primary head were simulated to have aborted. Irrigation after day 70 was considered to have only promoted the growth of tillers that failed to bear grain. This effect was simulated as a lodging loss as shown in figure 8.6(c).

Water Supply. Figure 8.7(a) shows the rapid rate at which water storage evaporation losses reduce the volume of water available for irrigation use and the significant influence that depth of water storage has on the proportion of water lost to evaporation. It was estimated that the volume of water available for irrigation at half bloom (60 days after planting) from dams that were 1, 2 and 4 m deep at planting was only 20, 50 and 72% of the volume available at planting.

Depth and Area of Irrigation. The depth of irrigation required to recharge soil moisture to capacity on the irrigation-area as time of irrigation is delayed is shown in figure 8.7(b). This figure assumes that soil moisture is at capacity at planting, and shows that the depth of irrigation that is required after 20, 40 and 60 days from planting is 58, 96 and 121 mm respectively. These depths are equivalent to 33, 54 and 68% of the available soil moisture range.

The combined effect of decreasing water storage and increasing depth of required irrigation on area of irrigation as time of irrigation is delayed is shown in figure 8.7(c). The unit of measurement for area in this figure is hectares per megalitre of water stored in the dam at planting. For example, if the dam at RSSRP is filled to capacity (400 ML) at planting with water stored to a depth of 2 m, then figure 8.7(c) shows that 0.38 ha/ML can be irrigated if irrigation is delayed to day 60. The area irrigated is thus 0.38 x 400 = 153 ha. However, if run-off only partially fills the dam to a depth of 1 m at planting (50 ML of water storage), then only 0.15 ha/ML can be irrigated at day 60 which gives 0.15 x 50 = 7.5 ha of irrigation.

Crop Production. The combined effects of changes in grain yield and decreases in area of irrigation on grain production (the product of yield/ha and area of irrigation), as time of irrigation is delayed, are shown in figure 8.7(d). The unit of measurement for production in this figure is tonnes per megalitre of water stored at planting. This unit is therefore a measure of the efficiency with which water stored at planting can be used for irrigation.

The two most important points in this figure are:

(i) the potentially very large increases in grain yield that are gained by delaying irrigation to heading are much reduced by the reduction in area of irrigation, and

(ii) grain production is maximized by delaying irrigation to day 56 when the depth of water storage at planting is 2 m or greater. However, the advantage of delaying irrigation until this time becomes less and less as the depth of water storage at planting decreases, because of the increasing importance of water storage evaporation losses. When the depth of water storage at planting is less than 1 m crop production decreases continuously as time of irrigation is delayed (figure 8.7(d)).

8.3 Experiment 3: Effects of Irrigation Timing and Frequency on Grain Sorghum Production.

8.3.1 Introduction.

Experiment 2 showed that grain yield per hectare and grain production was greatest if irrigation was timed at heading, provided the depth of water storage at planting was greater than one metre. However, Experiment 1 showed that more than one irrigation was required if grain yield per hectare was to be maximized. It was also shown in Experiment 1 that water supplies for irrigation were surplus to the demand of one irrigation scheduled at heading in 78 percent of years that cropping was simulated. Hence there is scope to increase grain production by using two or more irrigations.

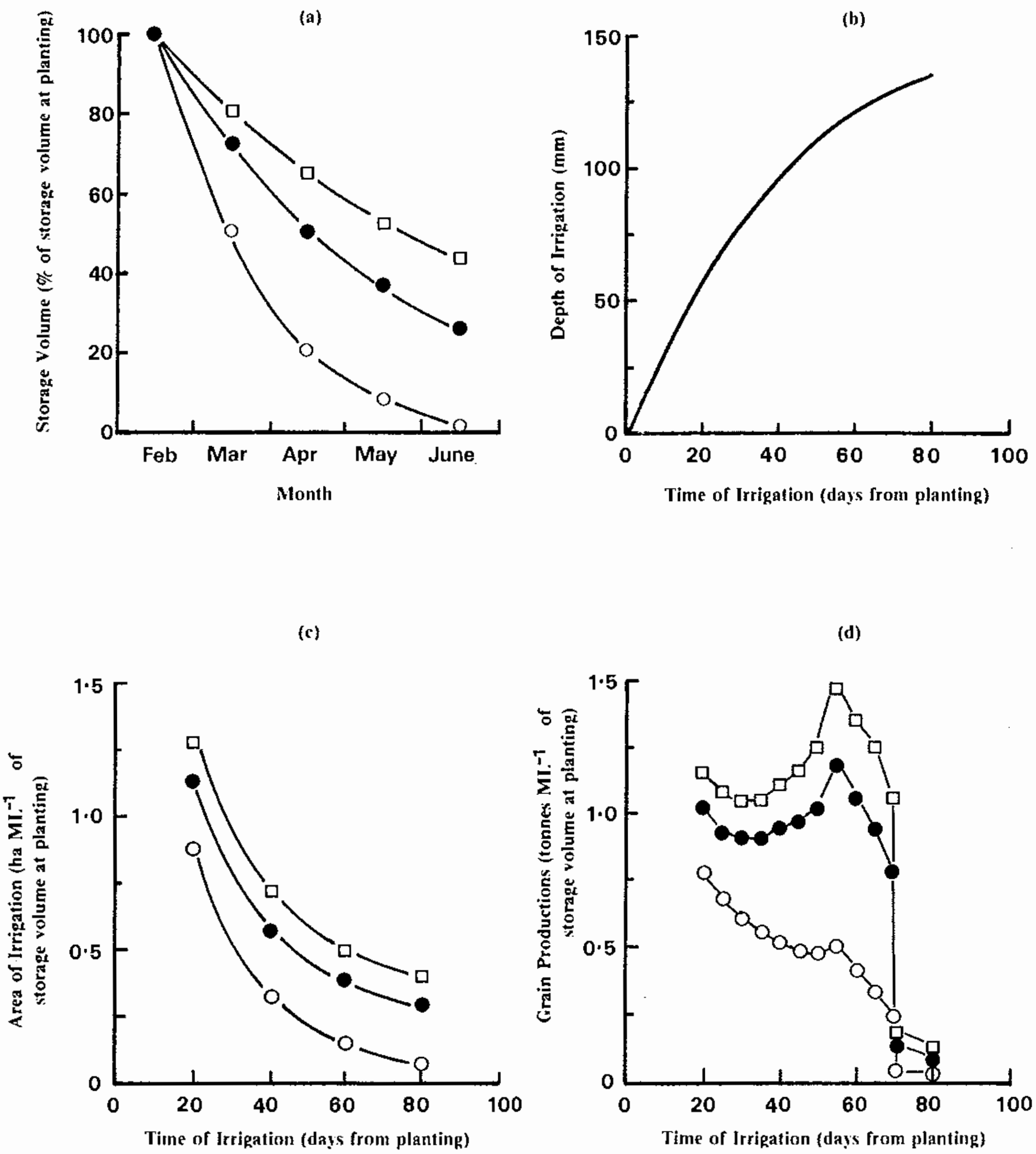


Figure 8.7 Simulated effects of time of irrigation (days after planting) on: (a) decreases in water storage due to evaporation losses, (b) depth of irrigation required to recharge soil moisture to capacity, (c) area of land that can be irrigated, and (d) irrigated grain production (The symbols ○ , ● and □ indicate that the depth of water storage in the dam at planting was 1, 2 and 4 m deep respectively).

This experiment investigates the effect of both irrigation timing and frequency on the long-term mean of grain sorghum production, and upon the annual variation in grain production.

8.3.2 Methods

The experiment is similar to Experiment 1 in that the same set of long-term weather records from the Richmond Post Office were used, and the same water storage design and set of management rules for planting and delaying irrigation from the scheduled time were used. The size of the irrigation-area was increased to 100 ha in this experiment because the irrigation-area of 40 ha in Experiment 1 was found to be too small to utilize stored water in most years.

The effects of 14 irrigation strategy treatments on grain production were simulated. In six treatments, only one irrigation was simulated, and this was scheduled at one of the following times: 25, 35, 45, 55, 65 or 75 standard days after planting. Two irrigations were simulated in six different treatments. In the first of these treatments irrigations were scheduled to occur 25 and 45 standard days after planting (denoted 25/45). The remainder of these treatments were: 25/55, 35/55, 35/65, 45/65, and 45/75. Three irrigations were simulated in one treatment, and they were timed at 25/45/65 standard days after planting. One treatment was a control of nil irrigation.

In those years of the simulation that the volume of water storage was not sufficient to irrigate the entire irrigation-area according to the appropriate schedule, then the water supply was rationed in the following way. If only one irrigation was scheduled, or if only one irrigation was remaining in the schedule, then the volume of water available for irrigation (VA) was set equal to the volume of water in the storage, and the area of irrigation (AI) was calculated from:

$$AI = \min(AC, VA/D)$$

where AC = Area of crop = 100 ha, and D = Depth of irrigation required to recharge soil moisture on the irrigation-area to capacity.

If two or more irrigations were remaining in the schedule, then forecasts of water supply and demand were made so that an approximately equal area of land would be watered at each irrigation. Where two irrigations were remaining in the schedule then the volume of water available for the first irrigation (VA1) was computed iteratively to satisfy:

$$V = VA1 + VE + VA2 \qquad (8.4)$$

where V = Volume of water in the dam immediately before the first irrigation is applied, VE = Forecast volume of water storage lost to evaporation between irrigations, VA2 = Volume of water available for second irrigation = VA1 x WD2/WD1, and where WD1 = Soil water deficit of the irrigation-area at the time of the first irrigation, and WD2 = Forecast soil water deficit of the irrigation-area at the time of the second irrigation.

This procedure assumes no rainfall to occur between irrigations, and that evaporative demand equals the long-term monthly means. The evapotranspiration relationships given in chapter 5 were used to forecast soil water deficit, and the water storage relationships given in chapter 4 were used to forecast water storage evaporation losses.

A similar iterative procedure to that given above was used when three irrigations were remaining in the schedule.

8.3.3 Results

Simulation results for catchment run-off and cropping frequency were the same in this experiment as in Experiment 1 because the same water storage design and planting strategy were used and so irrigated cropping was simulated in 29 out of 60 years.

Grain Yield. While water supplies were not sufficient to irrigate the entire irrigation-area in every year of cropping, they were sufficient to irrigate at least one hectare of the irrigation area in every year of cropping. The grain yield results that are given below refer only to the portion of the irrigation-area which received the scheduled irrigation strategy of each treatment.

Table 8.5 shows the mean effects of each irrigation treatment on the components of grain yield, and the cumulative percent frequency distribution of grain yield. These results show that increases in irrigation frequency led to increases in grain yield and decreases in annual variation of yield. Grain yield was smallest in the nil irrigation treatment, and greatest in the triple irrigation treatment.

The results in table 8.5 also show that the timing of a single irrigation had a large effect on the components of grain yield within the single irrigation strategies, and that yield was maximized by irrigation at day 55. In contrast, irrigation timing had little effect on grain yield within the double irrigation strategies because water stress during the critical anthesis phenophase was not severe in any of the treatments.

Water use efficiency, in terms of increased grain yield per millimeter of water applied, was maximized by a single irrigation at day 55. The mean water use efficiencies of a single irrigation at day 55, a double irrigation at days 25 and 55 and a triple irrigation at days 25, 45 and 65 were 20.0, 16.7 and 14.6 kg/ha/mm respectively. In the double irrigation strategy the irrigation at day 25 increased grain yield by 10.5 kg/ha/mm, and in the triple irrigation strategy the irrigation at day 65 increased grain yield by 7.3 kg/ha/mm. These results show a decreasing yield return to irrigation as irrigation frequency increased. The mean depth of water applied in the above single, double and triple irrigation strategies in those years of the simulation that seasonal rainfall was negligible (less than 20 mm) were 120, 180 and 259 mm respectively.

Area of Irrigation. The percentage of years in the 29 years of cropping that water supplies were not sufficient to irrigate the entire irrigation-area of 100 ha is shown in table 8.6. The mean area of land that was irrigated is also shown for each irrigation treatment. This data shows that as the frequency of irrigation increased and the timing of irrigation was delayed, that there was an increasing likelihood of water supply failing to meet requirements. Consequently, the mean area of irrigation was decreased.

Grain Production. Grain yield increased with increasing irrigation frequency, whereas water use efficiency and area of irrigation decreased. The result of these competing influences on the mean and frequency distribution of grain production are shown in table 8.6. The strategy which maximized long-term mean grain production was a double irrigation, with the first irrigation at day 35 and the second irrigation at day 65. However, this strategy did not maximize grain production in all of the 29 years that cropping was simulated. The triple irrigation strategy maximized production in 9 years out of 29 when irrigation supplies were plentiful, and a single irrigation at day 55 maximized production in 10 years out of 29 when irrigation supplies were not sufficient for more than one irrigation. When irrigation supplies were limited, then grain production from the triple irrigation strategy was low because the proportion of the irrigation-area that received irrigation was much lower than in other treatments, and because grain yield on the non-irrigated portion of the irrigation-area was less than 500 kg/ha.

The data in table 8.6 shows very little difference in grain production in four of the double irrigation strategies (treatments 9, 10, 11 and 12) which apply the first irrigation to boost grain number per hectare during the floral initiation or booting phenophases, and the second irrigation around flowering. Therefore, there is reasonable flexibility for management to alter time of irrigation without incurring substantial production losses. In contrast, the single irrigation strategies show a sharp peak in production when irrigation is applied at heading, and hence penalties to management for mistiming irrigation in this option would be substantial.

8.3.4 Discussion and Conclusion.

The results of this experiment are important for two reasons. Firstly, they describe the response in grain sorghum yield to irrigation and secondly, they show that in order to maximize grain production that both the frequency and area of irrigation should be adjusted to seasonal conditions, where the supply of and demand for irrigation water are variables.

Table 8.5 Effect of irrigation strategy on grain number, grain size, lodging losses and yield of grain sorghum**

Treatment No.	Irrigation Strategy		Mean Grain Number	Mean Grain Size	Mean Lodging Loss	Grain Yield (kg/ha)					
	Frequency	Timing*	$(10^6/\text{ha})$	(mg)	%	Mean	Min	20th Percentile	Median	80th Percentile	Max
1	Nil	-	84	18.1	41	1073	160	270	839	1966	3185
2	1	25	108	19.5	26	1746	237	785	1589	2892	3990
3	1	35	117	20.0	21	1983	294	1193	1828	2839	4107
4	1	45	116	20.9	15	2164	583	1463	1800	3026	4122
5	1	55	135	24.2	3	3154	2225	2650	3019	3658	4068
6	1	65	119	25.2	2	2929	2116	2468	2677	3474	4267
7	1	75	84	24.9	37	1495	267	309	1914	2463	4267
8	2	25/45	135	22.4	9	2854	728	1857	2615	3879	4267
9	2	25/55	151	24.5	3	3592	2762	3263	3661	4000	4267
10	2	35/55	152	24.6	2	3645	2762	3252	3701	4000	4267
11	2	35/65	152	25.3	2	3781	3144	3444	3821	4031	4267
12	2	45/65	143	25.4	2	3558	2884	3341	3470	3888	4267
13	2	45/75	135	25.5	2	3336	2674	2973	3414	3749	4267
14	3	25/45/65	153	25.4	2	3840	3145	3456	3888	4202	4267

* Irrigation timing is shown in standard days after planting.

** Means and frequency distribution are calculated for years of cropping.

Table 8.6 Effect of irrigation strategy on area of irrigation, water use and grain production in years of cropping.

Treatment No.	Irrigation Strategy		Percent of of years in which water shortage occurred	Mean Area of Irrign. (ha)	Mean Water Use (ML/ha)	Grain Production (tonnes)					
	Frequency	Timing*				Mean	Min	20th Percentile	Median	80th Percentile	Max
1	Nil	-	-	0	0.00	107	16	27	84	197	319
2	1	25	21	89	0.72	167	21	57	159	282	399
3	1	35	21	86	0.73	182	29	66	172	274	411
4	1	45	28	83	0.79	192	38	62	178	293	412
5	1	55	31	80	0.90	268	48	92	296	366	407
6	1	65	34	77	1.01	248	36	85	268	347	427
7	1	75	34	68	1.04	147	17	32	191	246	349
8	2	25/45	31	80	1.49	247	40	77	259	383	422
9	2	25/55	34	77	1.53	288	48	96	346	387	422
10	2	35/55	34	76	1.52	290	48	94	346	394	424
11	2	35/65	41	75	1.53	291	40	92	377	390	424
12	2	45/65	45	74	1.61	277	37	80	341	389	427
13	2	45/75	48	70	1.72	258	28	68	293	375	427
14	3	25/45/65	62	70	1.96	277	36	82	341	395	427

* Irrigation timing is shown in standard days after planting.

8.4 Experiment 4: Effects of Irrigation Management Rules on Grain Production.

8.4.1 Introduction

In Experiment 3 it was shown that irrigation at heading maximized water use efficiency, and that the optimum frequency of irrigation was dependent on seasonal conditions. When the supply of irrigation water was less than required, the management rule used in experiment 3 in the multiple irrigation treatments was to reduce the area of irrigation so that the area of land watered on each irrigation was approximately the same.

This experiment tests an alternative set of rules for seasonal management of a triple irrigation strategy. The management rules that are tested reduce the frequency of irrigation before the area of irrigation is reduced, and also give priority to irrigation at heading. This strategy is called a flexible irrigation strategy and is described in more detail as treatment 4 in section 8.4.2.

The size of the irrigation-area is varied from 1 to 640 ha in this experiment to extend the range of conditions relating to the supply of and demand for irrigation water. The water storage design in this experiment is the same as was used in Experiments 1 and 3 (i.e. 400 ML capacity and equivalent to the dam at RSSRP). The criteria used to determine time of planting in Experiment 1 was also used in this experiment.

8.4.2 Methods

A factorial design of four irrigation strategies by seven sizes of irrigation-area was used. Each treatment was simulated over the period 1 October 1918 to 30 September 1978. The seven treatments for size of the irrigation-area were 1, 20, 40, 80, 160, 320 and 640 ha. The four irrigation treatments were as follows:

Treatment Number	Name of Strategy	Number of Irrigations	Timing of Irrigation*		
			first	second	third
1	single	1	55	-	-
2	double	2	25	55	-
3	triple	3	25	45	65
4	flexible	3	25	55	75

* standard days after planting

When water supplies were less than irrigation demand in treatments 1, 2 and 3, then the management rules for seasonal alteration of the single, double and triple irrigation strategies were as described in Experiment 3. In these treatments the frequency of irrigation was maintained but the area of irrigation was reduced so that it would be approximately the same at each irrigation. In contrast, the management rules for seasonal alteration of the flexible irrigation strategy (treatment 4) gave priority to maximizing the area of irrigation at day 55. The only water used for irrigation at days 25 and 75 (i.e. the first and third irrigation) was water that was surplus to the requirement of irrigation at day 55. Therefore in situations of limited water supply, the first and third irrigations were reduced in area (and abandoned if necessary) so that as much land as possible could be irrigated at day 55.

The flexible irrigation strategy requires methods of forecasting water storage evaporation losses and crop irrigation requirements. The forecasting methods described in Experiment 3 were also used in this experiment. Further details of the flexible irrigation strategy decision rules were:

(i) The volume of water in the dam that was considered to be available for the first irrigation (WA1), was calculated by subtracting the following forecasts of water loss and use from the volume of the dam at the time of the first irrigation (V1): (a) the volume of water storage evaporation (VE) forecast to occur between the first and second irrigation, and (b) the forecast volume of water required for the second irrigation (WR2) to irrigate all of the irrigation-area. Thus, the water available for the first irrigation was calculated from:

$$WA1 = \max(0.0,\ V1 - VE - VR2) \qquad (ML) \qquad (8.5)$$

(ii) The volume of water available for the second and third irrigations (scheduled at days 55 and 75) was set equal to the volume of water in the dam at that time. Thus, no consideration was given to the water requirements of the third irrigation at the time of the second irrigation.

(iii) If the calculated volume of water available for each irrigation was less than that required to irrigate all of the irrigation–area, then the area of land watered at each irrigation was reduced in accordance with the availability of water for that irrigation.

(iv) If the calculated volume of water available for irrigation was less than 5 ML, or if soil moisture in the surface 30 cm of the irrigation–area was estimated to be greater than 60% of capacity, then irrigation was postponed, with decisions being made on a daily basis. The irrigation scheduled for day 25 was cancelled if it had not been applied by day 38. If the irrigation scheduled for day 55 was postponed, then the irrigation scheduled for day 75 was also postponed by the same amount. The irrigations scheduled for days 55 and 75 were cancelled if they had not been applied by day 84.

8.3.4 Results

Grain Production. Table 8.7 shows the effects of irrigation strategy and size of the irrigation area on: grain yield per hectare, water use, area of irrigation, and grain production in the 29 out of 60 years that cropping was simulated. The salient points in this table are:

(i) The grain yield per hectare of all irrigation treatments decreased as the size of the irrigation–area increased. This occurred because increases in the size of the irrigation–area led to an increase in the proportion of land that was not irrigated.

(ii) Although expansion in the size of the irrigation–area led to increases in grain production of all irrigation treatments, it also led to instability of production. For example, when the irrigation–area was 1 ha then the grain yield of the flexible irrigation strategy exceeded 3000 kg/ha in every year, however, when the irrigation–area was 640 ha then only one crop in five exceeded 3000 kg/ha. The effect of changes in the size of the irrigation–area on the variability of grain yield are shown more clearly in figure 8.8.

(iii) Within the single, double and triple irrigation treatments there was a significant interaction between irrigation frequency, size of the irrigation–area and climatic variability on predicted values of grain production as follows. When the irrigation–area was 1 ha then the triple irrigation strategy gave the highest production in all years because water supply was not limiting in any year. In contrast, the single irrigation gave the highest production in every year when the irrigation area was 640 ha. In this case, water supply limited the proportion of the irrigation–area that could be irrigated in every year of the simulation in all treatments. When the irrigation–area ranged from 20 to 160 ha then the mean grain production of the double irrigation strategy was greater than the mean production of the single and triple irrigation strategies (see figure 8.9). However, all three irrigation strategies gave equal highest production in some years. For example, when the irrigation–area was 80 ha the single and triple irrigation strategies gave equal highest grain production in 28 and 41 percent of years respectively.

(iv) In contrast to the other three irrigation strategies, the flexible irrigation strategy maximized grain yield, area of irrigation, and grain production at all sizes of the irrigation–area in every year of the simulation. Therefore the management rules of the flexible irrigation strategy were clearly superior to the rules used in the other irrigation treatments.

Economics of Grain Production. Because the flexible irrigation strategy had the highest production, it also gave the lowest cost of grain per tonne and the highest profits per hectare in all years of the simulation, and for all sizes of the irrigation area.

Treatment 9 in this experiment (40 ha irrigation-area and a single irrigation at day 55) is equivalent to the shallow storage design and irrigation strategy used in Experiment 1. The long-term mean profit per hectare of this treatment was $11/ha, whereas, the long-term mean profit per hectare using the flexible irrigation strategy for an irrigation-area of 40 ha was $25/ha. This comparison shows that the simulation experiments have revealed a more economically efficient method of scheduling irrigation.

Table 8.7 Effects of irrigation strategy and size of the irrigation area on grain yield, area of irrigation, water use and grain production*

Area of Cropping (ha)	Irrign. Frequency	Mean Grain Yield (kg/ha)	Mean Area of Irrign. (ha)	Mean Water Use (ML)	Grain Production (tonnes)			
					20th Percentile	Median	80th Percentile	Mean
1	1	3150	1	1	2.7	3.1	3.7	3.2
	2	3590	1	2	3.3	3.7	4.0	3.6
	3	3840	1	4	3.5	3.9	4.2	3.8
	flexible	3840	1	4	3.5	3.9	4.2	3.8
20	1	3050	19	20	52	61	73	61
	2	3390	18	32	55	73	80	68
	3	3370	17	40	52	76	80	67
	flexible	3500	19	38	69	74	80	70
40	1	2880	35	36	69	121	146	115
	2	3180	34	59	72	146	160	127
	3	3170	33	73	60	152	160	127
	flexible	3280	35	75	70	149	160	131
80	1	2740	65	66	84	239	293	219
	2	2980	62	106	87	283	315	238
	3	2930	59	139	74	298	321	234
	flexible	3050	66	137	84	290	321	244
160	1	2560	118	118	116	478	585	410
	2	2670	109	192	121	492	621	427
	3	2310	85	200	104	401	553	369
	flexible	2680	119	216	120	525	609	429
320	1	2230	191	183	210	702	1171	715
	2	1960	128	234	217	661	1012	628
	3	1730	94	222	168	554	890	555
	flexible	2240	193	266	218	702	1174	718
640	1	1700	210	198	323	1050	1850	1090
	2	1530	128	234	296	963	1659	980
	3	1420	94	222	269	850	1591	906
	flexible	1710	213	198	323	1056	1856	1097

* means and percentiles are calculated for the 29 years of cropping in the 60 year simulation period.

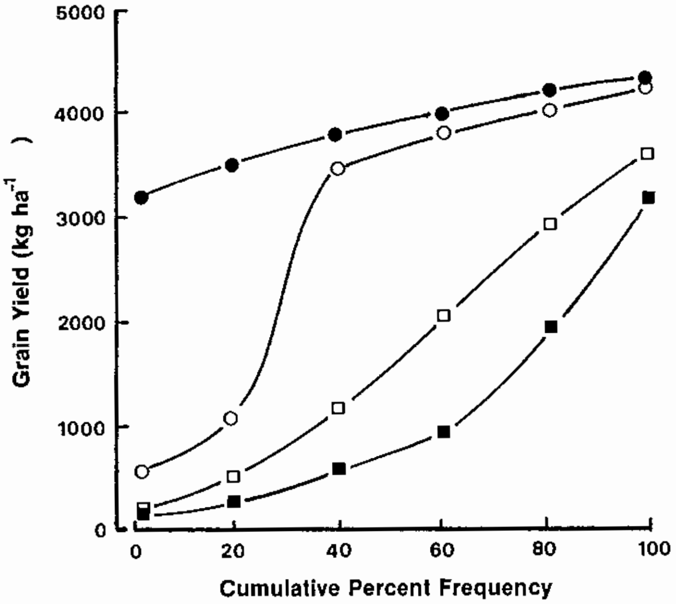


Figure 8.8 Simulated effect of size of the irrigation-area on the cumulative frequency distribution of grain sorghum yield per hectare found for the flexible irrigation strategy treatment. (Symbol code for size of irrigation area: ● = 1 ha, ○ = 80 ha, □ = 640 ha). The cumulative frequency distribution for yield of grain sorghum grown without irrigation is shown by ■).

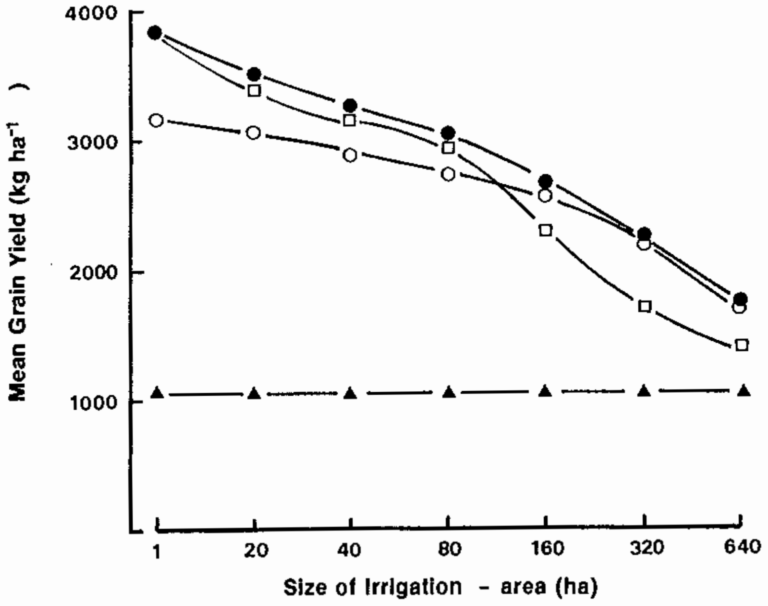


Figure 8.9 Effects of irrigation strategy and size of the irrigation-area on the mean yield per hectare of grain sorghum in years of cropping. (○ = single irrigation at day 55, □ = triple irrigation at days 25, 45 and 65, ● = flexible irrigation strategy, ▲ = yield of dryland grain sorghum production).

The effect of the size of the irrigation-area on costs per tonne of grain and profits per hectare (of the irrigation-area) for the flexible irrigation strategy are shown in table 8.8. While these results show that costs were minimized and profits maximized when the irrigation-area was 160 ha, the two main points in table 8.8 are firstly, the large effect of shallow storage design on profitability (an aspect further investigated in Experiment 6), and secondly, the large proportion of years in which profit was negative. Both fixed and operating costs for ploughing were incurred in all years, but in 52% of years income was zero because the criteria for planting were not satisfied to simulate cropping. The effects of planting strategy on the frequency of cropping, grain production and the economics of production are investigated in the next experiment.

8.4.4 Conclusion

Because the flexible irrigation strategy maximized both grain production and profits in all situations of water supply and irrigation demand, it was concluded that an efficient set of irrigation rules had been isolated. No doubt the rules could be slightly improved by small adjustments to the timing of irrigation. However, it is likely that such adjustments would lead to only very small improvements in crop production, probably of lesser magnitude than the accuracy of the model. It was therefore concluded that further simulation experiments on irrigation strategy were unnecessary, and that the flexible irrigation strategy should be used in all subsequent experiments.

Table 8.8 Effect of size of the irrigation-area on (a) cost of grain sorghum per tonne, and (b) profits per hectate of cropping.

(a) Cost of Grain ($/t)

Size of Irrign. Area (ha)	Percentiles*				Long-term mean
	20%	40%	60%	80%	
20	48	50	55	59	88
40	35	37	40	75	64
80	30	31	44	97	54
160	27	29	33	115	49
320	25	30	44	115	50
640	29	40	67	150	59

(b) Profit per hectare ($/ha)

Size of Irrign. Area (ha)	Percentiles**									Long-term mean
	2%	10%	30%	50%	60%	70%	80%	90%	98%	
20	-100	-100	-100	-100	65	85	115	130	145	-5
40	-65	-65	-65	-65	10	138	165	178	195	25
80	-53	-45	-45	-45	-16	160	188	203	220	40
160	-55	-31	-31	-31	-25	138	174	201	234	41
320	-55	-25	-25	-25	-23	68	154	201	231	33
640	-56	-35	-22	-22	-22	15	81	147	156	15

* Percentiles for 29 years of cropping.

** Percentiles for 60 year simulation.

8.5 Experiment 5: Effects of Planting Strategy on Grain Production

8.5.1 Introduction

The decision rules used in previous experiments to define the planting stategy of grain sorghum were found to result in a large proportion of years in which cropping was not simulated. These rules may have unnecessarily restricted cropping frequency because there were some years in the sixty year simulation in which sufficient run-off did not occur, but in which soil moisture was adequate for planting. In contrast, the results of Experiment 4 showed that the costs of cropping exceeded income in some years because water supplies were inadequate to ensure a high level of production. This result suggests that cropping may be more economically efficient if planting does not proceed until sufficient run-off has occurred to ensure irrigation of a large proportion of the irrigation-area.

The objective of this experiment is to examine alternative strategies of planting grain sorghum on the irrigation-area, and to determine their effect on grain production.

8.5.2 Methods

The water storage design in this experiment was the same as in Experiments 1, 3 and 4 (i.e. 400 ML storage capacity with a 1660 ha catchment and equivalent to the dam at RSSRP). The size of the irrigation area was 100 ha. The flexible irrigation strategy described in Experiment 4 was used.

Four planting strategies were simulated over the period 1918 - 78 using weather data from the Richmond Post Office. Planting was confined to the months December to March inclusive in all treatments. In treatment 1 planting was simulated to occur on the third day without rain following the first occasion in each year after the 1st December that rainfall recharged the surface 30 cm of soil on the irrigation-area to capacity.

In treatments 2, 3 and 4 planting was simulated to occur on the third day without rain following the first occasion in each year that the depth of catchment run-off accummulated since the 1st October was equal to or exceeded 5, 12 and 24 mm respectively. These values are equivalent to 20, 50 and 100% of the dam's water storage capacity. Treatment 2 was equivalent to the planting strategy used in all of the previous experiments.

8.5.3 Results and Discussion

The strategy of planting on soil moisture (treatment 1) maximized cropping frequency. Crops were simulated in 72 percent of years for this treatment compared to 48, 38 and 25 percent of years for the strategies which planted on 5, 12 and 24 mm of catchment run-off (treatments 2 to 4).

The effects of planting strategy on water use, grain production and costs of production are shown in table 8.9. These results show that as the depth of run-off required to initiate planting was increased, the mean of production in years of cropping was increased, but the long-term mean of production was reduced. Treatment 4 reduced cropping frequency to such an extent that the fixed costs from non-cropping years caused this treatment to have the highest cost per tonne of grain production (see table 8.9).

Cropping frequency and long-term mean grain production were maximized by using soil moisture conditions on the irrigation-area as the criteria for planting strategy (treatment 1). However, this treatment also gave the highest variability of annual production, because water supplies for irrigation were absent in 19% of years that crops were simulated, and inadequate for one watering of the entire irrigation-area in a further 16% of years. Consequently, costs exceeded income in 33% of the years that crops were simulated. In contrast, the risk of costs exceeding income was eliminated in treatment 3 because water supplies were adequate for at least one watering of the entire irrigation-area in every year that crops were simulated.

There were 20 years in the 60 year simulation period that crops were simulated in treatment 1 but not in treatment 3. The mean yield of these crops was only 1071 kg/ha, and production was sufficient to offset costs in only seven of the 20 years.

In those years of the simulation that costs exceeded income a management alternative could have been to cancel the grain harvest operation. If this had been done the frequency of successful cropping in treatments 1 and 2 would have been reduced to 48%

and 38% of years respectively, and the long-term mean grain production would have been reduced to 151 and 137 tonnes respectively. These values are little different from the cropping frequency and grain production of treatment 3 (i.e. 38% and 135 tonnes respectively).

8.5.4 Conclusion

The results did not show any treatment that was clearly superior to others, and therefore it was concluded that planting strategy should be selected by considering factors external to the model. These factors might be the attitude of management to risk, the availability of manpower for planting, or the value of failed crops for grazing.

8.6 Experiment 6: Effects of Shallow Storage Design on Crop Production

8.6.1 Introduction

This experiment investigates the effect of catchment area, stream gradient, storage capacity and size of the irrigation-area on crop production and costs of production. The first two of these design variables are mainly site dependent, because the range of dam sites that are available on properties is usually restricted. Storage capacity can be a site-dependent factor because selection of an appropriate bywash (i.e. the overflow by which excess water is discharged to the stream-bed on the downstream side of the dam wall) is sometimes of sufficient importance to dictate the height of water storage and hence storage capacity. Size of the irrigation-area is less frequently a site dependent factor.

Table 8.9 Effect of planting strategy on grain production, water use and cost of grain production.

Planting Strategy Treatments*	Median in years of cropping	Mean in years of cropping	Percentiles (all years of 60 year simulation included)							Sixty Year Mean
			30	40	50	60	70	80	90	
Grain Production (t)										
1	259	230	18	57	109	195	284	346	380	165
2	362	295	0	0	0	92	345	375	389	143
3	375	253	0	0	0	0	345	375	389	135
4	380	375	0	0	0	0	332	369	386	112
Water Use (ML)										
1	72	105	0	0	20	42	158	162	180	75
2	165	172	0	0	0	24	158	172	299	85
3	172	212	0	0	0	24	158	172	299	81
4	172	233	0	0	0	0	155	169	253	70
Cost of Grain ($/t)										
1	39	100	27	30	33	39	51	89	167	53
2	31	55	–	–	–	29	30	32	104	51
3	30	32	–	–	–	–	29	30	32	50
4	29	30	–	–	–	–	27	29	31	56

* Treatment 1. Plant when soil moisture in surface 30cm of irrigation-area is recharged to capacity.

Treatment 2. Plant after 5 mm of catchment run-off.

Treatment 3. Plant after 12 mm of catchment run-off.

Treatment 4. Plant after 24 mm of catchment run-off.

Catchment area is an important design variable because it influences the volume of run-off flowing to the dam. Stream gradient is of importance as it influences the proportion of stored water that is lost to evaporation, and the area of land that is available for ponded-area cropping. Storage capacity is of importance because it influences the volume of water available for irrigation, and the area of land available for ponded-area cropping. The size of the irrigation-area was shown in Experiment 4 to have large effects on both the mean and variability of production, and on the cost of production.

The above discussion shows that the effect of shallow storage design on crop production can be anticipated to some extent. However, because of climatic variability and competing influences, a series of simulations is required to quantify changes in the response surfaces of crop production and costs of crop production.

The first objective of this experiment was to determine the effect of shallow storage design on the response surfaces of crop production, variability of production and cost of production for both irrigated grain sorghum and ponded-area forage sorghum crops. The second objective was to determine principles of shallow storage design that minimize costs of total production (i.e. irrigated grain plus ponded-area forage), by determining optimum (i.e. least cost) combinations of storage capacity and size of the irrigation-area for a range of dam sites defined by catchment area and stream gradient.

8.6.2 Methods

The response surfaces of crop production and costs of production were determined by: (i) conducting a series of 60 year simulations with different combinations of the four design variables, and (ii) fitting quadratic, multiple regression equations to the simulation results. To minimize the number of computer simulations required to determine the response surfaces, and to simplify the numerical aspects of determining the response surface regression coefficients, a central composite rotatable design given by Cochran and Cox (1966, p 370) was chosen for the investigation. This experimental design required five values for each of the four shallow storage design variables and furthermore, these values were required in a geometrical sequence so that they could be transformed to a coded scale of -2, -1, 0, 1 and 2.

Values of the design variables that were considered to cover the likely range of shallow storage irrigation schemes were: catchment areas ranging from 400 to 4000 ha, stream gradients ranging from 1:125 to 1:2000, storage capacities ranging from 20 to 1000 ML and size of the irrigation-area ranging from 20 to 400 ha.

Catchment run-off was found to have a strong influence on crop production in Experiment 1, and thus it is useful to consider storage capacity in terms of depth of catchment run-off required to fill the water storage to capacity (e.g. 15 mm of run-off).

The five values of each variable that were chosen for use in the simulation treatments and their relationship to the coded scale were:

Coded Scale	Catchment Area (ha)	Stream Gradient	Storage Capacity* (mm of run-off)	Size of Irrigation-Area (ha)
-2	400.0	1:125	1.58	20.0
-1	711.3	1:250	5.00	42.3
0	1265.	1:500	15.8	89.4
+1	2245.	1:1000	50.0	189.0
+2	4000.	1:2000	158.0	400.0

* The values chosen for storage capacity correspond to the 35, 50, 65, 80 and 95% cumulative percent frequency levels found for annual run-off as calculated by equation 8.1.

The logarithmic equations that relate values of the shallow storage design variables to the coded scale are:

$X1 = 1.737 \ln (ACAT) - 12.41,$ (8.6)
where X1 = Transformed value of catchment area, and ACAT = Area of water storage catchment (ha).

$X2 = 0.869 \ln (SC) - 2.398,$ (8.7)
where X2 = Transformed value of storage capacity, and SC = Storage capacity of dam (mm of run-off required to fill the dam).

$X3 = 1.335 \ln (AC) - 6.000,$ (8.8)
where X3 = Transformed value of size of irrigation-area, AC = Size of irrigation area (ha).

$X4 = 1.443 \ln (1/G) - 8.996,$ (8.9)
where X4 = Transformed value of stream-gradient, G = Stream gradient (height/distance).

The experimental treatments required by the central composite, rotable design of Cochran and Cox were: (i) one treatment at the centre of the multi-dimensional space with the coded co-ordinate (0, 0, 0, 0), (ii) sixteen treatments formed by a 2^4 factorial of the four design variables set at the levels +1 and −1, and (iii) eight treatments formed from the co-ordinates (−2, 0, 0, 0), (2, 0, 0, 0), (0, −2, 0, 0), ... , (0, 0, 0, 2). These are referred to as the "star points" of the design.

These twenty-five treatments are shown in table 8.10, together with other characteristics of the treatments such as the volume of water storage, area of ponded-area, cost of water storage, cost of machinery and cost of farming operations.

The following polynomial equation was fitted to the simulation results to determine the response surfaces of crop production and costs of production:

$$\begin{aligned} Y = B_0 &+ B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 \\ &+ B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 + B_{44}X_4^2 \\ &+ B_{12}X_1X_2 + B_{13}X_1X_3 + B_{14}X_1X_4 + B_{23}X_2X_3 + B_{24}X_2X_4 + B_{34}X_3X_4 \end{aligned} \quad (8.10)$$

where Y = predicted value of response surface, X_1 to X_4 are coded values of the design variables defined by equations 8.6 to 8.9 respectively, and B = response surface regression coefficient (the subscript(s) identifies the variable(s) to which it pertains).

The coefficients of equation 8.10 were found using the method of Cochran and Cox (1966, p 342). The percent variance accounted for by each regression and the statistical significance of the linear, quadratic and interaction coefficients in the regression were computed. The regression equations were then used to compute a large number of values on the response surfaces so that iso-quants of production and costs of production could be plotted. Further simulations were then conducted for shallow storage designs that were identified as a design which minimized costs of production for a particular dam site (i.e. combination of catchment area and stream gradient).

8.6.3 Results and Discussion

Results from each simulation concerning the effect of changes in shallow storage design on the mean and variability of grain production from the irrigation-area, and forage production from the ponded-area, are shown in table 8.11. This table also shows the effect of design on costs of grain production. The regression equations that were fitted to describe the response surfaces defined by these simulation results are shown in table 8.12. All of the regression equations were found to account for 96 to 99% of the variation in the data, and therefore these equations provide a reliable and rapid method of predicting simulation results, which was much cheaper than the alternative of carrying out a large number of simulations and using a less powerful method of interpolating than that employed.

Table 8.10 Shallow storage design treatments used in Experiment 6 and their effect on water storage characteristics, size of the ponded-area and annual fixed costs

Treat-ment No.	Coded Values(1) of design variables				Catch ment area (ha)	Storage Capacity (mm of (run-off)	Size of Irrign. Area (ha)	Stream Gradient	Dam Size(2)		Maximum depth of dam (m)	Maximum size of ponded -area (ha)	Annual Fixed Costs	
	X1	X2	X3	X4					(ML)	(ML/ha)			Water storage(3) ($/ha)	Total(4) ($/ha)
1	-1	-1	-1	-1	711	5	42	1:250	36	0.9	2.2	4	14	61
2	-1	-1	-1	-1	2245	5	42	1:250	112	2.7	3.2	9	21	68
3	-1	1	-1	-1	711	50	42	1:250	356	8.7	4.8	21	37	85
4	1	1	-1	-1	2245	50	42	1:250	1123	26.7	7.0	46	82	129
5	-1	-1	1	-1	711	5	189	1:250	36	0.2	2.2	4	3	32
6	1	-1	1	-1	2245	5	189	1:250	112	0.6	3.2	9	5	34
7	-1	1	1	-1	711	50	189	1:250	356	1.9	4.8	21	8	37
8	1	1	1	-1	2245	50	189	1:250	1123	5.9	7.0	46	18	47
9	-1	-1	-1	1	711	5	42	1:1000	36	0.9	0.9	8	14	62
10	1	-1	-1	1	2245	5	42	1:1000	112	2.7	1.3	20	20	65
11	-1	1	-1	1	711	50	42	1:1000	356	8.7	1.9	48	26	73
12	1	1	-1	1	2245	50	42	1:1000	1123	26.7	2.8	109	44	92
13	-1	-1	1	1	711	5	189	1:1000	36	0.2	0.9	8	3	32
14	1	-1	1	1	2245	5	189	1:1000	112	0.6	1.3	20	5	33
15	-1	1	1	1	711	50	189	1:1000	356	1.9	1.9	48	6	35
16	1	1	1	1	2245	50	189	1:1000	1123	5.9	2.8	109	10	39
17	-2	0	0	0	400	15	89	1:500	63	0.7	1.7	9	7	40
18	2	0	0	0	4000	15	89	1:500	632	7.1	3.6	48	19	52
19	0	-2	0	0	1265	16	89	1:500	20	0.2	1.2	4	6	39
20	0	2	0	0	1265	158	89	1:500	2000	22.5	5.3	106	40	73
21	0	0	-2	0	1265	15	20	1:500	200	10.0	2.5	21	48	127
22	0	0	2	0	1265	15	400	1:500	200	0.5	2.5	21	3	36
23	0	0	0	-2	1265	15	89	1:125	200	2.2	6.3	9	17	50
24	0	0	0	2	1265	15	89	1:2000	200	2.2	1.0	44	10	43
25	0	0	0	0	1265	15	89	1:500	200	2.2	2.5	21	11	43

(1) X1 = 1.7372 ln (catchment area) - 12.408
X2 = 0.8686 ln (storage capacity) - 2.3979
X3 = 1.3352 ln (irrigation area) - 6.000
X4 = 1.4427 ln (1/stream gradient) - 8.996

(2) The units of dam size are: (i) volume (ML) and (ii) volume per hectare of the irrigation-area (ML/ha).

(3) This is the annual fixed cost of the dam wall and drop-inlet construction per hectare of the irrigation-area.

(4) This is the annual fixed cost per hectare of the irrigation-area for water storage, irrigation works, farm machinery, fencing and ploughing.

Table 8.11 Estimated effects of catchment area, stream gradient, storage capacity and size of the irrigation-area on grain sorghum production from the irrigation-area, forage sorghum production from the ponded-area and costs of grain sorghum production.

Treat. No.	Catch-ment area (ha)	Storage Capacity (mm of run-off)	Size of Irrign. Area (ha)	Stream Gradient	Irrigated Grain Production (tonnes)					Ponded-Area Forage Production (tonnes)					Cost of Grain Production($/t)	
					Percentiles in years of cropping			Index of Variation (%)*	Long-term mean	Percentiles in years of cropping			Index of Variation (%)*	Long-term mean	Median	Long-term mean
					20th	50th	80th			20th	50th	80th				
1	711	5	42	1:250	52	88	139	99	45	5	6	8	50	3.1	58	85.5
2	2245	5	42	1:250	133	150	169	24	73	11	13	17	46	7.2	38	59.2
3	711	50	42	1:250	67	152	169	67	66	7	12	16	75	6.2	43	75.7
4	2245	50	42	1:250	146	158	176	19	77	11	15	19	53	7.8	53	90.6
5	711	5	189	1:250	95	209	440	165	125	5	6	8	50	3.1	77	89.4
6	2245	5	189	1:250	214	352	556	97	184	12	13	18	46	7.2	50	68.1
7	711	50	189	1:250	140	589	711	97	234	9	25	33	96	11.4	33	54.9
8	2245	50	189	1:250	399	677	758	53	294	19	27	36	63	14.5	32	51.5
9	711	5	42	1:1000	26	60	123	162	34	10	12	16	50	6.7	83	113.1
10	2245	5	42	1:1000	86	126	158	57	59	25	29	39	48	15.5	44	69.4
11	711	50	42	1:1000	27	148	169	96	58	10	40	55	113	18.1	41	77.0
12	2245	50	42	1:1000	101	157	170	44	70	30	58	79	84	29.5	44	76.3
13	711	5	189	1:1000	65	185	423	194	114	10	12	16	50	6.7	86	98.0
14	2245	5	189	1:1000	151	278	518	132	155	25	29	39	48	15.5	62	74.3
15	711	50	189	1:1000	93	436	704	140	208	15	53	75	113	25.3	41	58.6
16	2245	50	189	1:1000	155	675	756	89	268	28	80	115	109	39.8	30	50.0
17	400	16	89	1:500	55	158	268	135	78	5	13	17	92	6.2	56	78.9
18	4000	16	89	1:500	309	333	359	15	157	28	40	47	48	20.2	33	49.0
19	1265	2	89	1:500	38	93	208	183	57	5	6	8	50	3.1	89	104.0
20	1265	158	89	1:500	102	324	358	79	134	12	32	48	113	15.5	40	70.5
21	1265	16	20	1:500	69	73	80	15	35	13	19	24	58	9.3	53	92.8
22	1265	16	400	1:500	262	614	1115	139	331	14	29	39	86	14.5	55	69.3
23	1265	16	89	1:125	219	315	345	40	139	9	12	16	58	6.2	34	53.1
24	1265	16	89	1:2000	55	221	331	125	97	18	59	80	105	27.9	48	67.7
25	1265	16	89	1:500	102	301	340	79	125	14	28	37	82	14.0	33	53.8

* The index of variation is defined by (P80-P20)*100/P50 where P20, P50, P80 are respectively the 20th, 50th and 80th percentiles of production in years of cropping.

Table 8.12 Response surface regression coefficients (of equation 8.10 in text) for crop production and costs of production

Response Surface Coefficient	Grain production in years of cropping (t)				Long-term mean production (t)			Long-term mean cost of production ($/t)	
	20th percentile	median	80th percentile	index of variation	irrigated grain	ponded forage	total	grain	total
B_0	102.0	301.0	340.0	79.1	125.0	14.0	139.0	53.8	52.0
B_1	55.3**	44.1**	23.5**	-31.1**	18.9**	3.5**	22.4**	-7.4**	-7.3**
B_2	18.1*	83.5**	57.8**	-22.1**	26.7**	4.7**	31.3**	-7.6**	-8.0**
B_3	44.2**	146.7**	236.0**	26.3**	70.5**	1.6**	72.1**	-6.5**	-3.1**
B_4	-36.3**	-23.8*	-5.2	20.8**	-9.0**	5.8**	-3.2	3.2*	0.4
B_{11}	17.2	-12.6	-6.5	-0.4	-1.8	-0.1	-1.7	2.7	2.5
B_{22}	-10.8	-21.6	-14.1	13.5**	-7.3*	-1.1	-8.3*	8.5**	8.1**
B_{33}	13.1	17.3	64.5**	-1.0	14.6*	-0.4	14.2	7.0**	5.6**
B_{44}	6.0	-9.8	-38.5	3.6	-1.7	0.9	-0.8	1.8	1.1
B_{12}	8.0	-1.4	-10.6	7.2*	-0.6	0.3	-0.3	7.7**	7.1**
B_{13}	14.5	26.5	14.8	3.4	9.0**	0.3	9.3*	-0.5	-0.5
B_{14}	-16.0	5.9	-1.1	-2.1	-1.3	1.9**	0.6	-2.2	-2.0
B_{23}	13.6	72.6**	56.1**	-5.8	22.9**	1.8**	24.7**	-6.3**	-5.7**
B_{24}	-13.1	-1.5	4.2	-1.5	-0.1	3.1**	2.9	-4.3**	-4.4**
B_{34}	-14.1	-12.9	-1.9	-0.4	-3.3	0.4	-2.9	-0.1	1.6
R^2	0.94	0.98	0.99	0.98	0.99	0.98	0.99	0.98	0.97

* Statistically significant at P.05 ** Statistically significant at P.01

R^2 = coefficient of determination

Results will be given in the following order: grain production, forage production and total production.

Irrigated Grain Sorghum Production. The effects of each design variable on grain production, variability of grain production and cost of production are shown in a series of plots in figure 8.10. In each plot one design variable is changed while the other three are held constant and equal to their coded value of zero (i.e. catchment area = 1265 ha, stream gradient = 1:500, storage capacity = 15.8 mm of run-off and irrigation-area = 89 ha). These results and the results in table 8.11 show that:

(i) The long-term mean grain production was increased, and the annual variation in grain production reduced, by increased catchment area, increased storage capacity and steeper stream gradient. This occurred because these changes in shallow storage design increased the supply of water for irrigation, either by increasing the volume of water stored, or by reducing evaporation losses. Thus, management goals of maximizing irrigated grain production and minimizing variability of production can be achieved by selecting dam sites which have large catchments and steep stream gradients.

(ii) Grain production was most affected by changes in the size of the irrigation-area, and least affected by changes in stream gradient.

(iii) Both the long-term mean and the variability of grain production were increased by increases in the size of the irrigation-area. Therefore changes in the size of the irrigation-area have conflicting effects on management goals which aim to both maximize production and minimize variability.

(iv) The regression coefficients of the grain production response surface equation in table 8.12 show that two interactions were statistically significant. They were catchment area by size of the irrigation-area, and storage capacity by size of the irrigation-area. Since the maximum volume of water that can be stored in a dam is the product of catchment area and storage capacity (expressed in mm of run-off), these interactions show that both the size of the dam (i.e. its maximum volume) and the size of the irrigation-area must increase together to maximize production.

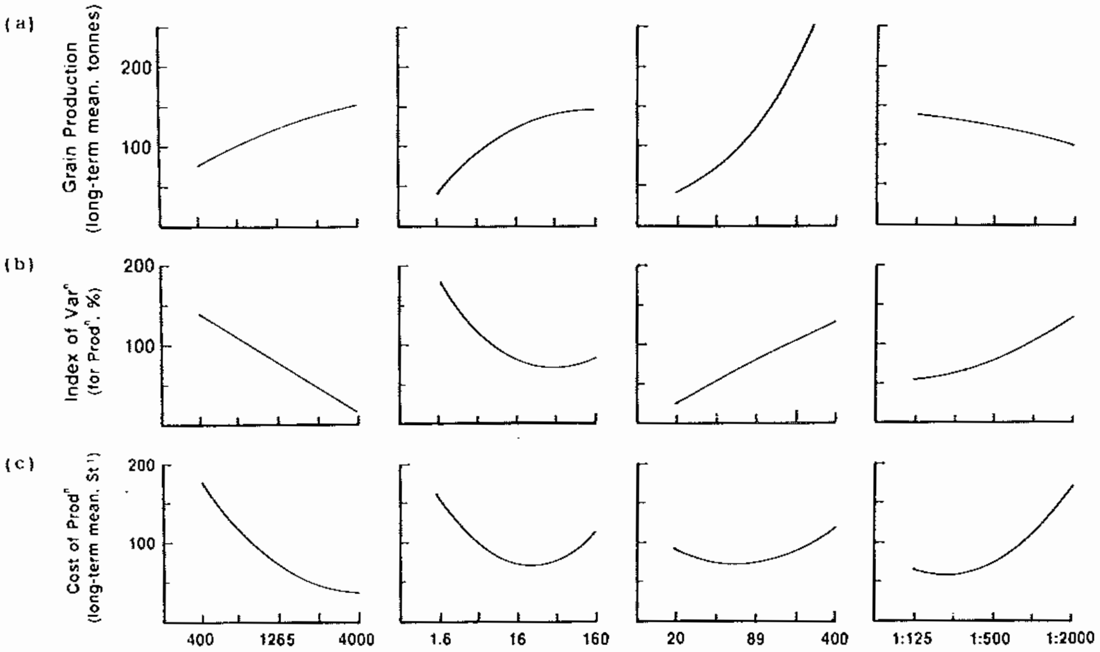


Figure 8.10 Effects of catchment area, storage capacity, size of irrigation area and stream gradient on (a) irrigated grain sorghum production, (b) variability of production and (c) cost of production. (The index of variation for production in (b) is equal to (P80-P20)x100/P50 where P20, P50, and P80 are the 20th, 50th and 80th percentiles of production in years of cropping).

(v) There were optimum values of storage capacity, stream gradient and size of the irrigation-area that minimized the cost of grain production. The long-term mean cost of grain per tonne was minimized ($46/t) when the size of the irrigation-area was 129 ha, when stream gradient was 1:483, and when water storage capacity was 441 ML (i.e. catchment area equal to 2943 ha and storage capacity equal to 15 mm of run-off). With this design, the long-term mean grain production was 192 tonnes, which is equivalent to a mean yield of 3080 kg/ha in the 29 years of cropping that were simulated. The flexible irrigation strategy results in Experiment 4 showed that two irrigations would be required in most years to achieve this mean yield.

(vi) The response surface regression equation of grain production costs per tonne in table 8.12 shows that all the coefficients of the interaction terms involving storage capacity were statistically significant. Therefore the storage capacity which minimized costs of production was dependent on the level of all the other design variables.

Ponded-Area Production. The results of simulation and the response surface equation of ponded-area forage sorghum production in tables 8.11 and 8.12 show that:

(i) Decreases in stream gradient and increases in catchment area, storage capacity and size of the irrigation-area led to increases in ponded-area production. This occurred because these changes in design increased the area of land available for cropping, either by increasing the area of land flooded by the dam, or by increasing the area of land exposed when water was used for irrigation.

(ii) Changes in stream gradient had a greater influence on ponded-area production than the other design variables. The large effect of stream gradient on the size of the ponded-area and the long-term-mean of forage production is shown by the data in table 8.13.

(iii) Forage production ranged from 3 to 40 tonnes when all combinations of the design variables at their coded values of -1 and +1 were simulated. In contrast the range in grain production from the irrigation-area was 34 to 294 tonnes for these treatments. Therefore, production from the ponded-area was very much lower than production from the irrigation-area.

(iv) The operating cost of ponded-area production was estimated to be $18 ± 2 $/t.

Table 8.13 Effects of stream gradient on the long-term means of crop production and costs of production*

	Stream Gradient				
	1:125	1:250	1:500	1:1000	1:2000
Maximum size of ponded area (ha)	16	24	37	35	80
Irrigated grain prodn. (t)	210	202	192	178	160
Ponded-area forage prodn. (t)	6	12	20	29	41
Total crop prodn. (t)	216	214	212	207	201
Grain prodn. cost ($/t)	54	49	47	49	54
Forage prodn. cost ($/t)**	18	18	18	18	18
Total prodn. cost ($/t)	52	47	44	44	45

* Values in this table were found by interpolation of response surfaces. The values of catchment area, storage capacity and size of the irrigation-area were those that minimized the cost of grain production, and were 2943 ha, 15 mm of run-off and 129 ha respectively.

** Only the operating cost of forage production is shown.

Total Production. Since forage production from the ponded-area was only a small fraction of the grain production from the irrigation-area (4 to 30%), the response surface of total crop production (i.e. grain plus forage) was very similar to the response surface for irrigated grain production. The response surface coefficients in table 8.12 show that the main difference in the response surface of grain and total production was in the response to stream gradient.

Stream gradient had very little effect on total crop production because decreases in grain production that were caused by decreases in stream gradient were compensated by increases in ponded-area production. This is shown by the data in table 8.13.

8.6.4 Optimizing Shallow Storage Design

Interpolation of response surface regression equations for the long-term mean of total production, and cost per tonne of total production, showed that there were many combinations of the design variables that gave the same level of production, and many other combinations of the design variables that gave the same cost of production. Lines on the response surface that link points of equal production are termed iso-quant lines, and lines that link points of equal cost are termed iso-cost lines.

This section identifies some general principles of shallow storage design by determining, for a range dam sites and levels of production, the combination of storage capacity and size of the 'irrigation-area that minimize the cost per tonne of total production.

The combinations of storage capacity and size of the irrigation-area for the catchment area and stream gradient of the dam site at RSSRP that give: (i) long-term mean production levels of 100, 200 and 300 tonnes, and (ii) long-term mean production costs of $80, $70, $60, and $50 per tonne, are shown in figures 8.11(a) and 8.11(b) respectively. Figure 8.11(a) shows for example, that a long-term mean production of 100 tonnes can be obtained from: (i) a storage capacity (SC) equivalent to 5 mm of run-off with an

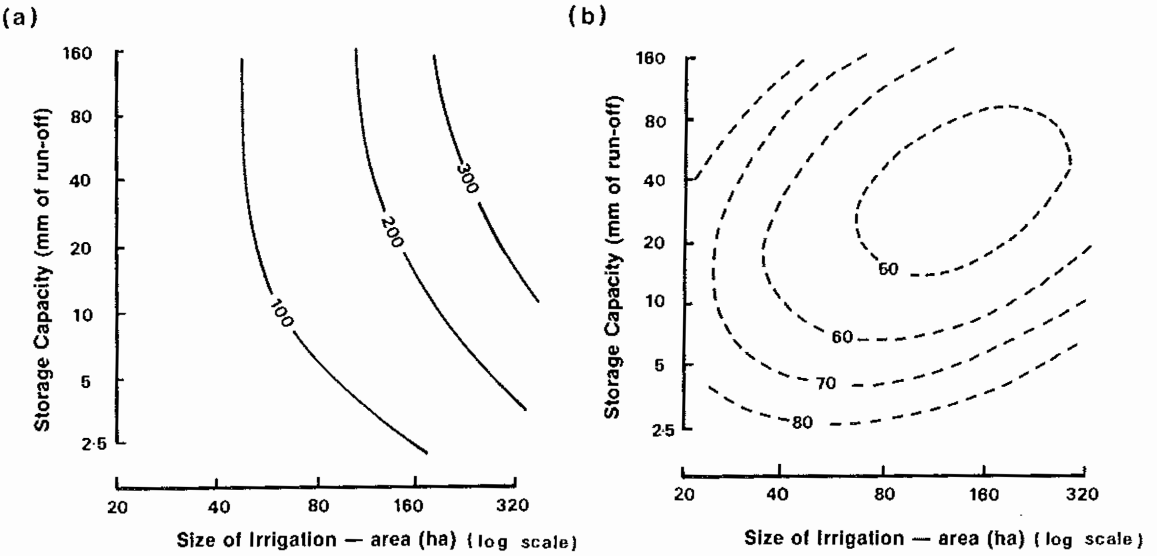


Figure 8.11 Effects of storage capacity and size of the irrigation-area (for the dam site at RSSRP) on: (a) 100, 200 and 300 tonne iso-quants of the long-term mean of total production, and (b) $80, 70, 60, 50 per tonne iso-cost lines for the long term mean of total production.

irrigation-area (AC) equal to 90 ha, or (ii) SC = 10 mm and AC = 62 ha, or (iii) SC = 20 mm and AC = 53 ha. To achieve higher levels of production then either or both storage capacity and irrigation-area must be increased.

Figure 8.11(b) suggests there is one combination of storage capacity and size of the irrigation-area that will minimize the cost per tonne of production. The combination of figures 8.11 (a) and (b) suggest there is also one combination of storage capacity and size of the irrigation-area that will minimize the cost per tonne on each of the production iso-quants.

The position of iso-quant and iso-cost lines with respect to storage capacity and size of the irrigation-area are unique for each dam site because of the influence that catchment area and stream gradient have on production and costs of production. Therefore least cost combinations of storage capacity and size of irrigation-area are also unique for each dam site.

The method adopted to find the optimum combination of storage capacity and size of the irrigation-area for a given level of total production was to search the production iso-quant defined by catchment area and stream gradient until the minimum cost of production was encountered.

Least cost combinations of storage capacity and size of the irrigation-area found for the dam site at RSSRP for long-term mean total production levels of 100, 200 and 300 tonnes are shown in figure 8.12 and were respectively: (i) 18 mm of run-off and 51 ha, (ii) 33 mm of run-off and 119 ha, and (iii) 52 mm of run-off and 206 ha. The iso-cline linking these points of minimum cost is called the 'least cost expansion path' and is shown in figure 8.12. The significant features of this figure are:

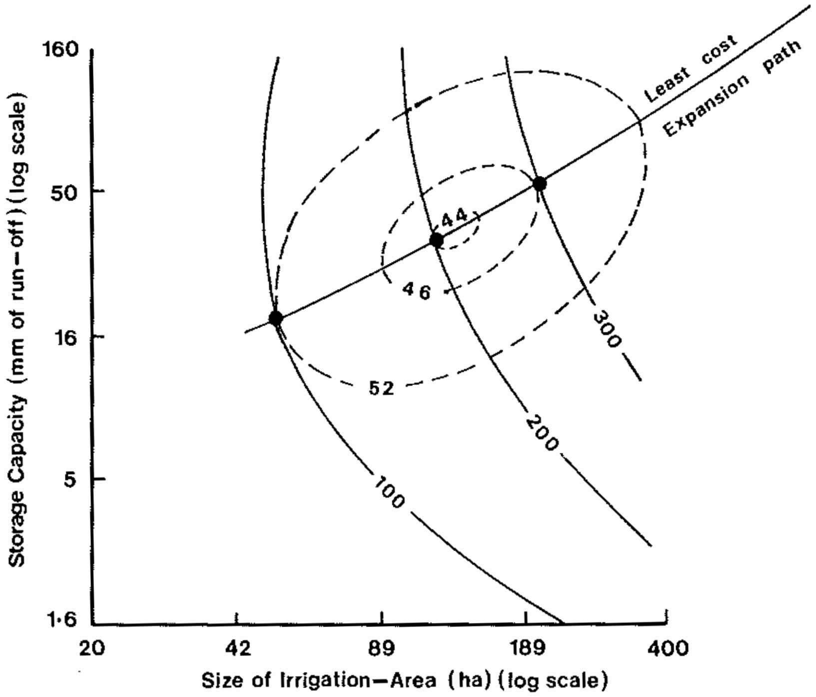


Figure 8.12 Least cost combinations of storage capacity and size of the irrigation-area at three levels of total production for the dam site at RSSRP. (100, 200 and 300 tonne production iso-quants are shown as the solid lines, iso-costs at $52, $46 and $44 per tonne are shown as the broken lines and optimum combinations of storage capacity and size of the irrigation-area are shown as the solid points).

(i) All points on the least cost expansion path are least cost combinations of storage capacity and size of the irrigation-area.

(ii) The iso-quants of both crop production and cost per tonne are almost parallel to the storage capacity axis at the point of least cost on the production iso-quant. Therefore, small deviations in storage capacity from its least cost value have little effect on production and cost of production. This is an advantage in water storage design since it allows some flexibility to select a bywash level that is perhaps more suited to the terrain than the level specified by the least cost storage capacity.

(iii) At the point of least cost on the 100 tonne iso-quant of total production the annual cost of increasing the size of the irrigation-area by one hectare was \$50.31. In contrast, the annual cost of increasing storage capacity so that an additional one hectare of land could be irrigated was only \$8.89. Since the low cost of water storage compared to the cost of farming is likely to remain true over a wide range of economic conditions, the above finding suggests that the least cost expansion path shown in figure 8.12 would also remain fairly constant over a wide range of economic conditions.

When crop production was simulated over 60 years using shallow storage designs equivalent to the points of least cost on the 100, 200 and 300 tonne iso-quants in figure 8.12, the results showed that:

(i) The least-cost storage capacities were large enough to supply two irrigations to their corresponding least-cost irrigation-areas, if the storages were full at the time of planting. Therefore, the optimum storage capacity was large enough to ensure near maximum grain yields. However variability in climate and catchment run-off reduced the mean frequency of irrigation, and consequently the mean yield per hectare of grain sorghum. In the 29 years of cropping, the average frequency of irrigation for the designs which minimized costs on the 100, 200 and 300 tonne iso-quants were 1.9, 1.6 and 1.4 per season respectively, and the corresponding mean grain yields were 3204, 2921 and 2722 kg/ha respectively.

(ii) At the points of least cost on the 100, 200 and 300 tonne iso-quants of total production the contribution of ponded-area forage sorghum to total production was 21, 16 and 11 percent respectively. Crop production from the ponded-area was therefore a minor part of total production, and decreased in significance as the required level of total production increased. Annual variation in the area of land cropped on the ponded-area was found to account for most of the annual variation in ponded-area forage production, and was 66, 86 and 87% respectively for the three designs given above. Therefore, annual variation in forage sorghum yield/ha had only a minor influence on ponded-area production, and hence only a very small influence on total crop production. This result suggests that any evaluation of shallow storage irrigation would be little effected by variation in ponded-area yields, and that use of a constant yield equal to the long-term mean would suffice most purposes.

The effect of catchment area and stream gradient on the optimum combination of storage capacity and size of irrigation-area are shown in figure 8.13, where least cost expansion paths are plotted for: (i) three levels of total production (100, 200 and 300 tonnes), (ii) three levels of catchment area (711, 1265 and 3343 ha), and (iii) three levels of stream gradient (1:250, 1:500, 1:1000). The unit of storage capacity in this figure is volume of water storage (in mega-litres) and is expressed as dam size. Regression analysis of the results in figure 8.13 showed that the least cost combinations of size of the irrigation-area and dam size could be estimated quite accurately with the following equations:

$$\mathrm{ACopt} = 0.727\ \mathrm{TP} + 0.120\ \mathrm{TP/ACAT} - 29.5 \qquad (8.11)$$

(Coefficient of determination = 0.99, N = 27), and

$$\mathrm{Dopt} = 3.19\ \mathrm{ACopt} - 0.721\ \mathrm{ACopt/ACAT} + 0.360/G - 113 \qquad (8.12)$$

(Coefficient of determination = 0.95, N = 27)

where ACopt = optimum size of irrigation-area (ha), Dopt = optimum dam size (ML), TP = required level of total production (long-term mean, tonnes), ACAT = area of catchment ('000 ha), and G = stream gradient of dam site.

These results show that the main factor affecting the optimum combination of dam size and size of the irrigation-area was the level of production required from the system. The mean effects of increasing the required production level from 100 to 300 tonnes were to: (i) increase the frequency of irrigation demand exceeding water supply, and (ii) increase the demand for irrigation water. These effects increased the optimum size of the irrigation-area from 0.57 to 0.75 ha per tonne of required production, and increased the optimum size of the dam from 237 to 638 ML. Because the proportion of water storage lost to evaporation decreased as depth of water storage increased, the optimum volume of water storage per hectare of cropping on the irrigation-area was reduced from 4.2 to 3.0 ML as the level of production increased from 100 to 300 tonnes.

The results also show that as the supply of water was reduced by decreases in catchment area, that it was necessary to reduce dam size and increase the irrigation-area in order to minimize costs of production. The mean effect of decreasing catchment area from 2249 ha to 711 ha was to increase the optimum size of the irrigation-area per tonne of production from 0.64 to 0.74 ha, and to decrease dam size per hectare of the irrigation-area from 3.9 to 3.2 ML.

Stream gradient had little effect on the optimum irrigation-area, but as stream gradient decreased the optimum dam size was greatly increased. Costs of production were reduced as stream gradient decreased from 1:250 to 1:1000, however the volume of water storage required per hectare of the irrigation-area was increased from 2.4 to 4.7 ML.

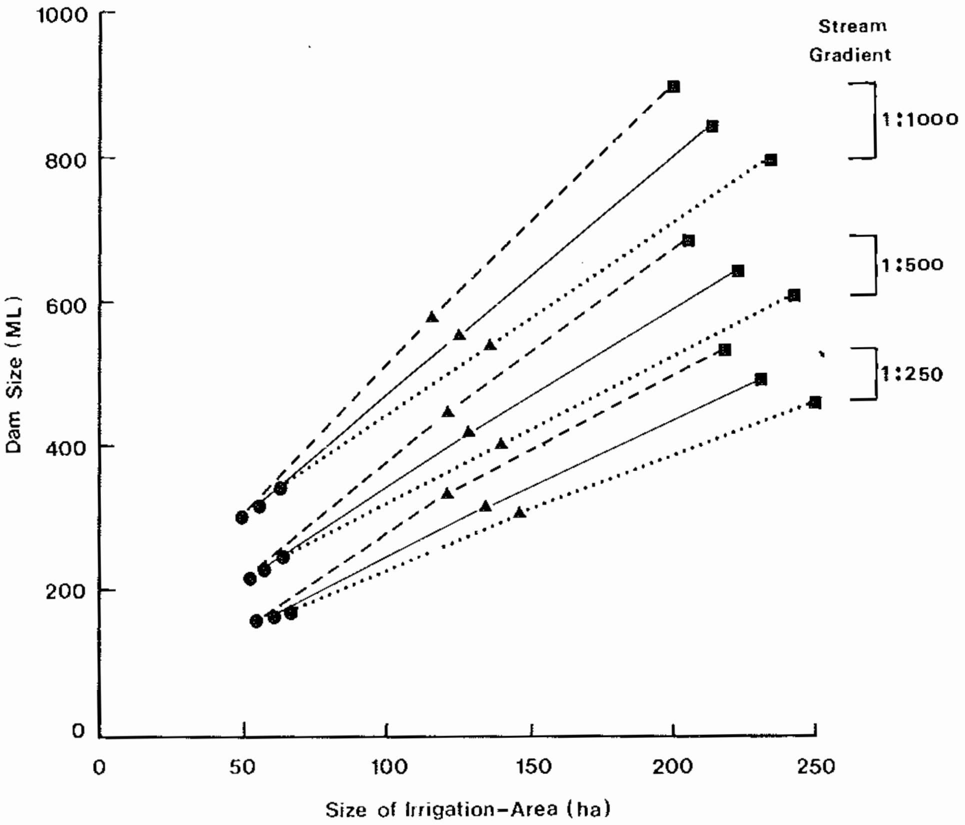


Figure 8.13 Effects of catchment area and stream gradient on least cost combinations of dam size and size of the irrigation-area at three levels of total production
(Production levels (tonnes): ● = 100, ▲ = 200, ■ = 300)
(Catchment areas (ha): ••••• = 711, —— = 1265, - - - = 2249)

In Experiment 3 the volume of water required for two irrigations that were timed 25 and 55 standard days after planting was found to be 1.5 ML/ha when averaged over all years and 1.8 ML/ha in years of low rainfall. Therefore, the volume of water required for two irrigations was equivalent to approximately one third to one half of the optimum dam sizes given above. Thus, water storage evaporation loss was the major component in the water balance of the dam.

The shallow storage design found to minimize the cost per tonne of total production was as follows: (i) catchment area = 2249 ha, (ii) stream gradient = 1:1000, (iii) storage capacity = 25.7 mm of run-off = dam size of 579 ML, and (iv) irrigation-area = 115 ha. The levels of ponded-area forage production, irrigated-area grain production and total production for this design were estimated to be 30, 170 and 200 tonnes respectively. The cost of production was estimated to be $43/t.

8.6.5 Conclusion

Conclusions concerning principles of shallow storage design were given earlier during the discussion of simulation results. Perhaps the most important conclusion of a general nature from this experiment is that changes in crop production caused by changes in shallow storage design were curvilinear and interactive. This finding necessarily excludes the use of simple methods such as linear, additive models to predict the productivity of shallow storage systems. In contrast to this finding, it was also found that two relatively simple equations could be used to determine the optimum combination of water storage capacity and size of the irrigation-area for a given dam site.

CHAPTER 9

DISCUSSION AND CONCLUSIONS

This chapter uses the simulation results of chapter 8 to evaluate the feasibility of shallow storage irrigation as a management option for properties on the Mitchell grass plains of north west Queensland. The essential features of the shallow storage irrigation concept given in chapter 1 were: (i) stabilization of grain sorghum production via application of one supplementary irrigation that was timed shortly before flowering, (ii) production of ponded-area forage sorghum, and (iii) conservation of grain and forage for subsequent use in supplementary stock feeding programmes which aim to increase annual production. While it was recognized that droughts would prevent crop production in some years, it was suggested that crop production would be possible in about 70% of years.

Some general conclusions are reached at the end of this chapter after discussing: limitations of the simulation results, principles of shallow storage design and management, the effect of climatic variability on the feasibility of shallow storage irrigation, and the feasibility of shallow storage irrigation in relation to animal production.

9.1 Limitations of the Simulation Results

The evaluation of shallow storage irrigation in this chapter depends on the validity of using the shallow storage system model for extrapolation. Care was taken in development of the model to incorporate the main factors and relationships affecting the performance of the system. It was concluded that the system's model could be used with reasonable confidence to simulate the performance of shallow storage systems through time at most localities on the Mitchell grass plains because:

(i) each of the models describing the main components of the system (i.e. catchment run-off, water storage, irrigated grain production and ponded-area forage production) gave reasonable agreement with observed data from RSSRP, and

(ii) the climate, topography, soils and vegetation of the Mitchell grass plains were shown to have a high degree of spatial homogeneity and were considered to be typified by the experimental site at RSSRP.

However, in abstracting the reality of a shallow storage system to a mathematical model it was necessary to omit some factors known to cause variation in crop production. For example, factors contributing to differences shown in chapter 3 between run-off from the gauged catchment and the dam's catchment at RSSRP, were not incorporated in the model. Similarly, the consequence of erratic plant establishment and bird damage on grain yield were not incorporated in the model although they were shown in chapter 5 to have significant effects on yield. In view of the above, the results of the simulation experiments reported in the previous chapter should be interpreted as a guide to the performance of shallow storage systems rather than an accurate description of system performance. For example, values determined by equations 8.11 and 8.12 as the optimum combination of storage capacity and size of the irrigation-area for a dam site, should be used to indicate the optimum region rather than precise values.

It was concluded that the methods of this study could have been improved if modelling and simulation had been conducted in parallel with the field experiments. Had this been done it is now apparent that more emphasis would have been given in the field experiments to measuring processes and relationships rather than the end results of statistically based experimental designs. For example, greater emphasis would have been attached to measuring plant growth rates and the influences of soil cracks, ploughing and plant cover on infiltration, evaporation and transpiration rates.

With the advantage of hind-sight, a major criticism of the study is now evident. This is the disproportionately small level of research that was directed to measuring the factors affecting variability of catchment run-off. A better balance of resources would have been obtained if run-off from a range of catchments had been measured. The Water Resources Commission's weir at RSSRP is the only run-off recording site on the Mitchell grass plains. There are some sites on major streams but information from these is not applicable to farm dams because of their much larger catchment areas.

9.2 Principles of Shallow Storage Design and Irrigation Management

The simulation experiments were found to be an effective way of isolating principles of shallow storage design and irrigation management that can be applied to improve the system's productivity and economic efficiency. This is illustrated in figure 9.1 where the time series of profits per hectare from irrigated grain production found in simulation experiment 6 are compared to the time series found in experiment 1.

Results from simulation experiment 6 showed that irrigated grain production was most efficient (in economic terms) if the shallow storage dam was constructed large enough to supply at least two irrigations to the irrigation area; and results from simulation experiment 4 showed that production was most efficient (in biological and economic terms) if a flexible irrigation strategy was used with three irrigations in the schedule, and with priority allocated to irrigation just before flowering. These results suggest a more intensive approach to irrigation management than was proposed, and hence an important shift in the concept of shallow storage irrigation away from supplementary irrigation.

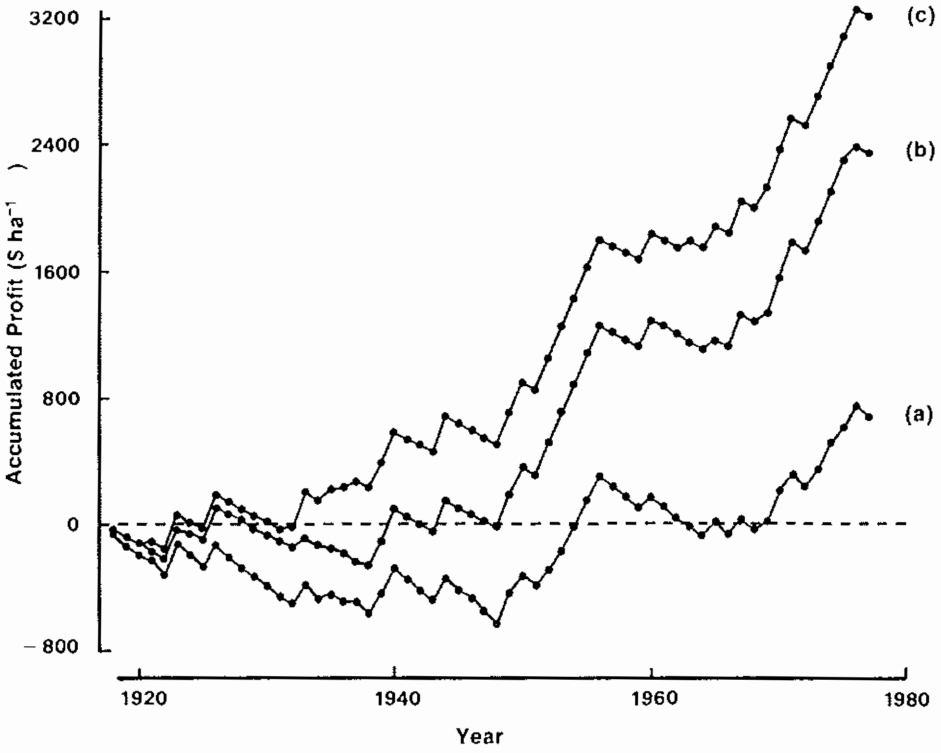


Figure 9.1 Simulated time series of accumulated profits per hectare from irrigated grain sorghum.

(a) Time series found in the first simulation experiment for the dam site at RSSRP, when the irrigation strategy, storage capacity and size of the irrigation-area suggested by Wegener and Weston (1973) were used.

(b) Time series found in simulation experiment 6 for the dam site at RSSRP, when a flexible irrigation strategy was used with the storage capacity and size of irrigation-area that minimized the long-term mean cost per tonne of total crop production.

(c) Time series found in simulation experiment 6 when a flexible strategy was used with the optimum combination of all design variables (i.e. catchment area, stream gradient, storage capacity and size of the irrigation-area) that minimized the long-term mean cost of grain production.

In discussing results from simulation experiment 6 it was stated that there was some flexibility to select a bywash level that was more suited to the terrain than the level specified by the storage capacity that minimized the cost per tonne of crop production. This is important because the risk of erosion to the bywash return slope of dams on the Mitchell grass plains is considerable. Extensive erosion occurred to the earthworks of the dam at RSSRP on three separate occasions during the period 1967 – 1981 and on one occasion some 5000 m^3 of earth was eroded from the bywash return slope.

The return slope of native pasture bywashes are prone to erosion because the tussock habit of native pasture causes turbulent water flow and provides little protection to the underlying and easily erodable clay soils. If dams are constructed on waterways which have a large catchment area, so that they will fill in a high proportion of years, then the risk of failure in irrigation supply is reduced but the risk of erosion to the bywash is increased. For example, if a dam is constructed to hold 10 mm of catchment run-off when full, then it is estimated from equation 8.1 that the dam will fill in 41% of years but will be required to bywash more than four times its capacity in more than 20% of years.

A problem found in simulating the system was the difficulty of introducing sufficient management flexibility in the model. For example, in the simulation experiments of chapter 8 there were three years that were simulated as non-cropping years on the irrigation-area because planting conditions were not satisfied until April. This was too late for planting of grain sorghum. A flexible planting strategy that switched from summer crops (grain sorghum) to winter crops (wheat or oats) would have therefore increased the reliability and productivity of the system. The simulated productivity of the system would have also been enhanced if the model had been designed to accommodate a second area of irrigated cropping if surplus irrigation supplies were available.

9.3 Effect of Climate Variability on the Feasibility of Shallow Storage Irrigation

Important conclusions of the study concern the effects of rainfall variability on catchment run-off, irrigation supplies and crop production. Variation in other climatic characteristics such as temperature and evaporative demand did not have large effects on variability of crop production.

The two main factors which led to the large variation in crop production were the low frequency of cropping and the unreliability of water supplies for irrigation. Because catchment run-off determined cropping frequency, irrigation supply and the maximum area of cropping on the ponded-area, the main effect of rainfall variability on crop production was through its effect on catchment run-off. The direct effects of rainfall variability on grain and forage yields were much less important.

The time series of profit per hectare from irrigated grain production in figure 9.1 shows that losses were frequent and persisted for more than three consecutive years on a number of occasions, particularly in the first half of the 60 year simulation period. These losses were caused by the lack of irrigation supply. Therefore the proposal that shallow storage irrigation would stabilize crop production was not substantiated.

The previous conclusion relies heavily on the results of run-off simulation and therefore the validity of using the run-off model for extrapolation warrants closer scrutiny. There are two possible sources of error. The first applies to the capacity of the model to accurately extrapolate prediction of run-off from the calibration period (10 years) to the full simulation period (60 years). The second lies in extrapolating the frequency distributions of run-off found for the gauged catchment at RSSRP to other catchments in the region. Other catchments, when compared to the gauged catchment would almost certainly show some differences in run-off characteristics because of small differences in soil type, vegetation and topography with larger differences in storm patterns, catchment area and grazing pressure.

The significance of the above extrapolation errors cannot be defined in quantitative terms because information is not available. However, the generality of the model can be defended to some extent because: (i) a wide range of seasonal conditions from extreme drought to record floods were experienced during the model's calibration period, and (ii) the infiltration characteristics of the soil were found to behave in a manner similar to a bucket so that run-off was largely dependent on daily rainfall and antecedent soil moisture.

Expectations of summer rainfall decrease in a south-westerly direction across the Mitchell grass plains and therefore expectations of run-off are also likely to decrease in this direction. Because Richmond lies on the northern boundary of the Mitchell grass plains (see figure 1.1) it is in a position of comparatively high summer rainfall. Therefore the gauged catchment at RSSRP probably has a run-off expectation that is higher than most catchments on the Mitchell grass plains. Consequently, shallow storage irrigation is likely to be less feasible at locations around Winton and Longreach than was found for Richmond. This could be tested by using weather records from a number of centres as input to the model.

One method of enhancing the viability of shallow storage irrigation would be to choose only those catchments on laterite or limestone formations. These catchments are known to produce more run-off than Mitchell grass catchments but they are relevant to only a small proportion of properties in the region (about 2%). A second method of increasing catchment run-off would be to denude the catchment area by over-grazing. However this is undesirable in terms of soil conservation and probably animal production.

The need to quantify the effects of climatic variability contained in long-term climatic records was proposed as one reason for using a modelling / simulation approach in this study. The simulation results suggest that the data recorded during the experimental period were biased when compared to long-term averages. For example, the mean and median of annual catchment run-off from 1968 to 1978 were observed to be 76 and 50 mm respectively, whereas the mean and median of the 60 year simulation for annual run-off were much less and were 35 and 5 mm respectively. While the frequency of cropping during the experimental period was 0.75 (six years in eight), the estimated cropping frequency in the 60 year simulation period was 0.48 and in one period there was only one year of cropping in eight years. It is therefore concluded that evaluation of shallow irrigation without reference to long-term weather records would have been misleading.

In view of the above comments some conclusions of a general nature can be made and are as follows:

(i) Short-term measurements of biological productivity can give misleading estimates of the mean and median in climates as variable as the climate of the Mitchell grass plains.

(ii) Where field experiments are conducted in variable climates it is important to measure the environmental conditions of the experiment and to then test the results over long periods of time. This implies that modelling and simulation are essential components of the research method.

(iii) It is important to obtain field data from a diversity of environmental conditions so that parameters in the model are not biased.

(iv) Emphasis should be attached to variation in short-term (5-10 years) production because of its relevance to the horizons of farm planning.

The sixty year means and probability distributions found in this study should be interpreted with some caution because they are sample estimates from an unknown but highly variable population. A similar conclusion was reached by White (1978). After generating a series of 50 year rainfall sequences for the Mitchell grass plains, White found that the most efficient system of sheep management was marginally dependent on which 50 year rainfall sequence was used in simulation.

9.4 Feasibility of Shallow Storage Irrigation in Relation to Animal Production

The rationale for shallow storage irrigation proposed in chapter 1 requires that the costs of cropping are regained through increased animal production.

Field trials at RSSRP showed that forage sorghum grown on the ponded-area was well suited for use as a grazing crop. Cattle were fattened after 3 months grazing during winter and spring, and were then sold to the butcher's market when premium prices were available. Live-weight gains were approximately 0.6 kg/head/day (Weston and Smith 1976). If an average beef price of $0.75/kg is assumed, then the gross return per animal is $41 after three months grazing.

Operating costs of ponded-area forage sorghum production were found in chapter 8 to be approximately $18/t. Assuming a grazing animal requires 333 kg/month, then the calculated net return after three months grazing is $23 per animal. This profit margin is reduced substantially if a proportion of the fixed costs (interest, depreciation and maintenance) of water storage are charged to the ponded-area. For example, if a 200 ML dam is built to store water from a 1200 ha catchment and if one fifth of the annual fixed costs for water storage are proportioned to the ponded-area, then estimates of fixed costs per beast fattened range from $7 to $49 as stream gradient at the dam site increases from 1:2000 to 1:125.

It was concluded that ponded-area cropping to fatten cattle could be a useful adjunct to irrigated cropping provided: (i) the purchase and selling prices of cattle were favourable, and (ii) irrigated cropping was economically viable so that most of the fixed costs of the water storage could be diverted away from the ponded-area.

Supplementary feeding of pregnant/lactating ewes with grain to increase reproductive rates was suggested as one way of improving sheep production on the Mitchell grass plains. An appropriate feeding ration could be 3 kg of grain per head per week for 12 weeks at the time of lambing. Such a programme would require 72 tonnes of grain per annum to feed an average flock of 2000 ewes. Provision of this quantity of grain is well within the long-term mean productivity of shallow storage schemes such as the scheme at RSSRP. However it would be necessary to stockpile large quantities of grain to ensure the continuity of the supplementary feeding programme during non-cropping years. Storage facilities for grain and losses of grain in storage would add substantially to the cost of grain.

If the feed ration given above increased the long-term mean lambing percentage by 10 percent from the current low level of 45 percent, the return per breeding ewe was estimated by White (1978) to be $0.70, and the break-even cost of feed to be $19.44/t. Comparison of this feed cost to the long-term, mean cost of crop production ($46 to $60/t) shows that lambing percentages must increase by up to 30% to just cover the cost of cropping. Such an improvement in reproductive rates would be very unlikely unless other factors in the environment governing lamb survival and genetic composition of the flock were improved.

This analysis suggests that shallow storage irrigation systems should either:

(i) concentrate on production of high value cash crops that are not linked to supplementary stock feeding programmes, or

(ii) be relegated to opportunistic agriculture in which annual land preparation before the wet season is avoided, and use of agricultural machinery is minimized. A system similar to this is being tested at the Queensland Department of Primary Industries Toorak Field Research Station at Julia Creek. Emphasis in this study is being attached to the ponded-area, where the benefit to sheep reproduction from shade trees as well as forage crops is being assessed.

9.5 General Conclusions

The main finding of this study is that crop production from shallow storage irrigation systems is not reliable and does not have the necessary low cost productivity for inclusion in animal production systems on the Mitchell grass plains of North West Queensland. Shallow storage irrigation has the biological capacity to boost animal production but it fails because of economic considerations.

Although the above conclusion is negative in terms of agricultural production, the study was successful with respect to evaluating an agricultural system. The results have been useful in countering a renewed interest by graziers in agriculture. This interest has arisen partly because of purchase of properties in the region by people with a background in farming and partly because of the many 'good seasons' that occurred during the 1970's.

In extending information to primary producers the author has found that information taken directly from the field experiments has been useful but of limited value. Producers have found it difficult to see the relevance of isolated pieces of information because of the problems of integrating to the whole system. In contrast, results from the simulation experiments have had an immediate impact on producers, particularly information such as the time series data in figure 9.1. Therefore, the study was successful in its objective of transforming field data to a form pertinent to management decision making.

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APPENDIX A: MONTHLY WEATHER RECORDS FROM RICHMOND POST OFFICE

Table A1	Monthly means of mean daily maximum temperature at screen height (°C).
Table A2	Monthly means of mean daily minimum temperature at screen height (°C).
Table A3	Monthly estimates of mean daily evaporative demand (mm) calculated by the method of Fitzpatrick (1968).
Table A4	Monthly totals of daily rainfall (mm).

APPENDIX A Table A1 Monthly means of mean daily maximum temperature at screen height (Observed at the Richmond Post Office, January 1941 to December 1975).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1941	33.0	34.6	33.4	29.2	27.6	24.2	25.9	26.6	32.3	36.1	37.0	37.9
1942	40.8	36.6	38.3	33.5	29.9	27.8	26.6	30.4	32.9	34.9	37.2	36.4
1943	37.2	33.9	36.4	33.6	27.6	24.7	27.4	28.9	31.7	36.2	37.6	38.9
1944	40.2	33.1	32.9	33.2	27.8	25.4	25.2	28.7	32.1	34.2	38.6	37.2
1945	38.1	36.9	33.1	31.7	27.5	27.3	24.6	31.4	32.5	34.9	38.4	39.2
1946	35.1	34.7	35.5	32.9	30.8	24.7	27.3	29.2	32.3	34.8	38.2	39.3
1947	40.1	33.8	34.9	31.4	29.0	28.1	27.3	28.6	30.3	34.3	37.5	37.4
1948	34.7	37.9	37.0	33.2	29.8	26.4	26.7	28.4	31.7	36.4	38.4	37.7
1949	37.2	36.2	34.2	30.4	28.2	23.5	25.3	27.9	31.1	35.7	36.6	37.7
1950	35.5	33.4	31.4	27.9	28.3	23.7	25.4	26.6	31.7	33.5	35.4	34.5
1951	31.9	34.2	35.6	33.3	28.7	25.2	25.6	26.9	31.5	35.6	39.0	39.4
1952	38.8	38.6	37.5	32.8	30.2	26.3	26.7	27.8	32.6	35.7	37.8	38.9
1953	33.3	31.2	33.8	34.4	27.2	26.7	26.0	26.0	31.0	36.6	37.4	39.9
1954	35.2	32.6	32.6	31.4	28.8	23.9	26.4	28.3	31.6	34.8	37.5	36.7
1955	36.4	33.3	30.7	29.9	26.4	25.5	25.7	29.5	31.4	35.6	36.2	38.2
1956	35.1	32.2	31.2	30.7	27.7	25.2	25.2	25.9	29.1	35.1	36.9	34.8
1957	32.9	35.1	32.2	34.2	28.6	26.9	24.4	28.2	31.6	36.4	37.8	38.5
1958	36.9	35.4	37.1	31.3	31.2	25.3	28.0	29.3	30.1	35.8	36.8	38.4
1959	35.3	36.1	34.1	32.6	27.0	25.9	24.7	28.4	31.0	35.5	38.1	39.2
1960	37.6	35.2	33.8	32.8	24.7	25.8	25.5	26.7	31.8	36.6	37.1	35.9
1961	35.0	35.8	34.9	34.1	28.3	24.9	25.7	26.4	31.9	35.4	36.7	38.1
1962	37.4	36.3	33.8	31.4	28.5	27.1	25.6	28.2	30.3	36.7	38.8	37.2
1963	36.1	35.4	34.7	29.9	28.7	25.1	24.4	27.9	31.8	33.0	37.6	38.1
1964	35.4	34.5	34.9	33.8	29.0	25.1	27.5	28.9	32.6	34.6	36.0	35.8
1965	37.6	38.1	33.4	33.4	30.0	26.1	23.9	29.2	32.5	35.1	38.4	34.9
1966	34.6	37.1	35.9	33.4	28.4	25.8	25.9	26.8	31.4	32.9	35.9	37.8
1967	39.8	36.6	34.1	33.3	28.8	24.2	23.9	27.3	31.6	36.4	37.7	38.2
1968	37.9	33.7	34.4	34.0	25.7	26.7	25.1	28.4	32.4	35.0	38.5	36.9
1969	37.8	38.4	36.2	33.1	29.6	26.0	27.5	29.8	29.8	35.8	38.3	37.7
1970	39.0	35.1	34.9	33.5	29.4	27.9	26.0	28.4	32.5	36.1	37.4	37.8
1971	38.9	36.2	31.6	28.1	27.4	24.5	24.6	30.9	33.8	38.0	37.7	38.0
1972	35.4	34.1	33.1	32.0	27.6	26.4	25.9	29.1	32.4	36.0	36.9	38.7
1973	38.2	34.5	34.9	31.6	31.0	29.5	27.9	30.5	31.2	35.9	36.0	36.8
1974	30.6	33.8	32.5	32.6	28.2	25.9	27.0	29.1	32.4	35.7	37.9	39.0
1975	35.3	32.6	34.1	31.7	30.0	26.3	29.1	29.4	34.1	34.4	38.2	35.2
MEAN	36.41	35.06	34.26	32.18	28.50	25.83	26.00	28.40	31.74	35.42	37.47	37.61
S.DEV.	2.42	1.82	1.82	1.69	1.43	1.34	1.25	1.37	1.03	1.07	0.90	1.36
C.V.%	6.65	5.20	5.32	5.25	5.01	5.19	4.79	4.83	3.25	3.01	2.39	3.72

APPENDIX A Table A2 Monthly means of mean daily minimum temperature at screen height (Observed at the Richmond Post Office, January 1941 to December 1975).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1941	21.6	21.2	21.9	17.3	14.0	9.1	6.2	6.3	12.7	17.9	22.4	21.8
1942	25.1	22.7	21.7	18.1	15.2	12.8	10.4	11.0	15.2	17.4	20.4	22.6
1943	22.6	22.8	19.9	16.9	12.0	6.7	7.2	9.8	14.6	19.2	20.1	22.1
1944	24.9	22.7	19.8	15.9	9.7	11.3	9.7	9.3	14.2	16.1	20.9	23.2
1945	23.1	23.1	20.4	16.4	11.6	12.1	9.4	11.8	13.1	17.7	20.2	23.5
1946	23.7	22.7	18.0	13.4	13.3	5.4	6.6	8.4	13.3	15.7	21.5	23.4
1947	24.1	22.2	22.3	14.4	13.6	10.4	8.7	12.4	15.6	17.7	19.5	21.6
1948	20.2	23.9	22.7	15.9	12.5	9.3	10.1	10.1	12.1	18.1	22.3	22.9
1949	22.6	23.6	22.4	15.7	12.3	6.3	6.8	9.3	14.2	20.1	19.4	23.1
1950	22.2	22.2	21.4	16.6	11.6	7.9	11.1	8.2	13.3	17.1	19.7	21.8
1951	21.5	20.6	18.6	13.4	10.2	7.8	6.9	6.7	11.8	16.1	19.1	20.6
1952	23.4	22.1	20.4	16.6	13.8	7.3	9.4	9.9	14.0	18.5	20.3	22.5
1953	22.8	19.8	18.9	17.5	8.8	7.7	7.0	7.7	12.8	17.6	20.5	23.0
1954	22.1	20.7	19.3	17.2	11.4	7.6	8.3	11.2	12.9	18.6	19.9	21.7
1955	22.5	22.3	20.5	17.4	12.6	11.3	10.3	10.3	13.3	19.6	19.2	19.8
1956	21.1	22.3	20.3	16.7	13.4	7.7	9.2	7.9	11.0	16.8	20.1	21.4
1957	20.9	22.1	19.7	16.4	11.1	11.5	8.5	8.8	10.8	17.6	18.9	22.8
1958	22.4	21.8	21.3	18.3	16.9	11.3	9.4	11.1	11.2	17.7	22.4	23.1
1959	23.2	22.1	21.6	18.2	15.4	11.4	9.7	9.6	14.5	17.5	21.5	23.4
1960	24.6	23.5	20.8	17.3	11.5	9.4	9.4	8.6	13.6	17.7	20.4	22.1
1961	22.9	22.9	19.6	19.5	12.7	8.0	8.6	7.6	14.6	19.9	21.9	22.2
1962	24.7	23.6	20.6	16.1	11.6	12.2	10.0	9.2	15.1	18.9	21.6	21.1
1963	23.2	23.3	22.3	17.7	12.9	9.3	6.3	11.9	12.3	17.3	20.5	22.3
1964	22.9	20.8	21.3	18.6	14.2	9.3	10.0	10.1	17.6	18.7	19.8	21.4
1965	22.2	22.5	21.1	16.4	15.2	11.0	6.2	11.7	14.7	18.1	20.8	21.7
1966	22.9	21.1	19.8	17.8	12.4	11.1	8.4	12.2	15.2	16.1	20.6	22.2
1967	24.4	24.2	21.2	17.7	13.1	11.7	9.9	9.4	11.6	19.1	22.2	22.4
1968	24.1	23.0	22.8	18.1	13.6	9.6	9.4	11.7	10.2	17.5	20.1	21.4
1969	23.9	24.5	21.6	16.4	14.5	10.2	12.1	12.9	10.1	18.8	19.1	21.9
1970	21.5	22.6	18.8	17.9	12.9	9.9	7.3	9.4	14.4	19.1	22.0	21.9
1971	22.7	23.4	20.9	16.8	11.1	7.6	7.7	12.3	14.8	16.8	17.0	21.8
1972	19.7	20.4	19.9	16.0	12.6	10.8	6.5	9.1	13.8	15.7	20.8	19.2
1973	22.2	22.3	21.0	17.7	14.1	11.8	10.0	12.1	13.5	16.3	21.0	22.0
1974	23.0	22.4	20.8	15.5	12.1	6.8	6.2	9.5	12.9	17.0	18.8	21.7
1975	21.6	21.3	20.1	15.8	11.1	9.0	9.5	9.7	16.1	17.2	19.5	21.8
MEAN	22.75	22.36	20.68	16.79	12.71	9.50	8.64	9.92	13.46	17.75	20.41	22.04
S.DEV.	1.29	1.11	1.20	1.33	1.69	1.95	1.59	1.70	1.70	1.17	1.21	0.95
C.V.%	5.65	4.96	5.78	7.95	13.25	20.52	18.35	17.10	12.63	6.59	5.92	4.30

APPENDIX A Table A3 Monthly estimates of mean daily evaporative demand calculated each month using the method of Fitzpatrick (1968) (Monthly temperature and vapour pressure data from the Richmond Post Office, January 1941 to December 1975 were used in calculations).

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1941	5.4	6.1	4.9	3.7	3.4	3.1	4.2	4.3	5.9	6.8	7.9	8.9
1942	9.8	6.7	7.6	5.3	4.6	3.6	3.8	4.9	6.2	6.8	8.4	8.2
1943	7.8	5.3	7.6	5.7	3.8	3.4	4.6	4.2	5.3	6.9	8.1	9.0
1944	9.2	4.8	5.2	5.9	4.1	2.9	3.3	4.9	6.0	6.7	9.1	8.0
1945	8.5	7.1	5.3	5.1	3.8	3.4	3.1	5.3	6.2	6.8	8.9	9.3
1946	6.2	5.7	6.7	5.7	5.0	3.3	4.0	4.6	5.8	6.8	8.4	8.8
1947	8.9	5.0	5.8	5.0	3.8	3.8	4.2	4.1	4.8	6.2	7.9	8.7
1948	6.8	8.0	6.7	5.4	4.2	3.5	3.5	4.4	5.5	7.2	8.5	8.8
1949	8.5	6.4	5.2	4.4	3.9	4.1	4.5	4.5	5.2	6.6	7.8	8.6
1950	7.1	5.1	3.4	2.7	4.2	2.9	3.1	4.2	6.0	6.0	8.2	6.4
1951	4.6	6.0	7.1	5.7	4.2	3.3	3.8	4.9	5.7	6.9	8.8	9.3
1952	9.2	9.0	8.0	5.2	4.3	4.2	3.8	4.1	5.6	6.4	8.1	9.2
1953	8.4	3.9	6.1	6.0	3.8	3.8	4.5	4.6	5.1	7.1	7.8	8.9
1954	7.0	4.9	4.8	4.2	4.2	2.8	4.2	4.2	4.9	6.9	7.8	8.0
1955	7.8	5.1	3.7	3.8	2.9	2.8	3.3	4.5	5.5	6.7	7.5	8.9
1956	6.9	4.4	4.5	4.2	3.7	3.6	3.5	4.3	4.9	6.2	7.9	6.4
1957	5.7	6.1	5.1	6.4	4.2	3.4	3.1	4.5	5.7	7.3	8.9	8.9
1958	8.2	6.5	7.3	4.3	4.2	2.7	3.9	4.5	4.9	6.9	7.3	8.6
1959	6.6	7.2	5.4	5.3	3.1	3.1	3.1	4.3	5.0	6.7	8.6	9.0
1960	7.8	5.7	5.7	5.1	2.8	3.1	3.1	3.5	5.4	7.3	8.0	7.0
1961	6.9	6.4	6.6	5.3	4.0	3.0	3.3	3.6	5.5	6.8	7.5	9.0
1962	7.5	6.4	5.6	4.8	3.7	3.3	3.3	4.2	4.6	6.8	8.5	7.9
1963	7.1	6.2	5.7	4.0	3.9	3.1	3.2	4.1	5.8	6.0	8.2	8.7
1964	7.0	5.5	6.0	5.3	3.8	3.1	3.9	4.2	5.4	6.1	7.7	7.0
1965	8.6	8.4	5.5	5.7	4.1	3.1	2.9	4.0	6.0	6.6	8.2	6.6
1966	6.2	7.7	6.5	5.3	3.8	2.9	3.3	3.5	4.9	6.1	7.7	8.3
1967	9.9	6.9	5.5	5.3	4.0	2.4	2.8	3.8	5.6	7.5	7.9	8.6
1968	8.5	5.0	5.3	5.7	2.9	3.7	3.3	4.1	6.5	7.6	9.3	8.6
1969	8.2	8.0	6.7	5.5	4.2	3.2	3.8	4.5	4.9	7.2	8.5	8.5
1970	9.7	6.2	7.0	5.3	4.0	3.8	3.6	4.1	5.7	7.4	8.1	8.6
1971	8.1	6.7	4.2	3.0	4.0	3.3	3.5	5.0	6.3	8.3	6.0	8.7
1972	7.8	6.3	5.8	5.3	3.8	3.5	3.8	4.9	6.1	7.1	8.2	10.1
1973	9.3	5.9	6.3	4.5	4.6	4.2	4.2	4.9	5.5	7.5	7.4	7.7
1974	3.3	4.9	4.6	5.6	4.3	3.9	4.3	4.5	6.0	7.3	9.0	8.9
1975	7.0	4.7	5.6	5.3	4.8	3.4	4.6	4.8	6.1	6.3	8.8	6.8
MEAN	7.59	6.12	5.80	5.00	3.95	3.33	3.67	4.37	5.56	6.85	8.14	8.37
SD	1.47	1.18	1.09	0.83	0.49	0.43	0.52	0.43	0.50	0.51	0.63	0.89
CV %	19.4	19.3	18.8	16.7	12.5	12.9	14.1	9.7	8.9	7.5	7.7	10.6

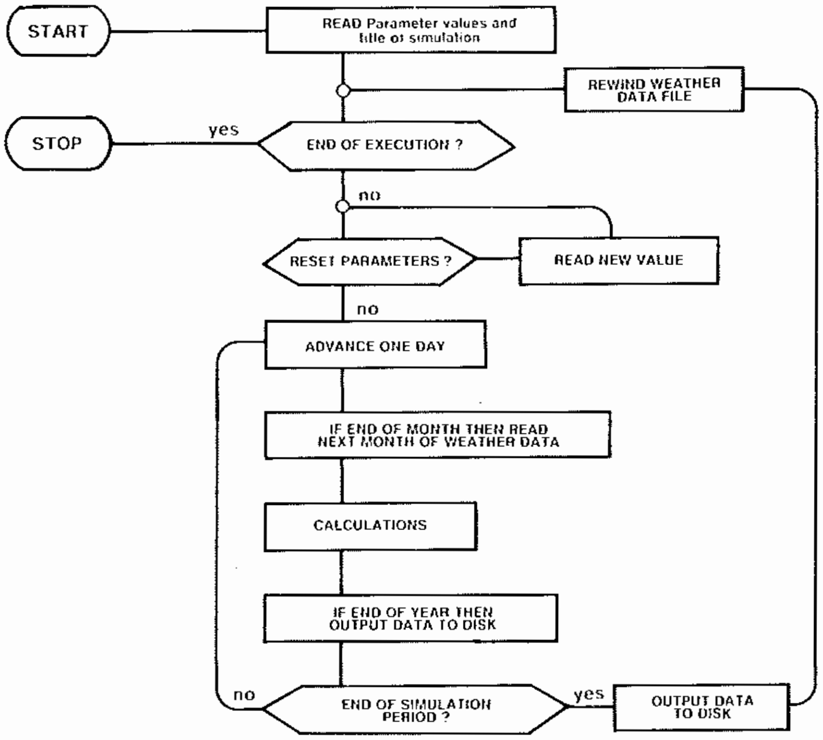
APPENDIX A Table A4 Monthly totals of rainfall recorded at the Richmond Post Office, October 1918 to September 1978.

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
1919	4	2	36	120	66	0	9	22	0	0	4	0	263
1920	0	0	9	187	56	29	135	93	20	15	6	2	550
1921	60	77	65	81	112	80	99	11	27	24	1	3	640
1922	134	1	77	74	128	0	0	0	5	2	0	0	421
1923	4	30	109	7	25	42	0	3	25	0	0	0	245
1924	11	0	12	30	307	131	129	0	0	0	34	0	654
1925	22	84	112	100	48	149	0	0	12	0	7	0	534
1926	5	5	10	73	2	0	1	6	0	0	0	28	130
1927	0	6	112	44	267	100	0	0	42	1	0	6	578
1928	6	2	152	29	34	5	0	0	4	0	0	0	232
1929	0	36	75	160	153	36	42	0	0	0	0	0	502
1930	0	61	33	181	155	15	1	134	7	0	0	0	587
1931	97	19	34	44	0	18	2	5	1	0	0	6	226
1932	17	112	75	57	46	5	1	20	2	0	0	0	335
1933	1	1	61	34	188	0	0	1	51	53	1	0	391
1934	4	81	57	88	153	4	35	16	6	19	0	1	464
1935	23	16	2	53	27	2	0	2	108	31	1	3	268
1936	6	6	9	107	49	152	2	66	9	95	0	29	530
1937	2	16	120	67	76	127	0	0	14	8	1	0	431
1938	2	45	15	162	149	17	0	0	0	31	0	0	421
1939	0	7	0	43	159	89	55	14	14	7	4	0	392
1940	47	43	15	32	451	54	13	1	5	0	0	0	661
1941	0	6	54	325	231	16	60	27	46	0	0	0	765
1942	3	20	22	5	124	13	23	45	8	0	0	13	276
1943	17	13	167	9	127	1	51	12	0	0	0	63	460
1944	21	33	48	26	191	11	1	18	4	51	0	0	404
1945	2	1	139	25	122	146	14	37	0	29	0	0	513
1946	4	0	18	221	114	1	0	0	1	0	0	1	360
1947	3	19	51	36	80	138	0	0	2	0	15	38	382
1948	25	2	122	135	33	7	0	0	0	21	0	0	345
1949	3	25	81	34	50	132	10	1	0	0	0	6	342
1950	62	20	66	94	213	214	142	5	18	20	2	9	865
1951	135	76	166	266	43	0	0	0	26	0	1	0	713
1952	26	19	17	19	9	2	34	18	0	0	3	2	149
1953	11	13	4	206	212	0	0	4	0	0	23	10	483
1954	0	4	24	157	199	214	8	0	24	0	3	5	638
1955	48	25	23	155	185	107	41	157	18	0	0	0	759
1956	11	14	26	139	252	64	47	75	34	23	15	0	700
1957	8	15	317	145	31	106	2	0	5	34	0	0	663
1958	13	24	48	82	48	103	6	5	36	0	0	0	365
1959	1	28	27	173	25	38	1	54	0	1	3	2	353
1960	0	4	11	26	189	13	7	50	1	2	8	6	317
1961	5	29	180	74	92	5	2	0	0	0	0	0	387
1962	0	51	31	156	90	85	2	18	4	6	0	59	502
1963	6	9	167	76	64	195	54	0	0	0	6	0	577
1964	13	0	8	216	122	21	19	28	33	3	0	10	473
1965	15	50	76	39	20	38	25	5	0	0	0	0	268
1966	6	6	107	247	24	1	0	2	7	0	38	12	450
1967	18	73	10	20	54	12	1	0	68	4	0	0	260
1968	4	5	31	12	226	41	23	55	0	22	0	0	419
1969	0	0	57	69	20	44	0	16	1	2	0	0	209
1970	0	3	141	44	138	23	1	0	0	0	0	14	364
1971	4	24	30	101	41	304	173	0	11	6	0	0	694
1972	12	24	67	119	18	225	0	0	0	0	0	0	465
1973	0	66	41	112	177	219	4	0	0	0	0	50	669
1974	0	205	58	665	102	115	1	24	0	0	6	9	1185
1975	1	6	126	243	217	94	38	0	15	0	1	2	743
1976	133	5	183	116	200	18	10	0	0	0	2	0	667
1977	4	26	195	92	95	56	24	7	0	0	0	0	499
1978	1	4	90	52	22	7	0	7	12	55	1	27	278
MEAN	18	27	70	108	114	65	22	18	12	9	3	7	474
PERCENTILES													
10	0	1	10	23	21	1	0	0	0	0	0	0	253
30	2	6	27	44	49	12	0	0	0	0	0	0	362
50	5	16	56	82	99	37	2	5	4	0	0	0	455
70	13	27	86	137	154	97	23	17	13	6	1	6	569
90	54	75	167	219	222	174	58	55	35	31	8	28	707

APPENDIX B: FLOW CHART AND COMPUTER PROGRAM OF SHALLOW STORAGE IRRIGATION SYSTEM MODEL

The shallow storage irrigation system model was run as two programs. The first program (named CATRUN) calculated run-off from the Mitchell grass catchment. CATRUN was used to generate a disk file of daily run-off for the simulation period 1 October 1918 to 30 September 1978. The second program (named SSISMO for Shallow Storage Irrigation System Model) contained all other components of the model. The run-off data file generated by CATRUN was read by SSISMO during simulation. Both programs were written in the language FORTRAN to be run on a Digital PDP-10 computer at the Prentice Centre, University of Queensland.

A flow chart of the SSISMO program is shown in figure B1. Variable names used in the SSISMO and CATRUN programs are defined in tables B2 and B4 respectively. FORTRAN listings of the SSISMO and CATRUN programs are given in tables B3 and B5 respectively. Input and outfiles from these programs were as follows:
SSISMO.FOR input files : B29.DAT, QPARAM.DAT, QFARM.DAT and QRUN.DAT,*
SSISMO.FOR output files : QDAT2.DAT, QDAT3.DAT and QDAT4.DAT,
CATRUN.FOR input files : B29.DAT, C68CAT.DAT and C100.DAT, and
CATRUN.FOR output files : C103.DAT, C103A.DAT, C104.DAT, C105.DAT.
* QRUN.DAT contains run-off data and is a condensed form of C103.DAT.



APPENDIX B. Figure B1 Flow chart of SSISMO program.

APPENDIX B Table B2 Variable names used in SSISMO

Array CAT (I) = Catchment Variable List (where I = 1 to 30)
CAT (1) = Soil moisture storage in layer 1 (mm)
CAT (2) = Soil moisture storage in layer 2 (mm)
CAT (3) = Soil moisture storage in layer 3 (mm)
CAT (4) = Soil moisture storage in layer 3 (mm)
CAT (5) = Sigma evap demand since WBCAT last accessed
CAT (6) = Sigma time since WBCAT accessed last (days)
CAT (7) = Evapotranspiration (mm)
CAT (3) = Run off (mm)
CAT (9) = Groundflow (mm)
CAT (10) = Dry matter yield of pasture (kg/ha)
CAT (11) = Sigma rain since WBCAT accessed last (mm)
CAT (12) to CAT (30) are spare

Array CS (K,J) = Crop Statistics Array (Irrigated Area)
where K = Crop Number (1 to 8)
J = Item (1 to 30)
CS (K,1) = Current soil moisture storage layer 1 (mm)
CS (K,2) = Current soil moisture storage layer 2 (mm)
CS (K,3) = Current soil moisture storage layer 3 (mm)
CS (K,4) = Current total soil moisture storage (mm)
CS (K,5) = Sigma Eo since WBIRR accessed last (mm)
CS (K,6) = Sigma time since WBIRR accessed last (days)
CS (K,7) = Current Biomet time since planting
CS (K,8) = Current Growing degree days since planting
CS (K,9) = GDD Collected since WBIRR accessed last (°C days)
CS (K,10) = Sigma Rain since WBIRR accessed last (mm)
CS (K,11) = Crop area (ha)
CS (K,12) = Potential Grain number (millions/ha)
CS (K,13) = Grain number filled (millions/ha)
CS (K,14) = Grain size (mg)
CS (K,15) = Yield before lodging (kg/ha)
CS (K,16) = Lodging loss (%)
CS (K,17) = Yield after lodging (kg/ha)
CS (K,18) = Total Production = YLD x AREA (tonnes)
CS (K,19) = Current Dry Matter Yield (kg/ha)
CS (K,20) = Total Dry Matter Yield (tonnes)
CS (K,21) = Hay yield = Total dry matter yield in week 14 (tonnes)
CS (K,22) = Sigma ET since planting (mm)
CS (K,23) = (spare)
CS (K,24) = Total DM yield (tonnes) end of May
CS (K,25) = Total DM yield (tonnes) end of June
CS (K,26) = Total DM yield (tonnes) end of July
CS (K,27) = Total DM yield (tonnes) end of August
CS (K,28) = Total DM yield (tonnes) end of September
CS (K,29) = spare Dryland Crop No.
CS (K,30) = spare

Array DAM (I) = Dam Variables (where I = 1 to 30)
DAM (1) = VOL = Volume of dam (ML)
DAM (2) = UT = Height of dam (mm)
DAM (3) = AREA = Area of dam surface (ha)
DAM (4) = SEO = Sigma evap demand since WBDAM accessed last (mm)
DAM (5) = STIME = Sigma time since WBDAM accessed last (days)
DAM (6) = EVAP = Sigma volume of evaporation from dam since 1st Oct. (ML)
DAM (7) = RAIN = Sigma volume of rainfall input to dam since 1st Oct. (ML)
DAM (8) = SINFLO = Sigma inflow to dam from catchment since 1st Oct. (ML)
DAM (9) = BYWASH = Sigma outflow from dam since 1st Oct. (ML)
DAM (10) = PONVOL = Sigma volume lost to ponded area since 1st Oct. (ML)
DAM (11) = RAIN = Sigma rain since WEDAM accessed last (mm)
DAM (12) = Maximum dam height this season (mm)
DAM (13) = Maximum dam volume this season (ML)
DAM (14) = VOLIRR = Sigma irrigation volume used since 1st Oct. (ML)
DAM (15) = Volume of dam at planting irrig crop (ML)
DAM (16) = Day no of last irrigation
DAM (17) = Value of M(42) after last irrigation
DAM (18) = Volume of dam before last irrig applied (ML)
DAM (19) = Volume of water available calculated (ML)
DAM (20) = Demand for water by crops 1-8 (ML)
DAM (21) = Surplus/Deficit of water after last irrigation (ML)
DAM (22) to DAN (30) are spare

Array GSP (I) = General Stats Ponded Area (where I = 1 to 50)
GSP (1) = Number of crops present
GSP (2) = Number of crops sown this season
GSP (3) = Total area of land in crop (ha)
GSP (4) = Total dry matter yield of ponded area for season (tonnes)
GSP (5) = Day number in period
GSP (6) = Number of periods (i.e., fortnights) since maximum dam height this season attained.
GSP (7) = Period number since 1st October
GSP (8) = Hay dry matter yield (tonnes)
GSP (9) = Planting delay index
GSP (10) = spare
GSP (11) = Height of dam at last access (mm)
GSP (12) = Upper height of last block planted (mm)
GSP (13) = Lower height of last block planted (mm)
GSP (14) = Total rainfall in the second last period (mm)
GSP (15) = Total rainfall in the last period (mm)
GSP (16) = Total rainfall in the current period (mm)
GSP (21) = Total planting costs of ponded area this season ($)
GSP (22) = Total costs of hay harvesting in ponded area this season ($)
GSP (23) = Cost of hay production ($/tonne)
GSP (24) = Grazing potential of dry matter production (wks/1000 sheep)
GSP (25) = Area of land harvested for hay (ha)
GSP (26) = Area of land sown this season (ha)
GSP (27) = No of days harvested for hay
GSP (30) =

End of Month Variable	May	July	Sept.
Total crop area (ha)	GSP(31)	GSP(36)	GSP(41)
Mean dry matter yield (kg/ha)	GSP(33)	GSP(37)	GSP(42)
Weighted crop age (wks)	GSP(33)	GSP(38)	GSP(43)
Total crop production (tonnes)	GSP(34)	GSP(39)	GSP(44)
Grazing potential (wks/1000 sheep)	GSP(35)	GSP(40)	GSP(45)

GSP (40) = No. of crops present at end of May
GSP (47) = No. of crops present at end of July
GSP (48) = No. of crops present at end of September
GSP (17), (18), (19), (20), (28), (29), (49), (50) are spare

APPENDIX B Table B2 Variable names used in SSISMO

Array M (I) = Integer Counter (where I = 1 to 100)
M (1) = Simulation run number
M (2) = Date (YYMMDD) of simulation
M (10) = Crop type (If M(10) = 1 then crop is grain sorghum)
M (11) = Grain Sorghum phenophase status
M (12) = Number of crop present

Irrigation Controls

M (41) = No of irrigations remaining in planting plan
M (42) = No of irrigations that have been applied
M (43) = No of irrigations deleted
M (44) = No of irrigations remaining till end of season
M (45) = No of irrigations planned at planting
M (47) = 0 or 1 (0 = normal, 1 = use flexible irrig strategy)
M (48) = 0 or 1 (0 = normal, 1 = use flexible planting strategy)
M (49) 0 or 1 (0 = normal, 1 = use flexible harvest strategy)

Output Controls (Write to disk)

M (51) = 0 or 1 (0 = normal, if = 1 then use OUT51)
M (52) = 0 or 1 (0 = normal, if = 1 then use OUT52)
M (53) = 0 or 1 (0 = normal, if = 1 then use OUT53)
M (56) = 0 or 1 (0 = normal, if = 1 then write M & P arrays)
M (60) = 0 or 1 (if = 1 then output headings)
M (61) = 0 or 1 (if = 1 then output headings)
Remaining variables in M array are spare.

Array MET (I) = Meteorological Data for Current Month
where I = items (1 to 40)
MET (1) to MET (31) = Daily rainfall for month
MET (32) = Monthly mean max. temp °C
MET (33) = Monthly mean min. temp °C
MET (34) = Monthly mean Eo (Fitz 1968) mm
MET (35) = Maximum of (o. and Rain - Pq)
MET (36) = Date
MET (37) = Monthly mean GDD for E57
MET (38) to MET (40) are spare

Array P (I) = Parameter Value (where I = 1 to 400)
Parameters are read from the file QPARAM.DAT shown at the bottom of Table B3. Some of the more important parameters are:
P (21) = Capacity of dam (ML) (=P(24)xP(398)/100)
P (24) = Catchment area (ha) (=P(397))
P (151) = Area of ploughing on irrigation-area (ha)
P (152) = Area of planting on irrigation-area (ha)
P (153), P (154) and P (155) = Scheduled time of first, second and third irrigations respectively (standard days)
P (164) = Initial water storage in dam (ML)
P (165), P (166) and P (167) = Initial water store in surface, sub-surface and sub-soil layers of irrigation-area (mm)
P (176), P(177) and P (178) = seasonally adjusted scheduled time of first, second and third irrigations respectively (standard days)
P (397) = Area of catchment (ha)
P (398) = Depth of run-off required to fill dam (mm)
P (399) = Size of irrigation-area (ha)
P (400) = Stream gradient at dam

Array PON (K,1) = Ponded Area Stats
where K = Crop number (1 to 8)
I = item (1 to 20)
PON (K,1) = Crop condition
PON (K,2) = Date planted (YYMMDD)
PON (K,3) = Upper height level (mm)
PON (K,4) = Lower height level (mm)
PON (K,5) = Current soil moisture (mm)
PON (K,6) = Sigma ET this period (mm)
PON (K,7) = Sigma Eo since last access (mm)
PON (K,8) = Sigma days since last access
PON (K,9) = Sigma time (weeks) from planting
PON (K,10) = Sigma rain since planting (mm)
PON (K,11) = area (ha)
PON (K,12) = Dry matter yield (kg/ha)
PON (K,13) = Total dry matter yield (tonnes)
PON (K,14) = Sigma temperature (°C)
PON (K,15) = Sigma ET since planting (mm)
PON (K,16) to PON (K,29) = spare

Array SIA (K,I,J) = Stats Irrigation Area
where K = Crop number (1 to 8)
I = Crop stage (1 to 10)
J = item number (1 to 20)

Item
1 = Crop index (0 = before planting, 1 = present, 2 = after harvest)
2 = Date at start of cropping period (YYMMDD)
3 = Duration of period (days)
4 = Soil moisture in layer 1 at start of period (mm)
5 = Soil moisture in layer 2 at start of period (mm)
6 = Soil moisture in layer 3 at start of period (mm)
7 = Sigma ET for period (mm)
8 = Sigma rainfall during period (mm)
9 = Sigma irrigation during period (mm)
10 = Sigma runoff during period (mm)
11 = Sigma groundflow during period (mm)
12 = Soil moisture in whole profile (0.90cm) at the end of the period (mm)
13 = Sigma Eo during period (mm)
14 = spare
15 = Water stress during period
16 = Damvol at start of period (ML)
17 = Irrig vol used during period (ML)
18 = Depth of catchment runoff during period (mm)
19 = Dry matter yld (kg/ha) at start of period
20 = spare

APPENDIX B Table B3 FORTRAN listing of SSISMO program

```
C**********************************************************************     0000
C                                                                           0001
C         SSISMO  --  SHALLOW STORAGE IRRIGATION SYSTEM MODEL               0002
C         ------      ---------------------------------------               0003
C                                                                           0004
C            FILE NAME = SSISMO.FOR                                         0005
C            DATE      = 1 SEPTEMBER 1983                                   0006
C                                                                           0007
C**********************************************************************     0008
C                                                                           0009
C                                                                           0010
        REAL TITLE(4)                                                       0011
        REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)           0012
        REAL GSP(50),PON(8,20),FSTRAT(60,7)                                 0013
        INTEGER DAY,MTH,YR,M(100)                                           0014
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT             0015
C2000---READ DATA --------------------------------------------              0016
        CALL QDATA                                                          0017
      OPEN(UNIT=22,FILE='QDAT2.DAT',ACCESS='SEQOUT')                        0018
      OPEN(UNIT=23,FILE='QDAT3.DAT',ACCESS='SEQOUT')                        0019
      OPEN(UNIT=24,FILE='QDAT4.DAT',ACCESS='SEQOUT')                        0020
      OPEN(UNIT=20,FILE='B29.DAT',ACCESS='SEQIN')                           0021
        TYPE 2996                                                           0022
 2996   FORMAT(' TITLE ? 4A5')                                              0023
        ACCEPT 2997,TITLE                                                   0024
 2997   FORMAT(4A5)                                                         0025
        TYPE 2998                                                           0026
 2998   FORMAT(' TES OR SIM ')                                              0027
        ACCEPT 2999,TEST                                                    0028
 2999   FORMAT(A3)                                                          0029
C-------SET INITIAL VALUES-------------------------------                   0030
 3000   CONTINUE                                                            0031
        CALL SET(TITLE)                                                     0032
        IF(M(1).LT.0)GOTO 9999                                              0033
        CALL WBCAT(1.,0.)                                                   0034
        IF(TEST.EQ.'SIM')GOTO 3030                                          0035
        M(40)=51                                                            0036
        CALL WBCAT(99.,0.)                                                  0037
        DO 3010 I=1,612                                                     0038
 3010   READ(20,26)YR                                                       0039
 3030   CONTINUE                                                            0040
        P9=P(9)                                                             0041
 3500   CALL SYEAR                                                          0042
        IF(TEST.EQ.'TES'.AND.M(40).EQ.55)GOTO 9000                          0043
C-----------------------------------------------------------                0044
 4000   CONTINUE     ! ******** COMMENCE DAILY LOOP ********                0045
C-------UPDATE TIME ----------                                              0046
        DAY=DAY+1                                                           0047
        CAT(6)=CAT(6)+1.                                                    0048
        DAM(5)=DAM(5)+1.                                                    0049
        GSP(5)=GSP(5)+1                                                     0050
        I=M(11)                                                             0051
        DO 4010 K=1,8                                                       0052
        CS(K,6)=CS(K,6)+1.                                                  0053
 4010   SIA(K,I,3)=SIA(K,I,3)+1.                                            0054
```

Comments in this column are to assist understanding and operation of the adjacent program.

SSISMO is an interactive FORTRAN program. A series of 60 year simulations may be carried out without terminating execution. Variables are stored in arrays as shown on page 329. The COMMON statement is used extensively to pass information from one subroutine to another.

SSISMO advances through simulated time using a daily time step, however event stepping procedures are used for water balance calculations. Weather data is READ one month at a time from the file B29.DAT(line 57 of program). Each weather record shows in the following order: year,month,monthly mean max temperature(C),monthly mean min temperature(C),monthly mean evaporative demand(mm/day),and 28 to 31 entries of daily rainfall(mm).

Parameter values are stored in 2 arrays; an M array of 100 values and a P array of 400 values. These parameters control the program (eg. output, irrigation strategy, shallow storage design) as well as defining nearly all values of constants in equations. While the M and P parameters are READ at the beginning of SSISMO (line 17) they may be altered interactively before the first simulation of 60 years and thereafter before each subsequent simulation of 60 years (see lines 198 to 219).

The following system commands will load, save and run SSISMO:

```
.LOAD SSISMO.FOR,STA:IMSL/SEA<CR>   (Note <CR> means CARRIAGE RETURN)
.SAVE<CR>
.RUN SSISMO<CR>
```

The first prompt of the program is 'TITLE ?'. Any string of 20 characters may be given as the title. This title is printed on all output. The second prompt is 'SIM OR TES' (ie. simulation or test). If TES is replied then the period is shortened from 60 years to 9 years (1 Oct 1969 to 30 Sep 1978). The third prompt is 'SET P/M VALUE'.This prompt is used to reset parameter values in the M and P arrays (see lines 198 to 219) and is repeated until execution of the program is terminated. A reply of 'END' terminates execution.

The following responses were used to run simulation experiment 1:

Prompt	Reply	Remarks
.	RUN SSISMO<CR>	
TITLE ? 4A5	SIMUL'N EXP 1<CR>	Title
TES OR SIM	SIM<CR>	Use 60 year simulation
SET P/M VALUE	YES M52 1<CR>	Use subroutine OUT52 for output
SET P/M VALUE	YES M45 1<CR>	Schedule one irrigation
SET P/M VALUE	YES M47 0<CR>	Do not use flexible irrign strategy
SET P/M VALUE	YES P153 55<CR>	Set time of irrign to day 55
SET P/M VALUE	YES P397 1660<CR>	Set catchment area = 1660 ha
SET P/M VALUE	YES P398 24<CR>	Depth of run-off to fill dam = 24mm
SET P/M VALUE	YES P399 40<CR>	Set size of irrign-area = 40 ha
SET P/M VALUE	YES P400 977<CR>	Set stream gradient at dam = 1:977
SET P/M VALUE	RUN P1 1<CR>	Start 60 year simul'n , output data
SET P/M VALUE	END<CR>	More simul'n not wanted, terminate
.		

```
C-------UPDATE MET DATA                                                    0055
        IF(DAY.LT.32.AND.MET(DAY).GE.0.)GOTO 4100                          0056
        READ(20,26,END=9000)YR,MTH,MET(32),MET(33),MET(34),                0057
     1                 (MET(I),I=1,31)                                     0058
   26   FORMAT(I3,I2,3F5.1,31F3)                                           0059
        GDD=(MET(32)+MET(33))/2.-P(58)                                     0060
        MET(37)=GDD                                                        0061
        DAY=1                                                              0062
 4100   CONTINUE                                                           0063
        DATE=FLOAT(YR*10000+MTH*100+DAY)                                   0064
        MET(36)=DATE                                                       0065
        RAIN=MET(DAY)                                                      0066
        MET(35)=AMAX1(0.,RAIN-P9)                                          0067
        E0=MET(34)                                                         0068
        X=AMIN1(P9,RAIN)                                                   0069
        CAT(11)=RAIN-X                                                     0070
        CAT(5)=CAT(5)+E0-X                                                 0071
        DAM(11)=RAIN-X                                                     0072
        DAM(4)=DAM(4)+E0-X                                                 0073
        I=M(11)                                                            0074
        DO 4200 K=1,8                                                      0075
        IF(CS(K,11).LE.0.)GOTO 4200                                        0076
        CS(K,10)=RAIN-X                                                    0077
        CS(K,5)=CS(K,5)+E0-X                                               0078
        SIA(K,I,13)=SIA(K,I,13)+E0-X                                       0079
 4200   CONTINUE                                                           0080
        J=IFIX(AMAX1(1.,GSP(1)))                                           0081
        DO 4201 I=1,J                                                      0082
 4201   PON(I,7)=PON(I,7)+E0-X                                             0083
 4205   CONTINUE                                                           0084
C-------------------------------------------------------------------        0085
C5000---UPDATE WBCAT,WBDAM,WBPON  IF(RAIN>P9)                               0086
        CAT(8)=0.                                                          0087
        IF(RAIN.LE.P9)GOTO 6000                                            0088
        CALL WBCAT(DATE,CAT(8))                                            0089
        I=M(11)                                                            0090
        SIA(1,I,18)=SIA(1,I,18)+CAT(8)                                     0091
        CALL WBDAM                                                         0092
        CALL WBPON(PON,MET(35),MET(32),MET(33))                            0093
        GSP(17)=GSP(17)+RAIN                                               0094
C-------------------------------------------------------------------        0095
 6000   CONTINUE  ! IRRIGATED CROPPING MODEL. --------------                0096
C6100---CALCULATE IRRIG CROP PHENOLOGY                                      0097
        IF(M(11).GT.1.AND.M(11).LT.9)CALL PHENOL(GDD)                      0098
C6200---UPDATE WATER BALANCE IF (RAIN>P9).                                  0099
        IF(RAIN.GT.P9)CALL WBIR                                            0100
C6250---CALL WBIR & DMYLD IF END OF MAX TIME STEP                           0101
        IF(M(11).EQ.1.OR.M(11).EQ.9)GOTO 6251                              0102
        IF(M(10).EQ.4.AND.CS(1,8).EQ.P(288))CALL WBIR                      0103
        IF(M(10).EQ.2.AND.CS(1,8).EQ.P(323))CALL WBIR                      0104
        IF(M(10).EQ.4.AND.AMOD(CS(1,8),P(299)).EQ.0.)CALL WBIR             0105
        IF(M(10).EQ.2.AND.AMOD(CS(1,8),P(322)).EQ.0.)CALL WBIR             0106
 6251   CONTINUE                                                           0107
C6300---PLANT CROP                                                          0108
        I=M(40)                                                            0109
```

There are 23 subroutines in the program. Their names, line at which they start and function are as follows:

QDATA	Line 147	Read parameters at start of execution
SET	182	Reset parameters interactively
SYEAR	300	Initialize variables at start of each year
WBCAT	349	Read catchment run-off data
WBDAM	375	Calculate water balance for dam
PHENOL	453	Calculate Sorghum phenology
WBIR	498	Irrigation-area water balance
WBIRR	534	" " " "
PIC	622	Plant irrigation-area
HIC	695	Calculate yield and production from irrigation-area
DMYLD	764	" " " " " " "
CRC	962	Irrigation management - create crop
CIRRIG	979	" " - crop irrigation
DAMIRR	999	" " - water availability in dam
PONMOD	1089	Main model for ponded-area
WBPON	1245	Water balance of ponded-area
WBPON2	1263	" " " " "
OUT51	1283	End of year output - use if M(51) = 1
OUT52	1370	" " " " - use if M(52) = 1
OUT53	1566	" " " " - use if M(53) = 1
ENR01	1596	End of run output
ENR02	1642	End of run output

Further comments in this column refer to adjacent lines.

If rain is greater than 3 mm then update water balance

If the current date (DATE) is equal to the date of planting in FSTRAT(I,1) then call the planting subroutine PIC

```
        IF(DATE.EQ.FSTRAT(I,1))CALL PIC
C6400---IRRIGATE CROP
        IF(M(44).EQ.0)GOTO 6410   ! NO MORE IRRIGATION
        I=M(42)
        IF(M(10).EQ.1)BMTI=FLOAT(IFIX(CS(1,8)/P(59)+.5))
        IF(M(10).EQ.2)BMTI=CS(1,8)
        IF(M(10).EQ.4)BMTI=CS(1,8)
        IF(BMTI.LT.P(176+I))GOTO 6410  ! TOO SOON
        CALL IRRIGN
 6410   CONTINUE
C6500---HARVEST CROPS
        I=M(40)
        IF(DATE.EQ.FSTRAT(I,2))CALL  HIC
```

If the current date is equal to the date of harvest in FSTRAT(I,2) then call subroutine HIC(Harvest irrigated crop)

```
C-------------------------------------------------------------
C7000---PONDED AREA CROPPING MODEL
        IF(GSP(5).LT.14.)GOTO 8000
```

Call the Ponded-area crop model at the end of each fortnight

```
        GSP(7)=GSP(7)+2
           GSP(5)=0.
        IF(MTH.GT.9)GOTO 8000  ! FORGET PON MODEL OCT-DEC
             CALL WBDAM
             CALL WBPON(PON,MET(35),MET(32),MET(33))
             CALL PONMOD
 8000   CONTINUE   ! ------------- END OF DAY -----------------
        TMP=MTH*100+DAY
        IF(TMP.NE.930)GOTO 4000
        IF(M(51).EQ.1)CALL OUT51
        IF(M(52).EQ.1)CALL OUT52
        IF(M(53).EQ.1)CALL OUT53
```

Call these output subroutines if the date is the 30th September and if the values of M51,M52,and M53 are set to 1.

```
        GOTO 3500
C-------------------------------------------------------------
 9000   CONTINUE  !  ******** END OF RUN *********
        CALL ENR02
        GOTO 3000
 9999   STOP
        END
C**********************************************************************
C
        SUBROUTINE QDATA
C       **********
C
        REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
        REAL GSP(50),PON(8,20),FSTRAT(60,7)
        INTEGER DAY,MTH,YR,M(100)
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
C2000---READ DATA ------------------------------------------
      OPEN(UNIT=20,FILE='QPARAM.DAT',ACCESS='SEQIN')
      READ(20,1)M
    1 FORMAT(7X,10I6)
      READ(20,2)P
    2 FORMAT(7X,10F6.0)
```

Subroutine QDATA reads the parameter values stored on the file QPARAM.DAT and the farm management data stored on file QFARM.DAT This subroutine also calls WBCAT to read all of the catchment run-off data from QRUN.DAT.

```
        P(124)=P(124)/100.
        P(128)=P(128)/100.
        P(130)=P(130)/100.
        P(132)=P(132)/100.
        P(137)=P(137)/1000.
```

Adjust place of decimal point in some parameters.

```
      P(282)=P(282)/100.                                            0165
      P(326)=P(326)/100.                                            0166
    CLOSE(UNIT=20,FILE='QPARAM.DAT')                                0167
```

Read dates of planting and harvest of irrigated grain sorghum for each year of the sixty year simulation.Store this information in the array FSTRAT.

```
C2200---READ FARMING STRATAGY                                       0168
      OPEN(UNIT=20,FILE='QFARM.DAT',ACCESS='SEQIN')                 0169
      READ(20,2210)HD                                               0170
      READ(20,2210)HD                                               0171
 2210 FORMAT(A5)                                                    0172
      READ(20,2230,END=2290)((FSTRAT(I,J),J=1,4),I=1,60)            0173
 2230  FORMAT(4F)                                                   0174
 2290 CONTINUE                                                      0175
      CLOSE(UNIT=20,FILE='QFARM.DAT')                               0176
      CALL WBCAT(0.,0.)                                             0177
```

Return to line 17.

```
      RETURN                                                        0178
      END                                                           0179
C*****************************************************************  0180
C                                                                   0181
```

This subroutine has two purposes. 1.To allow parameters in the model to be reset interactively at the start of each 60 year simulation. 2.To initialize arrays for the start of simulation and to calculate a number of parameters that are dependent on other parameters.

```
      SUBROUTINE SET(TITLE)                                         0182
C     **********                                                    0183
C                                                                   0184
      REAL TODAY(2),CLOCK(2),TITLE(4)                               0185
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)     0186
      REAL GSP(50),PON(8,20),FSTRAT(60,7)                           0187
      INTEGER DAY,MTH,YR,M(100)                                     0188
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT       0189
      CALL DATE(TODAY)                                              0190
      CALL TIME(CLOCK)                                              0191
      M(1)=M(1)+1                                                   0192
```

Write the date ,time and title of the simulation to each of the output disk files.

```
      WRITE(23,10)M(1),TODAY,CLOCK,TITLE                            0193
      WRITE(22,10)M(1),TODAY,CLOCK,TITLE                            0194
      WRITE(24,10)M(1),TODAY,CLOCK,TITLE                            0195
   10 FORMAT(1H1,/,4X,'RUN',I6,'  DATE ',2A5,'  TIME ',2A5,         0196
     1      2X,4A5)                                                 0197
 1000 CONTINUE  ! ***** RESET PARAMETERS INTERACTIVELY *******      0198
      TYPE 18                                                       0199
```

The words SET P/M VALUE appear on the terminal.The program waits to read values for SET,PARAM,NP and VAL. If SET=END then a -ve value is given to M(1) (see line 207) and the program will terminate when control is returned to the main program.
If PARAM=P then P(NP) is set equal to VAL (line 217).
If PARAM=M then M(NP) is set equal to VAL (line 218).
If SET=YES then the program loops back from line 219 to line 198 so that more parameters can be reset.
If SET=TYP then the value of up to 10 parameters can be displayed on the terminal(see lines 209 to 216).The program then loops back to line 198.
If SET is not equal to END,YES,or TYP then one parameter can be reset but the program then continues for execution of the simulation.

```
   18   FORMAT(X,'SET P/M VALUE')                                   0200
      ACCEPT 13,SET,PARAM,NP,VAL                                    0201
   13   FORMAT(A3,X,A1,I,F)                                         0202
      WRITE(22,14)SET,PARAM,NP,VAL                                  0203
      WRITE(23,14)SET,PARAM,NP,VAL                                  0204
      WRITE(24,14)SET,PARAM,NP,VAL                                  0205
   14   FORMAT(4X,A3,X,A1,I3,F12.5)                                 0206
      IF(SET.EQ.'END')M(1)=-M(1)                                    0207
      IF(SET.NE.'TYP')GOTO 17                                       0208
         IVAL=IFIX(VAL)                                             0209
      IF(PARAM.EQ.'P')TYPE 15,NP,IVAL,(P(I),I=NP,IVAL)              0210
      IF(PARAM.EQ.'P')WRITE(23,15)NP,IVAL,(P(I),I=NP,IVAL)          0211
   15    FORMAT(/,4X,'P',I3,' TO P',I3,2(5F12.5))                   0212
      IF(PARAM.EQ.'M')TYPE 16,NP,IVAL,(M(I),I=NP,IVAL)              0213
      IF(PARAM.EQ.'M')WRITE(23,16)NP,IVAL,(M(I),I=NP,IVAL)          0214
   16    FORMAT(4X,'M',I3,' TO M',I3,10I6)                          0215
         GOTO 1000                                                  0216
   17 IF(PARAM.EQ.'P')P(NP)=VAL                                     0217
      IF(PARAM.EQ.'M')M(NP)=IFIX(VAL)                               0218
      IF(SET.EQ.'YES')GOTO 1000                                     0219
```

```
        REWIND 20                                                      Set disk file containing weather data to it's first record.
          DAY=31
C3300---INITIALIZE ARRAYS-------------------
        DO 3310 J=1,20
        CAT(J)=0.
        DAM(J)=0.
        DO 3310 K=1,8
        CS(K,J)=0.
        DO 3310 I=1,10
 3310   SIA(K,I,J)=0.
        CAT(1)=P(161)
        CAT(2)=P(162)
        CAT(3)=P(163)
        DAM(1)=P(164)
        CAT(4)=CAT(1)+CAT(2)+CAT(3)
        CS(1,1)=P(165)
        CS(1,2)=P(166)
        CS(1,3)=P(167)
        CS(1,4)=P(165)+P(166)+P(167)
        CS(1,11)=1.
        SIA(1,1,1)=1.
        SIA(1,1,2)=P(168)
        SIA(1,1,4)=P(165)
        SIA(1,1,5)=P(166)
        SIA(1,1,6)=P(167)
        SIA(1,1,16)=P(164)
        M(11)=1
        M(40)=0
        M(60)=1
        M(61)=1
        P(24)=P(397)              !CATCH AREA
        P(21)=P(397)*P(398)/100.!DAMVOL                                Calculate max volume of dam.
        P(26)=(P(21)*1000.*6./3.141593*P(28)/P(400)**2)**0.333333      Calculate constant in equation 4.3
        P(151)=P(399)             !CROP AREA
        P(152)=P(399)             !CROP AREA
        P(22)=P(21)*1000./P(26)**3                                     Calculate max height of dam.
        P(261)=SQRT(.1*P(26)**2)*1000.
C-------CALC CRITICAL E0 FOR IRRIG AREA EVAP AND TRANSP FUNCTIONS       Calculate SEo at which S = LLEo(see p143 of text.).
        P(113)=EXP((P(41)+P(81)-P(82))/P(81))
        P(114)=EXP((P(43)+P(84)-P(85))/P(84))
        P(115)=EXP((P(45)+P(87)-P(88))/P(87))
        P(116)=EXP((P(41)+P(91)-P(92))/P(91))
        P(117)=EXP((P(43)+P(94)-P(95))/P(94))
        P(118)=EXP((P(45)+P(97)-P(98))/P(97))
        P(36)=EXP((P(31)+P(33)-P(34))/P(33))
        P(30)=EXP((P(31)+P(37)-P(38))/P(37))
C-------CALC MAX EVAP & TRANSPN RATES                                   See p151 to 154 of text.
        P(83)=P(81)/P(113)
        P(86)=P(84)/P(114)
        P(89)=P(87)/P(115)
        P(93)=P(91)/P(116)
        P(96)=P(94)/P(117)
        P(99)=P(97)/P(118)
        P(35)=P(33)/P(36)
        P(39)=P(37)/P(30)
```

```
C-------CALC GRAIN SORGHUM FIXED COSTS                                        See chapter 5 of text.
        H=P(26)
        A1=SQRT(P(21)*1000.*6./H/3.141592/2./P(28))*(H+1.)/H
        CWALL=.17*.6*(2.5*A1*(H+2.5) + 3*A1*(H+1.)**2)                        Annual fixed cost of dam wall.
        CDROP=.17*2000.                                                       Annual fixed cost of drop-inlet.
        CHEAD=.17*7.50*P(151)                                                 Annual fixed cost of head-ditch maintainance.
        CSYPH=.17*4.18*P(151)                                                 Annual fixed cost of syphons.
        CFENC=.17*400.*(2.+.02*P(151))                                        Annual fixed cost of fencing.
        P(346)=CWALL+CDROP+CHEAD+CSYPH+CFENC
        TRACKW=AMAX1(40.,16.*P(151)/60./.56)!    TRACTOR SIZE
        P(341)=TRACKW
        P(342)=0.092125*TRACKW+3.375!            TRACTOR COST/HR              See eq 7.1 in text.
        P(343)=TRACKW/25.!                       WIDTH DISC PLOUGH
        P(344)=TRACKW/16.!                         "   SWEEP  "
        P(345)=TRACKW/16.!                         "   COMBINE
        GEAR=P(343)*181.4 + P(344)*135.7 + P(345)*180.7! INTEREST             See table 7.2 in text.
        P(346)=P(346) + GEAR!                *** TOTAL FIXED COSTS ***
        MET(36)=P(168)
        TYPE *,P(21),P(26),CWALL,GEAR,P(346),P(151)
        IF(M(56).EQ.1)TYPE 2000,M,P
2000    FORMAT(10(X,'M',10I6,/),30(X,'P',10F12.5,/))
        RETURN
        END
C*******************************************************************
C
        SUBROUTINE SYEAR                                                      This subroutine is called at the start of each year(1st October)
C       **********                                                            Its main purpose is to reset a range of variables to zero.
C                                                                             These variables accumulate information for output at the end of
        REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)             each year.
        REAL GSP(50),PON(8,20),FSTRAT(60,7)
        INTEGER DAY,MTH,YR,M(100)
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
C1000---RESET ARRAYS TO ZERO ---------------------------------
        DO 1010 K =1,8
        DO 1010 I=1,10
        DO 1010 J=1,20
 1010   SIA(K,I,J) =0.0
        SIA(1,1,1) =1.
        SIA(1,1,2) = MET(36)
        SIA(1,1,4) =CS(1,1)
        SIA(1,1,5) = CS(1,2)
        SIA(1,1,6) =CS(1,3)
        SIA(1,1,16)=DAM(1)
        DO 1020 K=2,8
        DO 1020 J=1,30
 1020   CS(K,J) =0.
        CS(1,7)=1.
        CS(1,8)=0.
        CS(1,9)=0.
        CS(1,11)=1.
        DO 1021 J=12,30
 1021   CS(1,J)=0.0
        DO 1025 J=12,20
 1025   CS(1,J)=0.
        DO 1030 J=7,10
```

```
 1030   CAT(J) =0.                                                          0330
        DO 1040 J=6,14                                                      0331
 1040   DAM(J) =0.                                                          0332
        DO 1050 I=1,50       ! --- PONDED AREA -----                        0333
 1050   GSP(I)=0.                                                           0334
        DO 1052 I=1,8                                                       0335
        DO 1051 J=2,20                                                      0336
 1051   PON(I,J)=0.                                                         0337
 1052   PON(I,1)=-1.                                                        0338
        M(11)=1                                                             0339
        M(40)=M(40)+1                                                       0340
        M(41)=0                                                             0341
        M(42)=0                                                             0342
        M(43)=0                                                             0343
        M(44)=0                                                             0344
        RETURN                                                              0345    Return to line 42.
        END                                                                 0346
C*********************************************************************       0347
C                                                                           0348
        SUBROUTINE WBCAT(DATE,RUN)                                          0349    Read and store catchment run-off data produced by the program
C       **********                                                          0350    CATRUN.
C                                                                           0351
        REAL RUNCAT(400,2)                                                  0352
        IF(DATE.GT.0.)GOTO 30                                               0353
        OPEN(UNIT=20,FILE='QRUN.DAT',ACCESS='SEQIN')                        0354
        DO 5 J=1,3        ! SKIP HEADINGS                                   0355
    5   READ(20,10)HEAD                                                     0356    Read all catchment run-off data from file QRUN.DAT and store
   10   FORMAT(X,A1)                                                        0357    date and depth of run-off(mm) in array RUNCAT.Return to line 178
        READ(20,11,END=20)((RUNCAT(I,J),J=1,2),I=1,400)                     0358
   11   FORMAT(F7,F)                                                        0359
   20   I=1                                                                 0360
        CLOSE(UNIT=20,FILE='QRUN.DAT')                                      0361
        RETURN                                                              0362
C-------CHECK RUNOFF DATE                                                   0363
   30   CONTINUE                                                            0364    The depth of catchment run-off(RUN,mm) is set to the value shown
        IF(DATE.LT.10000.)I=IFIX(DATE)                                      0365    in RUNCAT(I,2) (where I = counter) if the current date (DATE)
        RUN=0.                                                              0366    is equal to RUNCAT(I,1),otherwise RUN is set to zero.
        IF(DATE.NE.RUNCAT(I,1))RETURN                                       0367
        RUN=RUNCAT(I,2)                                                     0368
        I=I+1                                                               0369
        RETURN                                                              0370
        END                                                                 0371
C*********************************************************************       0372
C                                                                           0373
        SUBROUTINE WBDAM                                                    0374    This subroutine calculates the water balance of the dam(see
C       **********                                                          0375    section 4.2 of text).
C                                                                           0376
        REAL P(400),MET(40),CAT(30)                                         0377
        INTEGER DAY,MTH,YR,M(100)                                           0378
        COMMON DAY,MTH,YR,M,P,MET,CAT,VOL,HT,AREA,SEO,STIME,                0379    VOL = DAM(10), HT = DAM(2), AREA = DAM(3), SEo = DAM(4),
     1         EVAPV,RAINV,SINFLO,BYWASH,PONVOL,RAIN,HMAX,VMAX              0380    STIME = DAM(5), EVAPV = DAM(6), RAINV = DAM(7),
        IF(STIME.EQ.0.)RETURN                                               0381    SINFLO = DAM(8), BYWASH = DAM(9), PONVOL = DAM(10),
    1   CONTINUE                                                            0382    RAIN = DAM(11), HMAX = DAM(12), VMAX = DAM(13).
        VOLMAX=P(21)*1000.                                                  0383    VOLMAX = Volume of dam when full(cubic metres).
        HTMAX=P(26)                                                         0384    HTMAX = Depth of dam when full(m).
```

```
      F=P(22)
      AREMAX=3.*F*HTMAX**2                                   See equation 4.4 in text.
C-------CONVERT TO METERS
      VOL=VOL*1000.
      HT=0.
      IF(VOL.GT.0.)HT=EXP(ALOG(VOL/F)/3.)                    From equation 4.3 in text.
      SE0=SE0/1000.
      RAIN=RAIN/1000.
C-------CALCULATE EVAP LOSS AND SIGMA EVAP LOSS VOLUME        See equations 4.9 and 4.10 in text.
      HT=AMAX1(0.,HT-SE0*P(23))
      VOLNEW=F*HT**3
      EVAPV=EVAPV + (VOL-VOLNEW)/1000.
      VOL=VOLNEW
   10 CONTINUE
C-------ADD RAIN AND CALC SIGMA RAIN VOL AND BYWASH VOL
      IF(RAIN.EQ.0.)GOTO 20
      IF(HT.LT..1)GOTD 20
      HTNEW=HT+RAIN                                          See p103 of text.
      VOLNEW=F*HTNEW**3
      IF(VOLNEW.GT.VOLMAX)BYWASH=BYWASH + (VOLNEW-VOLMAX)/1000.
      RAINV=RAINV + AMIN1(VOLNEW-VOL,VOLMAX-VOL)/1000.
      HT=AMIN1(HTMAX,HTNEW)
      VOL=F*HT**3
   20 CONTINUE
C-------CALCULATE RUNOFF VOLUME AND SIGMA INFLOW
      RUNVOL=CAT(B)*P(24)*10.          !P(24) =CAT AREA
      IF(RUNVOL.LE.0.)GOTO 40
      SINFLO=SINFLO+RUNVOL/1000.
C-------CALCULATE INCREASE IN DAM HEIGHT DUE TO RUNOFF,SIGMA
C-------PONDED LOSS AND SIGMA BYWASH LOSS
      WD=P(25)     !WD=WATER DEF OF PONDED AREA
      AREA=F*3.*HT**2
      VOLDEF=VOLMAX-VOL+(AREMAX-AREA)*WD
      IF(RUNVOL.GE.VOLDEF)GOTO 35
      H=EXP(ALOG((VOL + RUNVOL)/F)/3.)
C     0.=NEWVOL +PONLOSS-OLDVOL-RUNVOL
      I=0
   30 I=I+1
      Y=F*H**3+3.*WO*F*(H**2-HT**2)-VOL-RUNVOL               Use Newton's numerical iteration method to calculate PONLOS and
      Y1=3.*F*H**2 +6.*WD*F*H                                changes in VOL,HT and AREA due to run-off(see pp104-106 of text)
      H=H-Y/Y1
      IF(I.GT.50)GOTO 34
      IF(ABS(Y).LT.01..AND.ABS(Y1).GT.10000.)GOTO 34
      IF (ABS(Y).GT..001)GOTO 30
   34 PONLOS=WD*(F*3.*H**2-AREA)
   35 IF(RUNVOL.GE.VOLDEF)PONLOS=(AREMAX-AREA)*WD
      PONVOL=PONVOL+PONLOS/1000.
      VOLNEW=VOL+RUNVOL-PONLOS
      IF(VOLNEW.GT.VOLMAX)BYWASH=BYWASH+(VOLNEW-VOLMAX)/1000.
      VOL=AMIN1(VOLMAX,VOLNEW)
      HT=EXP(ALOG(VOL/F)/3.)
   40 CONTINUE
C-------CALCULATE SURFACE AREA OF DAMAND CONVERT BACK TO ML, MM AND HA
      AREA=F*3.*HT**2
      VOL=VOL/1000.
```

```
        HT =HT *1000.
        HMAX=AMAX1(HMAX,HT)
        VMAX=AMAX1(VOL,VMAX)
        AREA=AREA/10000.
        RAIN=0.
        SE0=0.
        CAT(8)=0.
        STIME=0.
   50   CONTINUE
        RETURN
        END
C**********************************************************************
C
        SUBROUTINE PHENOL(GDD)
C       **********
C
```

This subroutine calculates phasic development of irrigated grain sorghum.

```
        REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
        REAL GSP(50),PON(8,20),FSTRAT(60,7)
        INTEGER DAY,MTH,YR,M(100)
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
        GOTO(100,200,300,400)M(10)
100     CONTINUE ! =========GRAIN SORGHUM PHENOLOGY MODEL ======
        DO 105 K=1,8
        CS(K,8)=CS(K,8)+GDD
105     CS(K,9)=CS(K,9)+GDD
```

Advance Heatsum by to days amount of GDD.

```
        I=M(11)
        BMT=FLOAT(I)+(CS(1,8)-P(48+I))/(P(49+I)-P(48+I))
        CS(1,7)=BMT
        IF(CS(1,8).LT.P(49+I))RETURN
```

I = phenophase number.
BMT = Biometriological time ,Phenophases are shown in table 5.4

Return to line 98 if there is no advance in phenophase.

```
        GOTO 500
200     CONTINUE ! ===== SUDAX PHENOLOGY =====
        CS(1,8)=CS(1,8)+1.
        CS(1,7)=2.+CS(1,8)/P(321)
        I=IFIX(CS(1,7))
        IF(I.EQ.M(11))RETURN
        GOTO 500
300     CONTINUE ! ===WHEAT PHENOL ====
400     CONTINUE ! === OATS PHENOL ======
500     CONTINUE ! =======INCREASE M(11) AND SIA ======
        CALL WBDAM
        CALL WBIR
```

Update water balance of dam and irrigation-area if phenophase has changed,advanced phenophase.

```
        M(11)=M(11)+1
        I=M(11)
        DO 509 K=1,8
        IF(CS(K,11).EQ.0)GOTO 509
        SIA(K,I,4)=CS(K,1)
        SIA(K,I,5)=CS(K,2)
        SIA(K,I,6)=CS(K,3)
        SIA(K,I,1)=FLOAT(I)
        SIA(K,I,2)=MET(36)
        SIA(K,I-1,12)=CS(K,4)
        SIA(K,I,16)=DAM(1)
        SIA(K,I,19)=CS(K,19)
509     CONTINUE
        RETURN
```

```
      END
C*********************************************************************
C
      SUBROUTINE WBIR
C     **********
C
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
      REAL GSP(50),PON(8,20),FSTRAT(60,7)
      INTEGER DAY,MTH,YR,M(100)
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
      I=M(11)
      DO 10 K=1,8
      IF(CS(K,11).LE.0.)GOTO 10
      IF(CS(K,6).EQ.0.)GOTO 10
      CALL WBIRR(CS(K,1),CS(K,2),CS(K,3),CS(K,4),CS(K,5),CS(K,6),
     1           ET,ETG,RUN,GND,CS(K,10),MET(36),CS(1,8),CS(K,19))
      KK=K
      IF(M(11).GT.1)CS(K,22)=CS(K,22)+ET
      IF(M(10).EQ.2.AND.M(11).GT.1.AND.M(11).LT.9)CALL DMYLD(ETG,KK)
      IF(M(10).EQ.4.AND.M(11).GT.1.AND.M(11).LT.9)CALL DMYLD(ETG,KK)
      SIA(K,I,7)=SIA(K,I,7)+ET
      SIA(K,I,8)=SIA(K,I,8)+CS(K,10)
      IF(I.LT.3.OR.I.GT.7)GOTO 5
      IF(M(10).NE.4)GOTO 5
      IF(SIA(K,I,8).LT.P(281))GOTO 5
      IF(CS(K,23).EQ.0.)CS(K,23)=CS(K,22)
    5 CONTINUE
      SIA(K,I,10)=SIA(K,I,10)+RUN
      SIA(K,I,11)=SIA(K,I,11)+GND
      SIA(K,I,12)=CS(K,4)
      SIA(K,I,13)=SIA(K,I,13)+CS(K,5)
      CS(K,5)=0.0
      CS(K,6)=0.0
      CS(K,10)=0.0
   10 CONTINUE
      RETURN
      END
```

Subroutine for water balance of irrigation area. Irrigation strategy may divide the irrigation area in 8 blocks. The water balance of each block must be checked.

If the area of block K = 0, or if the water balance has already been calculated today, then skip to statement 10.

```
C*********************************************************************
C
      SUBROUTINE WBIRR(S1,S2,S3,S4,SEO,STIME,ET,ETG,RUNOFF,
     1            GNDFLO,RAIN,DATE,GDD,DMY)
C     **********
C
      REAL P(400),INFIL,INRATE
      INTEGER DAY,MTH,YR,M(100)
      COMMON DAY,MTH,YR,M,P
C    WBIRR CALCULATES THE DAILY WATER BALANCE OF THE IRRIGATED AREA
        S1MAX=P(41)
        S1MIN=P(42)
        S2MAX=P(43)
        S2MIN=P(44)
        S3MAX=P(45)
        S3MIN=P(46)
   10 CONTINUE
C---- EVAPOTRANSPIRATION MODEL ----------------------------------
```

Subroutine for water balance of any block K of irrigation area.

```
C-------CALCULATE COVER
        COVER=0.
        IF(M(10).EQ.1.AND.GDD.GT.0.)COVER=1./(1.+99.*EXP(-.005310*GDD))     See equation 5.44 in text.
        IF(M(10).EQ.2.AND.DMY.GT.0.)COVER=1.-EXP(-P(326)*DMY)
        IF(M(10).EQ.4.AND.DMY.GT.0.)COVER=1.-EXP(-P(282)*DMY)
C-------CALCULATE ET FROM BARE SOIL FUNCTION                                 See equation 5.32 in text.
        E1=(1.-COVER)*ETFN(S1,S1MAX,S1MIN,SE0,P(81),P(82),P(83),P(113))
        E2=(1.-COVER)*ETFN(S2,S2MAX,S2MIN,SE0,P(84),P(85),P(86),P(114))
        E3=(1.-COVER)*ETFN(S3,S3MAX,S3MIN,SE0,P(87),P(88),P(89),P(115))
C-------CALCULATE ET FROM FULL COVER FUNCTION                                See equation 5.38 to equation 5.43 in text.
        T1=COVER*ETFN(S1,S1MAX,S1MIN,SE0,P(91),P(92),P(93),P(116))
        T2=COVER*ETFN(S2,S2MAX,S2MIN,SE0,P(94),P(95),P(96),P(117))
        T3=COVER*ETFN(S3,S3MAX,S3MIN,SE0,P(97),P(98),P(99),P(118))
C-------CALCULATE ET                                                         See equation 5.27 in text.
        ET1=AMIN1(E1+T1,S1-S1MIN)
        ET2=AMIN1(E2+T2,S2-S2MIN)
        ET3=AMIN1(E3+T3,S3-S3MIN)
        ET=ET1+ET2+ET3                                                       See equation 5.28 in text.
C-------CHANGE SOIL STORES
        S1=S1-ET1
        S2=S2-ET2
        S3=S3-ET3
        S4=S1+S2+S3
C-------CALC ET FOR GROWTH                                                   For growth of irrigated forage not grain yield.
        ETG=ET
        IF(S1.LT.P(311))ETG=ETG-ET1
        IF(S2.LT.P(312))ETG=ETG-ET2
        IF(S3.LT.P(313))ETG=ETG-ET3
        ETG=AMAX1(0.,ETG)
   40   CONTINUE
C---- INFILTRATION RUNOFF MODEL---------------------------------
         RUNOFF=0.
         GNDFLO=0.
         IF(RAIN.EQ.0.)GOTO 100
C       CALCULATE INFIL TO S1                                                See equation 5.46 in text.
         S1 =S1 + RAIN*(1-P(49))
         XS = AMAX1(0.,S1-S1MAX)
              IF(S1.GT.S1MAX)S1=S1MAX
C     CALCULATE INFIL TO S2                                                  See equation 5.47 in text.
         S2 = S2 + XS + RAIN*P(49)/2.
         XS = AMAX1(0.,S2-S2MAX)
              IF(S2.GT.S2MAX)S2=S2MAX
C       CALCULATE CRACK VOL,INFIL TO S3, RUNOFF AND GROUNDFLOW
        XS=XS+RAIN*P(49)/2.
        CRACKV=P(76)+P(77)*AMAX1(0.,P(78)-S3)                                See equation 5.48 in text.
        IF(XS.LE.CRACKV)INFIL=XS
        IF(XS.GT.CRACKV)INFIL=CRACKV+P(79)*TANH((XS-CRACKV)/P(79))          See equation 5.50 in text.
        RUNOFF=XS-INFIL
        S3=S3+INFIL
        GNDFLO=AMAX1(0.,S3-S3MAX)
        S3=AMIN1(S3,S3MAX)
  100    CONTINUE
        S4=S1+S2+S3
        RETURN
        END
```

```
C*****************************************************************    0605
C                                                                      0606
      FUNCTION ETFN(S,SMAX,SMIN,SE0,A,B,C,EOCRIT)                      0607    Function used to calculate evapotranspiration using the event
C     ********                                                         0608    stepping method described on pp 143-154 of text.Eocrit is the
C                                                                      0609    value of SEo when S = LLEo(see p 143)(see also lines 257 to 265
      ETFN=0.                                                          0610    of program).
      IF(S.LE.SMIN)GOTO 10                                             0611
      E0=SE0+ABS((S-SMAX)/C)                                           0612
      IF(E0.GT.EOCRIT)E0=SE0+EXP((S-B)/A)                              0613
      IF(E0.LE.0.)GOTO 10                                              0614
      ETFN=S-(A*ALOG(E0)+B)                                            0615    See equation 5.20 in text.
      IF(E0.LT.EOCRIT)ETFN=S-(C*E0+SMAX)                               0616    See equation 5.21 in text.
   10 CONTINUE                                                         0617
      RETURN                                                           0618
      END                                                              0619
C*****************************************************************    0620
C                                                                      0621
      SUBROUTINE PIC                                                   0622    Subroutine for planting irrigated crops.
C     **********                                                       0623
C                                                                      0624
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)        0625
      REAL GSP(50),PON(8,20),FSTRAT(60,7)                              0626
      INTEGER DAY,MTH,YR,M(100)                                        0627
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT          0628
C6310---UPDATE WATER BALANCE                                            0629
      CALL WBIR                                                        0630    Update water balance.
      CALL WBDAM                                                       0631
C6320---PLANT CROPS                                                    0632
      M40=M(40)                                                        0633
      M(10)=FSTRAT(M40,3)                                              0634
      M10=M(10)                                                        0635
      M(11)=2                     ! INCREASE CROP INDEX                0636
      M(12)=1                     ! NO OF CROPS                        0637
      IF(M10.GT.2)GOTO 6325                                            0638
      M(44)=M(45)                                                      0639
      P(171)=P(153)   ! GRAIN & FORAGE SORGHUM IRRIG STRAT             0640
      P(172)=P(154)                                                    0641
      P(173)=P(155)                                                    0642
      GOTO 6326                                                        0643
 6325 CONTINUE                                                         0644
      M(44)=M(46)     ! SET OATS IRRIG STRAT                           0645
      P(171)=P(157)                                                    0646
      P(172)=P(158)                                                    0647
      P(173)=P(159)                                                    0648
 6326 CONTINUE                                                         0649
      P(176)=P(171)                                                    0650
      P(177)=P(172)                                                    0651
      P(178)=P(173)                                                    0652
C-------CALC CROP AREA                                                 0653
      VOL=DAM(1)                                                       0654
      DAM(15)=DAM(1)                                                   0655
      M44=M(44)                                                        0656
      VOLP=0.                                                          0657
      IF(FSTRAT(M40,4).EQ.1.)GOTO 6330                                 0658
C------ NO IRRIG AT PLANTING                                           0659
```

```
      IF(M(48).EQ.1)P(152)=AMIN1(P(151),AMAX1(P(149),P(150)*DAM(1)))    0660
      IF(M10.LE.2)AREA=P(152)                                           0661
      IF(M10.GE.3)AREA=P(301+M44)*VOL                                   0662
      GOTO 6340                                                         0663
 6330 CONTINUE ! IRRIG CROPS AT PLANTING                                0664
      IF(M10.LE.2)AREA=P(152)*VOL                                       0665
      IF(M10.GE.3)AREA=P(305+M44)*VOL                                   0666
      VOLP=AREA*(P(40)-CS(1,1)-CS(1,2)-CS(1,3))/100. ! VOL PLANT IRRIG  0667
      DAM(1)=DAM(1)-VOLP                                                0668
      DAM(14)=DAM(14)+VOLP                                              0669
      SIA(1,2,9)=P(40)-CS(1,1)-CS(1,2)-CS(1,3)                          0670
      SIA(1,2,17)=VOLP                                                  0671
      CS(1,1)=P(41)                                                     0672
      CS(1,2)=P(43)                                                     0673
      CS(1,3)=P(45)                                                     0674
      CS(1,4)=P(40)                                                     0675
 6340 CONTINUE                                                          0676
      CS(1,11)=AREA                                                     0677
      CS(1,7)=2.                                                        0678
      CS(1,8)=0.                                                        0679
      CS(1,19)=0.                                                       0680
      CS(1,22)=0.                                                       0681
      CS(1,23)=0.                                                       0682
      SIA(1,2,4)=CS(1,1)                                                0683
      SIA(1,2,5)=CS(1,2)                                                0684
      SIA(1,2,6)=CS(1,3)                                                0685
      SIA(1,2,1)=2.                                                     0686
      SIA(1,2,2)=MET(36)                                                0687
      SIA(1,2,16)=DAM(1)+VOLP                                           0688
      M(41)=M(44)                                                       0689
 6350 CONTINUE                                                          0690
      RETURN                                                            0691
```

Return to line 110.

```
      END                                                               0692
C*******************************************************************    0693
C                                                                       0694
      SUBROUTINE HIC                                                    0695
C     **********                                                        0696
C                                                                       0697
```

Subroutine to calculate yield and components of yield of irrigated grain sorghum.

```
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)         0698
      REAL GSP(50),PON(8,20),FSTRAT(60,7)                               0699
      INTEGER DAY,MTH,YR,M(100)                                         0700
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT           0701
C6510---UPDATE WATER BALANCE                                            0702
      CALL WBDAM                                                        0703
      CALL WBIR                                                         0704
C6520---CALCULATE YIELDS                                                0705
```

These are potentially 8 different crop areas on the irrigation area.Calculate yield per hectare on each area.

```
      IF(M(10).NE.1)GOTO 6530                                           0706
      DO 6529 K=1,8                                                     0707
      IF(CS(K,11).EQ.0.)GOTO 6529                                       0708
C    ---CALC WATER STRESSES                                             0709
```

See equation 5.58 in text.

```
      WSF=AMAX1(0.0,P(129)-P(128)*SIA(K,4,7))                           0710
      WSB=AMAX1(0.0,P(131)-P(130)*SIA(K,5,7))                           0711
      WSA=AMAX1(0.0,P(133)-P(132)*SIA(K,6,7))                           0712
C    ---CALC PLANT DENSITY, POT GRAIN NUMBER & GRAINS FILLED            0713
      D=P(121)*P(122)/100.                                              0714
```

```
      PGNH=P(125)*D/(1+P(126)*D)
      GNFILL=PGNH*(1-WSF)*(1-WSB)*(1-WSA)
C   ---CALC GRAIN SIZE
      ETFILL=AMIN1(147.5,SIA(K,6,7)+SIA(K,7,7))
      TIMEFL=SIA(K,6,3)+SIA(K,7,3)
      TEMP=AMIN1(3.,AMAX1(-3.5,800./TIMEFL+2.5-22.6))
      GSIZE=AMAX1(P(134),AMIN1(P(135),P(136)*ETFILL+P(137)*ETFILL**2
     1      +P(138)*TEMP+P(139)))
C    ---CALC PROPORTION OF CROP LODGED AND GRAIN NUMBER HARVESTED
      PLODGE=AMIN1(0.8,P(142)*EXP(P(143)*(GSIZE-15.0)))
      IF((1-WSF)*(1-WSB)*(1-WSA).LT..5.AND.SIA(K,7,7).GT.40.)
     1     PLODGE=AMAX1(PLODGE,.8)
      GNHARV=GNFILL*(1.-PLODGE)
C   ---CALC YIELD/HA BEFORE AND AFTER LODGING AND TOTAL YIELD
      YHABL=GNFILL*GSIZE
      YHA  =GNFILL*GSIZE*(1-PLODGE)
      IF(M(49).EQ.1.AND.YHA.LT.P(144))CS(K,11)=.1
      GPROD=YHA*CS(K,11)/1000.
C-------PUT YIELD ATTRIBUTES INTO ARRAYS
      SIA(K,4,15)=WSF
      SIA(K,5,15)=WSB
      SIA(K,6,15)=WSA
      CS(K,12)=PGNH
      CS(K,13)=GNFILL
      CS(K,14)=GSIZE
      CS(K,15)=YHABL
      CS(K,16)=PLODGE
      CS(K,17)=YHA
      CS(K,18)=GPROD
 6529 CONTINUE
C-------INCREMENT CROP INDEX & RESET ARRAYS
 6530 CONTINUE
      M(11)=9
      DO 6539 K=1,8
      IF(CS(K,11).EQ.0.)GOTO 6539
      SIA(K,9,1)=9.
      SIA(K,9,2)=MET(36)
      SIA(K,9,4)=CS(K,1)
      SIA(K,9,5)=CS(K,2)
      SIA(K,9,6)=CS(K,3)
      SIA(K,9,16)=DAM(1)
      SIA(K,9,19)=CS(K,19)
 6539 CONTINUE
      IF(M(47).EQ.1.AND.P(170).GT.P(154)-P(176))M(42)=M(42)-1
      IF(M(47).EQ.1.AND.P(170).GT.P(154)-P(176))P(176)=-1
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE DMYLD(ET,K)
C     **********
C
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
      REAL GSP(50),PON(8,20),FSTRAT(60,7)
      INTEGER DAY,MTH,YR,M(100)
```

PGNH = Potential grain No.per hectare(equation 5.56 in text).

See equation 5.60 in text.

See equation 5.61 in text.

This subroutine was developed to calculate the dry matter yield of irrigated forage sorghum and oats.

```
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
      IF(M(10).NE.2)GOTO 6630
C-------CALC FORAGE SORGHUM DM YIELD ------------------------------
      TX=1
      WUE=P(331)*TX*AMIN1(1.,CS(K,22)/P(332))
      GROWTH=WUE*ET
      IF(CS(1,8).LE.P(323))GROWTH=0.
      CS(K,19)=AMIN1(P(325),CS(K,19)+GROWTH)  ! YLD KG/HA ------
      CS(K,20)=CS(K,11)*CS(K,19)/1000.        ! TOT YIELD ------
      IF(CS(1,8).EQ.P(324))CS(K,21)=CS(K,20)  ! HAY YIELD ------
      IF(MTH.LT.6)CS(K,24+MTH)=CS(K,20)       ! JAN TO MAY YLDS ----
      TYPE 10,DAY,MTH,YR,ET,WUE,GROWTH,CS(K,19),CS(K,22),CS(K,23)
     1  ,P(176),P(177),P(178),(M(I),I=41,46)
      RETURN
 6630 CONTINUE
      IF(M(10).NE.4)GOTO 6650
C-------CALCULATE DM YIELD OF OATS ------------------------------
      TX=1.
      IF(CS(K,23).GT.0.)GOTO 6644
C-------CALC GROWTH ON SEMINAL ROOTS ONLY
      WUE=P(289)*TX
      GROWTH=WUE*ET
      IF(CS(1,8).LE.P(288))GROWTH=0.
      CS(K,19)=AMIN1(P(292),CS(K,19)+GROWTH)
      GOTO 6645
 6644 CONTINUE ! CALC GROWTH ON SECONDARY ROOTS
      TLAG=P(291)
      SETIN=AMAX1(0.1,CS(K,22)-CS(K,23))
      SF=(P(290)-P(289))/(P(294)-P(291))
      WUE=P(289)+SF*(SETIN-TLAG*TANH(SETIN/TLAG))
      WUE=AMIN1(P(290),WUE) * TX
      GROWTH=WUE*ET
      CS(K,19)=AMIN1(P(293),CS(K,19)+GROWTH)
 6645 CONTINUE
      CS(K,20)=CS(K,11)*CS(K,19)/1000.
      IF(M(11).EQ.IFIX(P(297)))CS(K,21)=CS(K,20) ! HAY YIELD
      IF(MTH.GT.4.AND.MTH.LT.10)CS(K,24+MTH-5)=CS(K,20)
 6650 CONTINUE
      TYPE 10,DAY,MTH,YR,ET,WUE,GROWTH,CS(K,19),CS(K,22),CS(K,23)
     1  ,P(176),P(177),P(178),(M(I),I=41,46)
   10 FORMAT(3I3,6F10.1,3F5.1,6I4)
      RETURN
      END
C*******************************************************************
C
      SUBROUTINE IRRIGN
C     *********
C
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
      REAL GSP(50),PON(8,20),FSTRAT(60,7)
      INTEGER DAY,MTH,YR,M(100)
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
C----------------------------------------------------
C1000---UPDATE CURRENT WATER BALANCES
      CALL WBDAM
```

Subroutine IRRIGN contains the management rules for irrigation of grain sorghum. IRRIGN calls the subroutines DAMIRR(to determine how much water is available for irrigation).

```
      CALL WBIR
C----------------------------------------------------
 2000 CONTINUE
C-----CHECK CONDITIONS OKAY FOR IRRIGATION
      IF(DAM(1).LT.5.)GOTO 7000
      IF(M(10).GT.2)GOTO 2010
      IF(CS(1,4).GT.P(174))GOTO 7000   !DELAY IRRIG- SOIL TOO WET
      IF(CS(1,1).GT.P(175))GOTO 7000   !TOP SOIL TOO WET DELAY IRRIG
      GOTO 2020
 2010 CONTINUE ! SOIL CONDITIONS FOR WINTER CEREALS
      IF(M(42).EQ.0.AND.CS(1,23).EQ.0.)GOTO 2020
      IF(CS(1,4).GT.P(296))GOTO 7000 ! SOIL TOO WET DELAY IRRIG
 2020 CONTINUE
C3000---CALCULATE WATER AVAILABLE AND IRRIGN REQQUIREMENTS
      WD = (P(40)-CS(1,4))
      I=M(40)
      BMT=FLOAT(IFIX(CS(1,8)/P(59)+.5))
      CALL DAMIRR(WA,DAM(1),WD,MET(34),P(176),P(177),P(178),
     1          BMT,CS(1,11))
      IF(WA.LT..5)GOTO 7000      ! NOT ENOUGH WATER
      WRC1 =CS(1,11) * (P(40) -CS(1,4))/100.
      WRC2 =CS(2,11) *(P(40)-CS(2,4))/100.
      WRC3 =CS(3,11)*(P(40)-CS(3,4))/100.
      WRC4=CS(4,11)*(P(40)-CS(4,4))/100.
      DAM(16)=CS(1,8)/P(59)
      DAM(17)=FLOAT(M(42)+1)
      DAM(18)=DAM(1)
      DAM(19)=WA
      DAM(20)=WRC1+WRC2+WRC3+WRC4
      DAM(21)=DAM(1)-DAM(20)
C--------------------------------------------------------
C4000---GOTO FIRST,SECOND OR THIRD IRRIGATION
      I=M(11)
      M(42)=M(42)+1
      M(44)=M(44)-1
      GOTO(4100,4200,4300)M(42)
C-------FIRST IRRIGATION
 4100 CONTINUE
      IF(WA.LT.WRC1)CALL CRC(2,1,WA,P(40),CS,SIA)
      IF(CS(1,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(1,I,17),SIA(1,I,9),
     1   CS(1,11),CS(1,1),CS(1,2),CS(1,3),CS(1,4),P(41),P(43),P(45)
     2   ,CS(1,22),CS(1,23))
      GOTO 9000
C-------SECOND IRRIGATION
 4200 CONTINUE
      IF(WA.LT.WRC1)CALL CRC(3,1,WA,P(40),CS,SIA)
      IF(CS(1,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(1,I,17),SIA(1,I,9),
     1   CS(1,11),CS(1,1),CS(1,2),CS(1,3),CS(1,4),P(41),P(43),P(45)
     2   ,CS(1,22),CS(1,23))
      IF(WA.LT..5)GOTO 9000
      IF(WA.LT.WRC2)CALL CRC(4,2,WA,P(40),CS,SIA)
      IF(CS(2,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(2,I,17),SIA(2,I,9),
     1   CS(2,11),CS(2,1),CS(2,2),CS(2,3),CS(2,4),P(41),P(43),P(45)
     2   ,CS(2,22),CS(2,23))
      GOTO 9000
```

WD = Water deficit of irrigation area(mm).

BMT = Stage of phasic development.

```
C-------THIRD IRRIGATION
 4300   CONTINUE
        IF(WA.LT.WRC1)CALL CRC(5,1,WA,P(40),CS,SIA)
        IF(CS(1,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(1,I,17),SIA(1,I,9),
     1     CS(1,11),CS(1,1),CS(1,2),CS(1,3),CS(1,4),P(41),P(43),P(45)
     2     ,CS(1,22),CS(1,23))
        IF(WA.LT..5)GOTO 9000
        IF(WA.LT.WRC2)CALL CRC(6,2,WA,P(40),CS,SIA)
        IF(CS(2,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(2,I,17),SIA(2,I,9),
     1     CS(2,11),CS(2,1),CS(2,2),CS(2,3),CS(2,4),P(41),P(43),P(45)
     2     ,CS(2,22),CS(2,23))
        IF(WA.LT..5)GOTO 9000
        IF(WA.LT.WRC3)CALL CRC(7,3,WA,P(40),CS,SIA)
        IF(CS(3,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(3,I,17),SIA(3,I,9),
     1     CS(3,11),CS(3,1),CS(3,2),CS(3,3),CS(3,4),P(41),P(43),P(45)
     2     ,CS(3,22),CS(3,23))
        IF(WA.LT..5)GOTO 9000
        IF(WA.LT.WRC4)CALL CRC(8,4,WA,P(40),CS,SIA)
        IF(CS(4,11).GT.0.)CALL CIRRIG(WA,DAM(1),SIA(4,I,17),SIA(4,I,9),
     1     CS(4,11),CS(4,1),CS(4,2),CS(4,3),CS(4,4),P(41),P(43),P(45)
     2     ,CS(4,22),CS(4,23))
        GOTO 9000
C ------DELAY IRRIGATION
 7000   CONTINUE
        IF(M(10).GT.2)GOTO 7010
C ------GRAIN SOGHUM DELAY
        IF(M(10).EQ.1)STEP=MET(37)/P(59)
        IF(M(10).EQ.2)STEP=1.
        D21=P(177)-P(176)
        D32=P(178)-P(177)
        IF(M(42).EQ.0)GOTO 7002
        IF(M(42).EQ.1)GOTO 7005
        IF(M(42).EQ.2)GOTO 7006
        IF(M(42).GT.2)GOTO 9000
 7002   IF(M(47).EQ.0)GOTO 7004
        IF(P(176).GT.0)P(176)=P(176)+STEP!    FLEX IRRIG STRAT DELAY
        GAP=P(154)-P(176)
        IF(GAP.GT.P(170))GOTO 7003
        M(42)=1
        M(41)=M(41)-1
        M(43)=M(43)+1
        M(44)=M(44)-1!            P(176) IS SET TO -1 IN GRYLD MODEL
 7003   X=P(179)
        GOTO 7015
 7004   CONTINUE!        SET IRRIG STRATS DELAY
        IF(P(176).GT.0)P(176)=P(176)+STEP
        IF(P(177).GT.0..AND.D21.LE.P(170))P(177)=P(177)+STEP
        IF(P(178).GT.0..AND.D32.LE.P(170))P(178)=P(178)+STEP
        X=P(179)
        GOTO  7015
 7005   IF(P(177).GT.0.)P(177)=P(177)+STEP
        IF(P(178).GT.0..AND.D32.LE.P(170))P(178)=P(178)+STEP
        X=P(179)
        GOTO 7015
 7006   IF(P(178).GT.0.)P(178)=P(178)+STEP
```

```
        X=P(179)                                                           0935
        GOTO 7015                                                          0936
  7010  CONTINUE                                                           0937
C ------DATS IRRIG DELAY                                                   0938
        IF(M(42).EQ.1)GOTO 7011                                            0939
        IF(M(42).EQ.2)GOTO 7012                                            0940
        IF(P(176).GT.0.)P(176)=P(176)+1.                                   0941
  7011  IF(P(177).GT.0.)P(177)=P(177)+1.                                   0942
  7012  IF(P(178).GT.0.)P(17B)=P(178)+1.                                   0943
        X=P(180)                                                           0944
  7015  CONTINUE                                                           0945
        IF(P(176).GT.X)GOTO 7020                                           0946
        IF(P(177).GT.X)GOTO 7020                                           0947
        IF(P(178).GT.X)GOTO 7020                                           0948
        GOTO 9000                                                          0949
  7020  IF(P(176).GT.X)P(176)=-1                                           0950
        IF(P(177).GT.X)P(177)=-1                                           0951
        IF(P(178).GT.X)P(178)=-1                                           0952
        M(41)=M(41)-1       ! NUMBER OF IRRIGS LEFT IN PLAN                0953
        M(43)=M(43)+1       ! NUMBER OF IRRIGS DELETED                     0954
        M(44)=M(44)-1     ! NUMBER IRRIGS TO GO                            0955
        GOTO 9000                                                          0956
  9000  CONTINUE                                                           0957
        RETURN                                                             0958
        END                                                                0959
C**********************************************************************    0960
```

This subroutine divides the irrigation area.If there is not enough water available in the dam to irrigate all of block K then a portion of block is not irrigated.The area of this portion = AREA(line 967).The area of block K is diminished(line 968). A block with a new number (KN) is formed.

```
C                                                                          0961
C       SUBROUTINE TO CREATE A CROP                                        0962
C       **********                                                         0963
C                                                                          0964
        SUBROUTINE CRC(KN,K,WA,S4MAX,CS,SIA)                               0965
        REAL SIA(8,10,20),CS(8,30)                                         0966
        AREA =CS(K,11)-WA*100./(S4MAX-CS(K,4))                             0967
        CS(K,11) = CS(K,11)-AREA                                           0968
        DO 10 J=1,30                                                       0969
    10  CS(KN,J)=CS(K,J)                                                   0970
        DO 20 I=1,10                                                       0971
        DO 20 J=1,20                                                       0972
    20  SIA(KN,I,J)=SIA(K,I,J)                                             0973
        CS(KN,11) = AREA                                                   0974
        RETURN                                                             0975
        END                                                                0976
C**********************************************************************    0977
```

This subroutine reduces volume of dam by the volume of water used in irrigation and resets soil water storage of block K on irrigation area to maximum capacity.

```
C                                                                          0978
C       SUBROUTINE TO IRRIGATE A CROP                                      0979
C       **********                                                         0980
C                                                                          0981
        SUBROUTINE CIRRIG(WA,DAMVOL,SUMVOL,SUMDEP,AREA,                    0982
     1            S1,S2,S3,S4,S1MAX,S2MAX,S3MAX,CSK22,CSK23)               0983
        S4MAX=S1MAX+S2MAX+S3MAX                                            0984
        VOL=(S4MAX-S4)*AREA/100.                                           0985
        DAMVOL=DAMVOL-VOL                                                  0986
        SUMVOL=SUMVOL+VOL                                                  0987
        SUMDEP=SUMDEP+S4MAX-S4                                             0988
        WA=WA-VOL                                                          0989
```

```
        S1=S1MAX
        S2=S2MAX
        S3=S3MAX
        S4=S4MAX
        IF(CSK23.EQ.0.)CSK23=CSK22
        RETURN
        END
C*********************************************************************
C
C    SUBROUTINE DAMIRR
C    -----------------
C       THIS SUBROUTINE CALCULATES THE AMOUNT OF WATER AVAILABLE
C       IN THE DAM FOR IRRIGATION
        SUBROUTINE DAMIRR(WAVAIL,DAMVOL,WD1,E0,TIR1,TIR2,TIR3,BMT,AREA1)
C       **********
C
        REAL P(400)
        INTEGER DAY,MTH,YR,M(100)
        COMMON DAY,MTH,YR,M,P
        VOL=DAMVOL*1000.
        F=P(22)
        P9147=P(91)+P(94)+P(97)
        P9258=P(92)+P(95)+P(98)
        IF(M(47).EQ.1)GOTO 100
        GOTO(10,20,30)M(44)
C---------------------------------------------
   10   CONTINUE
C       LAST IRRIGATION
        WAVAIL=VOL/1000.
        RETURN
C---------------------------------------------
   20   CONTINUE
C       SECOND LAST IRRIGATION
C       CALCULATE SIGMA EVAP FOR DAM BETWEEN IRRIGATIONS
        DAYS=TIR2-TIR1
        IF(M(41).EQ.3)DAYS=TIR3-TIR2
        EDAM1=E0*DAYS*P(23)/1000.             ! P(23)=DAM/FITZ EVAP RATIO
C-------CALCULATE EXPECTED WATER DEFICIT IN CROP1 AT SECOND IRRIG
        ECROP1=E0*(DAYS-1.)
       WD2=P(40)-(P9147*ALOG(ECROP1)+P9258)
       WDR2=WD2/WD1
       GOTO 40
   30   CONTINUE
C       THIRD LAST IRRIGATION
C-------CALCULATE SIGMA EVAP BETWEEN IRRIGATIONS
       DAYS1=TIR2-TIR1
       DAYS2=TIR3-TIR2
       EDAM1=E0*DAYS1*P(23)/1000.
       EDAM2=E0*DAYS2*P(23)/1000.
C-------CALCULATE EXPECTED CROP DEFICITS AT 2ND LAST
C      AND LAST IRRIGNS
       ECROP1=E0*(DAYS1-1.)
       ECROP2=E0*(DAYS2-1.)
       WD2=P(40)-(P9147*ALOG(ECROP1)+P9258)
       WD3=P(40)-(P9147*ALOG(ECROP2)+P9258)
```

WAVAIL = Volume of water available for irrigation.
DAMVOL = Current volume of water in dam.
WD1 = Water deficit of block 1 on irrigation area.
Eo = Current evaporation demand.
TIR1 = Timing of first irrigation.
TIR2 = Timing of second irrigation.
TIR3 = Timing of third irrigation.
BMT = Stage of phasic development.
AREA 1 = Area of crop No.1

M(47) = 0 or 1. If M(47) = 0 then irrigate using method described on p 247 of text. If M(47) = 1 then use flexible irrigation strategy(see pp 253-256).

Expected crop deficit at last irrigation.

Expected crop deficit at second irrigation.
Expected crop deficit at third irrigation.

```
      WDR2=WD2/WD1
      WDR3=WD3/WD1
C-------CALCULATE WATER AVAILABLE FOR IRRIGN
   40 CONTINUE                                                          Use numerical iteration to find WAVAIL.
      V=0.
      VI=10000.
   41 V=V+VI
      VOL=DAMVOL*1000.
      VOL=VOL-V
      IF(VOL.LE.0.)GOTO 42
      H2=EXP(ALOG(VOL/F)/3.)
      H3=H2-EDAM1
      VOL=F*H3**3
      VOL=VOL-WDR2*V
      IF(VOL.LE.0.)GOTO 42
      IF(M(41)-M(42).EQ.2)GOTO 41
      H4=EXP(ALOG(VOL/F)/3.)
      H5=H4-EDAM2
      VOL=F*H5**3
      IF(VOL.GT.WDR3*V)GOTO 41
   42 CONTINUE
      IF(VI.LT.100.)GOTO 43
      V=V-VI
      VI=VI/10.
      GOTO 41
   43 CONTINUE
      WAVAIL=V/1000.
      RETURN
C   FLEXIBLE IRRIG STRATEGY -----------------------------
  100 CONTINUE
      IF(M(42).GT.0.)WAVAIL=DAMVOL
      IF(M(42).GT.0.)RETURN
      EDAM=E0*P(23)*(TIR2-TIR1)/1000.!   EVAP DEPTH IN METRES
      H1=EXP(ALOG(DAMVOL*1000./P(22))/3.)
      H2=AMAX1(0.,H1-EDAM)
      VEVAP=DAMVOL-P(22)*H2**3/1000.!    EVAP VOLUME (ML)               Expected dam evaporation from first to second irrigation.
      ECROP=E0*(TIR2-TIR1)
      WD2=(P(40)-(P9147*ALOG(ECROP)+P9258))/1000.!   DEPTH CROP EVAP (M)     Expected crop deficit at second irrigation.
      VCROF=AREA1*WD2*10.!                IRRIG VOLUME (ML)             Expected volume of water required for second irrigation.
      WAVAIL=AMAX1(0.,DAMVOL-VEVAP-VCROP)
      RETURN
      END
C*********************************************************************
C
      SUBROUTINE PONMOD                                                 Ponded area cropping sub-model.
C     **********
C
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
      REAL GSP(50),PON(8,20),FSTRAT(60,7)
      INTEGER DAY,MTH,YR,M(100)
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
      DO 10 I=1,8
      IF(PON(I,1).EQ.1)PON(I,9)=PON(I,9)+2.    ! UPDATE TIME
   10 CONTINUE
  100 CONTINUE ! ----- CALC DAM HT CHANGE -------------------
```

```
      HT1=GSP(11)
      HT2=DAM(2)
      IF(HT1-HT2)200,500,300
  200 CONTINUE ! ----- FLOODING -----------------------------          Water level in dam has increased.
      IF(HT2.LE.GSP(14)-P(262))GOTO 260
      DO 210 I=1,8       ! --- ALL EXISTING BLOCKS FLOODED --
      DO 210 J=1,20
  210 PON(I,J)=0.
      GSP(1)=0.      ! CROPS PRESENT=0
      GSP(3)=0.
      GSP(4)=0.
      GSP(6)=0.
      GSP(14)=DAM(12)   ! MAX DAM HT THIS SEASON
      GSP(11)=HT2
      GSP(12)=GSP(14)   ! UPPER LEVEL LAST BLOCK
      GSP(13)=AMAX1(0.,GSP(14)-P(262)) ! LOWER LEVEL
      GOTO 299
  260 CONTINUE  ! PARTIAL FLOODING OF CROP LAND
      DO 290 I=1,8
      IF(PON(I,1).EQ.0.)GOTO 290 ! CROP I ALREADY FLOODED
      IF(HT2.LE.PON(I,4))GOTO 290 ! NO CHANGE, HT<LOWER LEVEL
      IF(HT2.GE.PON(I,3))GOTO 270 ! COMPLETE FLOODING CROP I
C     CROP I IS PARTIALLY FLOODED
      X=(PON(I,3)-HT2)/(PON(I,3)-PON(I,4))
      IF(X.LT..5)PON(I,5)=P(31) ! SET SM TO MAX
      IF(X.LT..5)PON(I,7)=0.    ! SET SIGMA E0 = 0
      GSP(12)=PON(I,3)          ! UPPER LEVEL LAST BLOCK
      GSP(13)=PON(I,4)          ! LOWER LEVEL   "   "
      GOTO 290
  270 CONTINUE                ! CROP I FLOODED
      GSP(1)=GSP(1)-1.          ! NO OF CROPS PRESENT
      GSP(3)=GSP(3)-PON(I,11)   ! TOTAL AREA OF CROPS
      DO 280 J=1,20
  280 PON(I,J)=0.
  290 CONTINUE
  299 CONTINUE
      GOTO 500
  300 CONTINUE  ! ---------- PLANTING ----------------------          Water level in dam has decreased.
      WEEDHT=GSP(14)-P(262)                                            Check conditions for planting.
      DO 310 I=1,8
      IF(PON(I,1).LT.1.)GOTO 310
      IF(PON(I,9).GT.P(269))WEEDHT=PON(I,4)
  310 CONTINUE
      IF(HT2.GT.WEEDHT)GOTO 399  ! TOO WEEDY                          Delay planting a new strip.
      IF(MTH.GT.9)GOTO 399       ! TOO EARLY
      IF(MTH.LT.IFIX(P(264)))GOTO 399 ! TOO EARLY
      IF(MTH.GT.7)GOTO 399       ! TOO LATE
      IF(GSP(13)-HT2.LT.P(263))GOTO 398 ! NOT ENOUGH EVAP
      IF(GSP(14).LT.P(261))GOTO 398 ! MAX HT DAM TOO LOW
      IF(GSP(1).EQ.8.)GOTO 398       ! 8 ALREADY PLANTED
      I=IFIX(GSP(1)+1.)          ! BLOCK NUMBER                        Plant a new strip.
      PON(I,1)=1.     ! STATUS
      PON(I,2)=FLOAT(YR*10000+MTH*100+DAY)
      PON(I,3)=GSP(13) ! UPPER HT
      IF(GSP(9).EQ.-1.)PON(I,3)=GSP(11)
```

```
      PON(I,4)=HT2      ! LOWER HT
      PON(I,5)=P(31)-14.    ! S=SMAX
      PON(I,6)=0.       ! SIGMA ET
      PON(I,7)=0.       !SIGMA E0
      PON(I,8)=0.
      PON(I,9)=0.       ! SIGMA TIME(WKS) FROM PLANT
      PON(I,10)=0.      ! SIGMA RAIN FROM PLANT
      X1=GSP(13)/1000.
      X2=HT2/1000.
      PON(I,11)=3.*P(22)*(X1**2-X2**2)/10000.     ! BLOCK AREA          See equation 6.4 in text.
      GSP(1)=GSP(1)+1. ! NUMBER OF CROPS PRESENT
      GSP(2)=GSP(2)+1. ! TOT NO CROPS SOWN THIS SEASON
      GSP(26)=GSP(26)+PON(I,11)  ! TOT AREA SOWN THIS SEASON
      GSP(12)=GSP(13)  ! UPPER LEVEL OF LAST BLOCK PLANTED
      GSP(13)=HT2      ! LOWER LEVEL
      GSP(21)=GSP(21)+PON(I,11)*4.42+PON(I,11)/0.56/P(345) *
     1        (2.385*P(345) + P(342))!     *** TOT PLANTING COSTS ***
398   CONTINUE
      GSP(9)=0.
      GOTO 500
399   CONTINUE
      GSP(9)=-1.
      GOTO 500
500   CONTINUE  ! ----------- HARVEST --------------------              Calculate forage sorghum production.
      DO 510 I=1,8
      IF(PON(I,1).LT.1.)GOTO 510
      TI=1.                                                              See equation 6.14 in text.
      TEMP=(MET(32)+MET(33))/2.
      IF(TEMP.LT.P(258))
     1   TI=EXP((TEMP-P(258))**2/-P(259))
      CI=1.                                                              See equation 6.10 in text.
      AGE=PON(I,9)
      IF(AGE.LT.P(254))CI=EXP((AGE-P(254))**2/-P(255))
      SRAIN=0.                          ! SIGMA RAIN                     See p 211 in text.
      IF(AGE.EQ.4)SRAIN=GSP(17)
      IF(AGE.EQ.6)SRAIN=GSP(16)+GSP(17)
      IF(AGE.GE.8)SRAIN=GSP(15)+GSP(16)+GSP(17)
      XNI=1.
      IF(SRAIN.GT.0.)XNI=P(257)+P(252)*AMIN1(SRAIN,P(253)
      GROWTH=P(251) * PON(I,6) * TI * CI * XNI                           See equation 6.12 and 6.13 in text
      PON(I,12)=AMIN1(P(260),PON(I,12)+GROWTH)                           Dry matter yield/ha of strip I.
      PON(I,15)=PON(I,15)+PON(I,6)
      PON(I,13)=PON(I,11)*PON(I,12)/1000.   ! BLOCK PRODN TONNES         Dry matter production from strip I.
      IF(PON(I,9).EQ.P(256))GSP(8)=GSP(8)+PON(I,13) ! HAY YIELD PON AREA
      IF(PON(I,9).EQ.P(256))
     1GSP(22)=GSP(22) + PON(I,11)*8.82 + 5.2*PON(I,13)! HAY HARVEST COST
      IF(PON(I,9).EQ.P(256).AND.GSP(8).GT.1.)
     1GSP(23)=(GSP(21)+GSP(22))/GSP(8)!          *** HAY COST/TONNE ***
      IF(PON(I,9).EQ.P(256))GSP(25)=GSP(25)+PON(I,11)    ! AREA HARV FOR
      IF(PON(I,9).EQ.P(256))GSP(27)=GSP(27)+1.
      PON(I,6)=0.
510   CONTINUE
      X=0.
      AREA=0.
      TOTY=0.
```

```
      WA=0.
      DO 520 I=1,8
      IF(PON(I,1).LT.1.)GOTO 520
      X=X+1.
      AREA=AREA+PON(I,11)
      TOTY=TOTY+PON(I,13)
      WA=WA+PON(I,13)*PON(I,9)
  520 CONTINUE
      GSP(1)=X
      GSP(3)=AREA
      GSP(4)=TOTY
      I=0
      IF(MTH.EQ.5)I=1
      IF(MTH.EQ.7)I=6
      IF(MTH.EQ.9)I=11
      IF(I.EQ.0)GOTO 530
      GSP(30+I)=AREA
      GSP(31+I)=TOTY/AMAX1(.1,AREA)*1000.
      GSP(32+I)=WA/AMAX1(.01,TOTY)
      GSP(33+I)=TOTY
      GSP(34+I)=TOTY/P(270)
      IF(MTH.EQ.5)GSP(46)=GSP(1)
      IF(MTH.EQ.7)GSP(47)=GSP(1)
      IF(MTH.EQ.9)GSP(48)=GSP(1)
  530 CONTINUE
  900 CONTINUE !----------- END ----------------
      GSP(6)=GSP(6)+2.
      GSP(11)=HT2
      GSP(17)=0.
      GSP(16)=GSP(17)
      GSP(15)=GSP(16)
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE W8PON(PON,RAIN,TMAX,TMIN)
C     **********
C
C
C     CALC WATWR BALANCE OF PONDED AREA CROPS
      REAL PON(8,20)
      TEMP=(TMAX+TMIN)/2.
      DO 10 I=1,8
      IF(PON(I,1).LT.1.)GOTO 10
      IF(PON(I,7).EQ.0.)GOTO 10
      CALL WBPON2(RAIN,PON(I,7),PON(I,5),PON(I,6),PON(I,9))
      PON(I,7)=0.      ! SIGMA EO
      PON(I,8)=0.
      PON(I,10)=PON(I,10)+RAIN
   10 CONTINUE
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE WBPON2(RAIN,SEO,SM,SET,AGE)
C     **********
```

Water balance of ponded area.

```
C                                                                            1265
        REAL P(300)                                                          1266
        INTEGER M(100),DAY,MTH,YR                                            1267
        COMMON DAY,MTH,YR,M,P                                                1268
        SMAX=P(31)                                                           1269
        SMIN=P(32)                                                           1270
        CI=EXP((AMIN1(AGE,P(254))-P(254))**2/-P(255)                         1271
        E=(1.-CI)*ETFN(SM,SMAX,SMIN,SE0,P(33),P(34),P(35),P(36))             1272    Use ETFN function given at line 607.
        T=     CI *ETFN(SM,SMAX,SMIN,SE0,P(37),P(38),P(39),P(30))            1273
        ET=AMIN1(SM-SMIN,E+T)                                                1274
        SET=SET+ET                                                           1275
        SM=SM-ET+RAIN                                                        1276
        SM=AMAX1(SM,SMIN)                                                    1277
        SM=AMIN1(SM,SMAX)                                                    1278
        RETURN                                                               1279
        END                                                                  1280
C**********************************************************************      1281
C                                                                            1282
        SUBROUTINE OUT51                                                     1283    End of year output subroutine. OUT51 gives much more detail of
C       **********                                                           1284    irrigated and ponded area crops than OUT52.
C                                                                            1285
        REAL TODAY(2),CLOCK(2),CROP                                          1286
        REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)            1287
        REAL GSP(50),PON(8,20),FSTRAT(60,7)                                  1288
        INTEGER DAY,MTH,YR,M(100)                                            1289
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT              1290
        CALL DATE(TODAY)                                                     1291
        CALL TIME(CLOCK)                                                     1292
C1000---UPDATE WATER BALANCES--------------------------                       1293
C!!     CALL WBCAT                                                           1294
        CALL WBDAM                                                           1295
        CALL WBIR                                                            1296
        DO 1100 K=1,8                                                        1297
 1100   SIA(K,9,12)=CS(K,4)                                                  1298
C2051---M51 OUTPUT------------------------------------                         1299
        IF(M(51).EQ.0)RETURN                                                 1300
        IF(M(11).EQ.1)RETURN                ! RETURN IF M11=1                1301
        WRITE (23,511) M(1),TODAY,CLOCK,YR                                   1302
        DO 8 K=1,8                                                           1303
        DO 8 I=1,9                                                           1304
    8   DAM(14)=DAM(14)+SIA(K,I,17)                                          1305
        WRITE (23,513) (DAM(J),J=1,10),DAM(14),DAM(12),DAM(13)               1306
    9   CONTINUE                                                             1307
        IF(M(10).EQ.1)CROP='G SOR'                                           1308
        IF(M(10).EQ.2)CROP='F SOR'                                           1309
        IF(M(10).EQ.3)CROP='WHEAT'                                           1310
        IF(M(10).EQ.4)CROP=' OATS'                                           1311
        DO 12 K=1,8                                                          1312
        IF(CS(K,11).EQ.0.)GOTO 12                                            1313
        WRITE (23,516)CROP,K                                                 1314
        DO 10 I =1,9                                                         1315
   10   WRITE(23,517)(SIA(K,I,J),J=1,19)                                     1316
        IF(M(10).EQ.1)WRITE(23,520)CS(K,11),(CS(K,J),J=13,18)                1317
        IF(M(10).EQ.2)WRITE(23,521)CS(K,11),CS(K,21),(CS(K,J),J=24,28)       1318
        IF(M(10).EQ.4)WRITE(23,523)CS(K,11),CS(K,21),(CS(K,J),J=24,28)       1319
```

```
  12   CONTINUE
 511   FORMAT (1H1,//,10X,'RUN',I6,3X,2A5,
    1      3X,2A5,'  ENDYR SUMMARY 19',I2)
C
 513   FORMAT(/,5X,'DAM',
    1  5X,'CURRENT...VOL.....HT...AREA....#EO.....#T',
    2  5X,'SIGMA YR..EVAP...RAIN....RUN....BYW....PON....IRR',
    1        '...MAXH...MAXV',/,
    3  20X,5F7.1,12X,5F7.1,F7.1,2F7)
C
 514   FORMAT(//,5X,'IRRIGATED AREA STATS')
 515   FORMAT(/,5X,'CROP NUMBER',I3,'  AREA = 0')
 516   FORMAT(/,5X,'IRRIGATED  ',A5,'  CROP NO',I3,
    1        '  WATER BALANCE',/,5X,
    1  'BMT...DATE...#T...S1...S2.....S3...#ET.#RAIN..#IRR..#RUN',
    2  '..#GND..S4...#EO.....#T...WST..DAMV..IRRV..RUND....DMY',/)
 517   FORMAT(5X,F3,F8,3F5,5F6,F5,F6,2F6,F6.2,3F6.1,F6)
 520   FORMAT(/,5X,'AREA =',F6.1,'  GNNO =',F6.1,'  GSIZE =',F6.1,
    1            '  YHA8L =',F6.0,'  LL % =',F4.2,'  YHA =',F6,
    2            '  TOT Y =',F7.0)
 521   FORMAT(/,5X,'AREA =',F6.1,'  HAY Y =',F6.1,' END MTH YLDS',
    1   ' JAN =',F6,' FEB =',F6,' MAR =',F6,' APR =',F6,' MAY =',F6)
 523   FORMAT(/,5X,'AREA =',F6.1,'  HAY Y =',F6.1,' END MTH YLDS',
    1   ' MAY =',F6,' JUN =',F6,' JUL =',F6,' AUG =',F6,' SEP =',F6)
       WRITE(23,524)
 524   FORMAT(/,5X,'PONDED AREA FORAGE SORGHUM',/,
    1  5X,'...CROP,..PLANT,...UP H,..LOW H,....SM.,..#TIME,..#RAIN,',
    2  '...#ET.,...AREA,...Y HA,..TOT Y,..MTEMP')
       DO 526 I=1,8
       IF(PON(I,1).EQ.1.)WRITE(23,527)I,(PON(I,J),J=2,5),
    1   PON(I,9),PON(I,10),PON(I,15),(PON(I,J),J=11,14)
 526   CONTINUE
 527   FORMAT(5X,I5,3X,7F8,4F8.1)
       WRITE(23,528)GSP(1),GSP(2),GSP(8),GSP(21),GSP(22),GSP(23)
 528   FORMAT(/,5X,'CROPS=',F3,'  SOWN=',F3,'  HAY YLD=',F6.1,
    1  '  PLANT= $',F6,'  HARV= $',F6,'  HAY = $',F6,' /TONNE')
       WRITE(23,530)
       DO 529 I=1,3
       K=31+(I-1)*5
       L=35+(I-1)*5
       X=' MAY '
       IF(I.EQ.2)X=' JUL '
       IF(I.EQ.3)X=' SEP '
 529   WRITE(23,531)X,(GSP(J),J=K,L)
 530   FORMAT(/,15X,'  AREA    Y/HA    W AGE    TOT Y    WKS G')
 531   FORMAT(5X,A5,5X,5F8.1)
       RETURN
       END
C**********************************************************************
C
       SUBROUTINE OUT52
C      **********
C
       REAL TODAY(2),CLOCK(2),CROP,PROFIT(10)
       REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
```

End of year output subroutine.

```
        REAL GSP(50),PON(8,20),FSTRAT(60,7)
        INTEGER DAY,MTH,YR,M(100)
        COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
        CALL DATE(TODAY)
        CALL TIME(CLOCK)
C1000---UPDATE WATER BALANCES--------------------------
C!!     CALL W8CAT
        CALL W8DAM
        CALL W8IR
        DO 1100 K=1,8
 1100   SIA(K,9,12)=CS(K,4)
 2052   CONTINUE   !------ M52 OUTPUT -----------------
        IF(M(11).GT.1)GOTO 5203
        GOTO 5259
        WRITE(23,5202)
 5202   FORMAT(5X,'-1')
        GOTO 5259
 5203   CONTINUE
        IF(M(52).EQ.0)GOTO 2053
        L=M(40)
        ACA=0.           !ALL CROPS AREA
        ACTY=0. !ALL CROPS TOT Y
        DCA=0  ! AREA DRYLAND CROP
        DCTY=0.  ! TOT Y
        DCYH=0.   ! YLD/HA
        AICA=0.   ! AREA ALLIRRIG CROPS
        AICTY=0.
        AICYH=0
        OICA=0.   ! OTHER IRRIG CROPS AREA
        OICTY=0.
        OICYH=0.
        WUAIC=0.
        WUOIC=0.
        WUNO1=0.
        WUEAIC=0.     !WATER USE EFFICIENCY ALL IRRIG CROPS
        AICCT=0.   ! ALL IRRIG CROPS COST/TONNE
        DCCT=0.   ! DRYLAND CROPS COST/TONNE
C----    CACC ALL CROPS TOT YIELD AND AREA
        DO 5205 K=1,8
        ACA=ACA+CS(K,11)
 5205   ACTY=ACTY+CS(K,18)
C----   IDENTIFY DRYLAND CROP
        NDRY=0
        DO 5211 K=1,8
        DO 5210 I=2,8
        IF(SIA(K,I,17).GT.0.)GOTO 5211
 5210   CONTINUE
        IF(CS(K,11).EQ.0.)GOTO 5211
        NDRY=K
        GOTO 5212
 5211   CONTINUE
 5212   CONTINUE
        IF(NDRY.EQ.0)GOTO 5215
        DCA=CS(NDRY,11)   !----DRYLAND CROP STATS
        DCYH=CS(NDRY,17)
```

```
      DCTY=CS(NDRY,18)
 5215 CONTINUE
      IF(NDRY.EQ.1)GOTO 5220
      AICA=ACA-DCA   ! --- ALL IRRIG CROP STATS
      AICTY=ACTY-DCTY
      AICYH=AICTY/AICA*1000.
 5220 CONTINUE
      IF(NDRY.EQ.1)GOTO 5225
      OICA=ACA-DCA-CS(1,11)    ! ---- OTHER IRRIG CROP STAT¢S
      OICTY=ACTY-DCTY-CS(1,18)
      IF(OICA.GT.0)OICYH=OICTY/OICA*1000.
 5225 CONTINUE
      IF(NDRY.EQ.1)GOTO 5240
      DO 5235 I=2,8
      DO 5230 K=2,8
 5230 WUOIC=WUOIC+SIA(K,I,17)    ! ---- WATER USE CALCS
 5235 WUNO1=WUNO1+SIA(1,I,17)
      WUAIC=WUOIC+WUNO1
      WUEAIC=AMAX1(0.01,AMIN1(AICTY/(DAM(8)-DAM(9)),9.))
      IF(DAM(8).LT.5.)WUEAIC=0.1
 5240 CONTINUE
      IF(NDRY.NE.0)DCCT=AMIN1(999.,(P(181)+P(183))/DCYH*1000.)
      IF(NDRY.NE.1)AICCT=AMIN1(999.,(P(181)+P(182)*M(42)
     1   +P(183))/AICYH*1000.)
C---------OUTPUT
      IF(M(60).EQ.1.OR.M(51).EQ.1)WRITE(23,5245)
 5245 FORMAT(8X,'..IRRIG.I',15X,'CROP 1',15X,'I',6X,'OTHERS',6X,'I',
     1 12X,'ALL IRRIG',11X,'I',7X,'DRYLAND',/,
     2 4X,'PDAT.T1.T2.T3I.GNNO.GSIZ.LL...YHA..AREA.TOTY...WU.I',
     3 '..YHA..AREA.TOTY.I..YHA..AREA.TOTY...WU..WUE..COSTI',
     4 '.N..YHA..AREA.TOTY..COST')
      WRITE(23,5250)SIA(1,2,2),P(176),P(177),P(178),
     1 CS(1,13),CS(1,14),CS(1,16),CS(1,17),CS(1,11),CS(1,18),WUNO1,
     2 OICYH,OICA,OICTY,
     3 AICYH,AICA,AICTY,WUAIC,WUEAIC,AICCT,
     4 NDRY,DCYH,DCA,DCTY,DCCT
```

Write data on irrigated crop production to QDAT3.DAT at the end of each year(eg.data given in Appendix C Table C3).

```
 5250 FORMAT(F8,3F3,' ',
     1 F5,F5.1,F4.2,F6,F5,F6,F5,' ',
     2 F6,F5,F6,' ',
     3 F6,F5,F6,F5,F5.2,F5,' ',
     4 I2,F6,F5,F6,F5)
      IF(M(60).EQ.1)WRITE(24,5252)
 5252 FORMAT(4X,'.PLV.DAY.NO...VOL..WA...S:D',
     1   '.NO.AREA.NO.AREA..HAY.$TON',
     1   3('.NO.AREA..KGHA.AGE..T.YLD'))
      XM42=FLOAT(M(42))
      WRITE(24,5253)YR,
     1         DAM(15),DAM(16),XM42,DAM(18),DAM(19),DAM(21),
     1         GSP(1),GSP(26),GSP(27),GSP(25),GSP(8),GSP(23),
     1         GSP(46),(GSP(IK),IK=31,34),
     1         GSP(47),(GSP(IK),IK=36,39),
     1         GSP(48),(GSP(IK),IK=41,44)
```

Write data on dam and ponded area to QDAT4.DAT at the end of each year(ie. data given in Appendix C Table C4).

```
 5253 FORMAT(I3,F5,F4,F3,F5,F5,F6,
     1        F3,F5,F3,F5,F5,F5,
     1        3(F3,F5,F6,F5.1,F6))
```

```
 5259   CONTINUE
C-----------------PROFITS AND LOSSES---------------------------
        IF(M(61).EQ.1)WRITE(22,5260)
 5260   FORMAT(4X,'.APLO..APLA..AIRR',
     1  '..HRS...YLD...WUE...COS$...INC$..C$T..P$T.',
     1  '   P1$    P2$    P3$   .P4$    P5$ ',
     2  '   P6$    P7$    P8$    P9$ ')
        IF(M(11).EQ.1)GOTO 5266
        AHARV=0.
        APLANT=P(152)
        AIRRIG=0.
        DD 5262 K=1,8                        ! FIND PLANT & IRRIG AREAS
        DO 5261 I=2,8
        IF(SIA(K,I,9).GT.0.)AIRRIG=AIRRIG+CS(K,11)
 5261   CONTINUE
        AHARV=AHARV+CS(K,11)
 5262   CONTINUE
        TOTYLD=AICTY+DCTY!                          **** TOTAL YIELD ****
        TWUE=AMAX1(0.01,AMIN1(9.,TOTYLD/(DAM(8)-DAM(9))))!   *** WUE ***
        IF(DAM(8).LT.5.)TWUE=0.1
        APLOU=P(151)
        HDISC=APLOU/0.6/P(343)!                  *** LABOUR ***
        HSWEEP=APLOU/.64/P(344)
        HCOMB=APLANT/.56/P(345)
        HFURR=APLANT/.64/P(344)
        HIRR=AIRRIG/1.25
        HHDM=AICA/4.00
        HHARV=AHARV/2.46
        HSTORE=HHARV
        HRSLAB=HDISC+HSWEEP+HCOMB+HFURR+HIRR+HHDM+HHARV+HSTORE
        CTH=P(342)                      ! COST TRACTOR/HR *** COSTS ***
        CPLOU=HDISC*(1.27*P(343)+CTH)+HSWEEP*(.95*P(344)+CTH)
        SEED=APLANT*4.98
        CPLANT=HCOMB*(2.385*P(345)+CTH)+HFURR*(.95*P(343)+CTH)+SEED
        CIRR=HHDM*(.95+CTH) + AIRRIG*3.87
        CHARV=AHARV*29.80
        CSTORE=HSTORE*4. + TOTYLD*2.50
        CTOTOP=CPLOU+CPLANT+CIRR+CHARV+CSTORE
        TOTCOS=CTOTOP+P(346)!                         *** TOTAL COST ***
        COSTON=AMIN1(999.,TOTCOS/TOTYLD)
        TOTREV=80.0 * TOTYLD  !                  **** INCOME ****
        PROTON=80.0 - COSTON
        GOTO 5267
 5266   CONTINUE
        APLOU=P(151)
        APLANT=0.
        AIRRIG=0.
        HDISC=APLOU/.6/P(343)
        HSWEEP=APLOU/.64/P(344)
        HRSLAB=HDISC+HSWEEP
        CTOTOP=HDISC*(1.27*P(343)+P(342))+HSWEEP*(.95*P(344)+P(342))
        TOTCOS=P(346)+CTOTOP
        TOTYLD=0.
        TWUE=0.
        TOTREV=0.
```

Calculate costs and returns from irrigation area.

APLOU = Area ploughed (ha).
AHARV = Area harvested(ha).
APLANT = Area planted(ha).
AIRRIG = Area irrigated(ha).

TOTYLD = Total grain production from irrigation area(tonnes).

HRSLAB = Total hours of labour for grain production.

TWUE = Water use efficiency of grain production.

```
      COSTON=0.
      PROTON=0.
 5267 CONTINUE
      K=1!                        **** PROFIT MATRIX ****
      FIXED=P(346)
      PROFIT(K)=AMAX1(-99999.,AMIN1(999999.,
     1          TOTREV - FIXEO - CTOTOP))
      DO 5263 K1=1,2
      DO 5263 K2=1,2
      DO 5263 K3=1,2
      K=K+1
      PROFIT(K)=AMAX1(-99999.,AMIN1(999999.,
     1          TOTYLD*P(358+K1)-FIXED*P(356+K2)-CTOTOP*P(354+K3)))
 5263 CONTINUE
      WRITE(22,5265)YR,APLOU,APLANT,AIRRIG,
     1 HRSLAB,TOTYLD,TWUE,TOTCOS,TOTREV,COSTON,PROTON,
     1 (PROFIT(K),K=1,9)
 5265 FORMAT(I3,3F6,2F6,F6.2,2F7,2F5,9F7)
      IF(M(11).GT.1)M(60)=0
      M(61)=0
 2053 CONTINUE
      RETURN
      END
```

Write the following data to QDAT2.DAT at the end of each year: year,area of land ploughed,planted and irrigated,hours of labour,and total grain production,water use efficiency,grain cost/tonne and grain profit/tonne(ie. data given in Appendix C Table C5).

```
C**********************************************************************
C
      SUBROUTINE OUT53
C     *********
C
      REAL TODAY(2),CLOCK(2),CROP
      REAL P(400),MET(40),CAT(30),DAM(30),CS(8,30),SIA(8,10,20)
      REAL GSP(50),PON(8,20),FSTRAT(60,7)
      INTEGER DAY,MTH,YR,M(100)
      COMMON DAY,MTH,YR,M,P,MET,CAT,DAM,CS,SIA,GSP,PON,FSTRAT
      CALL DATE(TODAY)
      CALL TIME(CLOCK)
C1000---UPDATE WATER BALANCES-------------------------
C!!   CALL W8CAT
      CALL WBDAM
      CALL W8IR
      DO 1100 K=1,8
 1100 SIA(K,9,12)=CS(K,4)
C-------PONDED AREA OUTPUT ---------------------------------
      IF(M(53).EQ.0)GOTO 2054
      DO 5301 I=1,8
      IF(PON(I,1).LT.1.)GOTO 1505
 5301 WRITE(23,5302)(PON(I,J),J=1,15)
 5302 FORMAT(/,10X,F3,F8,2F6,F5,F4,F5,2F3,F5,F5.1,F7.1,F5,F2,F5)
 1505 CONTINUE
      WRITE(23,5303)GSP
 5303 FORMAT(/,10X,5F15.1)
 2054 CONTINUE
C3000---UPDATE END OF RUN SUMMARY ------------------------
      RETURN
      END
C**********************************************************************
```

End of year output subroutine.

End of 60 year simulation output.

```
C
      SUBROUTINE ENR01
C     **********
C
      DIMENSION X(70,24),XM(30),S(30),P(400),R(70,70)
      INTEGER M(100)
      COMMON DAY,MTH,YR,M,P
      IF(M(52).NE.1)GOTO 90
      CLOSE(UNIT=24,FILE='QDAT4.DAT')
      OPEN(UNIT=24,FILE='QDAT4.DAT',ACCESS='SEQIN')
      N=0
      MM=24
      DO 30 I=1,70
      READ(24,20,END=40)(X(I,J),J=1,MM)
   20 FORMAT(8X,3F3,21F)
      N=N+1
   30 CONTINUE
   40 CONTINUE
      IX=70
```

Calculate 60 year means, the subroutine BECORI is a systems subroutine available to FORTRAN and hence it is not listed as part of this program.

```
      CALL BECORI(X,N,MM,IX,XM,S,R,IER)
      WRITE(22,50)(XM(J),J=1,MM)
      WRITE(23,50)(XM(J),J=1,MM)
      WRITE(22,60)(S(J),J=1,MM)
      WRITE(23,60)(S(J),J=1,MM)
   50 FORMAT(X,130('-'),/,X,'MEAN   ',3F3,
     1 F5,F5.1,F4.2,F6,F5,F6,F5,' ',
     2 F6,F5,F6,' ',
     3 F6,F5,F6,F5,F5.2,F5,' ',
     4 F2,F6,F5,F6,F5)
   60 FORMAT(X,'S DEV  ',3F3,
     1 F5,F5.1,F4.2,F6,F5,F6,F5,' ',
     2 F6,F5,F6,' ',
     3 F6,F5,F6,F5,F5.2,F5,' ',
     4 F2,F6,F5,F6,F5,
     5 /,X,130('-'))
      WRITE(23,70)M(1),M(45),P(171),P(172),P(173),P(174),P(175)
      WRITE(22,70)M(1),M(45),P(171),P(172),P(173),P(174),P(175)
   70 FORMAT(X,'RUN',I6,'   PLANNED IRRIGS',I3,
     1 '    TIMING',3F5,'    SM REQ',2F6.1)
      WRITE(23,80)
   80 FORMAT('      ASSUMPTIONS; CAT & PON NOT MODELLED, DAM=400ML'
     1 ' AT PLANT, PLANT DATES SELECTED')
      CLOSE(UNIT=24,FILE='QDAT4.DAT')
   90 CONTINUE
      RETURN
      END
C**********************************************************************
C
```

End of 60 year simulation output.

```
      SUBROUTINE ENR02
C     **********
C
      REAL P(400)
      INTEGER M(100)
      COMMON DAY,MTH,YR,M,P
      WRITE(24,70)M(1),M(45),P(171),P(172),P(173),P(174),P(175)
```

```
   70  FORMAT(4X,'RUN',I6,'   PLANNED IRRIGS',I3,
     1 '    TIMING',3F5,'    SM REQ',2F6.1)
       RETURN
       END
C*******************************************************************
```

```
M00     0 21178     0     1   147     1    20     0     0     0
M01     0     1     1     0     0     0     0     0     0     0
M02     1     1     7     3     8     5     1     4     1     1
M03     0     0     0     0     0     0     0     0     0     0
M04     0     0     0     0     1     1     0     0     0     0
M05     0     0     0     1     0     0     0     0     0     0
M06     0     0     0     0     0     0     0     0     0     0
M07     0     0     0     0     0     0     0     0     0     0
M08     0     0     0     0     0     0     0     0     0     0
M09     1     2     3     4     5     6     7     8     9     0
P00    1.    0.    0.    0.    0.    0.    0.    0.    3.    0.
P01  38.4   3.9  78.9  18.1 217.6  81.9   0.4   5.0    1.   0.0
P02  400.  50.0 0.782 1660. 0.064 2.000    0. 10.00    0. 58.00
P03 550.0 282.5-43.22 724.3 0.000 0.000-68.49 780.7 0.000 335.0
P04  40.0   7.5  80.0  25.0 215.0 125.0    5.    0. 00.45 0.000
P05  200.  600. 1000. 1400. 1800. 2200. 3600.   2.5 24.27    0.
P06    5.   70.   19.    5..00700 5.400    0..00700 5.100    0.
P07    5.   70.   19.    5. .0070 5.000 0.800 173.0 15.00    0.
P08-6.386 47.99-.6712-11.30 118.5-0.137-16.97 288.6-0.082 0.000
P09-7.304 51.73-0.539-13.84 118.5-0.315-18.61 257.6-0.692 0.000
P10    0.    0.    0.    0.    .2    .4    .8    1.    1.    0.
P11750210750228    0.    0.    0.    0.    0.    0.    0.    0.
P12 20.00 50.00 50.00-.8108 66.76 .3271     0 .5345 .3100 .7414
P13 .4300 .6133 .4600 14.00 27.50 .2187-.7436-.7408 9.136 0.000
P14 00.00 0.721-.3665 500.0 0000. 0000. 0000. 0000. 10.00 0.640
P15 500.0 500.0 50.00 -1.00 -1.00 -1.00 43.00 77.00 -1.00 -1.00
P16    5.   25.  125. 5.000   7.5   25.  125.01001.    0. 20.00
P17   -1.   -1.   -1. 264.0 27.00    0.    0.    0.   85.  90.0
P18   80.   10.   10.    0.    0.    0.    0.    0.    0.    0.
P19    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P20 0.000 0.120 0.000 0.000 14.00 40.00 130.0 324.0 402.0 0.000
P21 0.000 7.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P22 180.0 160.0 170.0 183.0 0.000 0.000 0.000 0.000 0.000 0.000
P23 30.00 35.00 40.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P24 15.00 20.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P25 20.00 0.004 50.00 8.000 30.44 10.00 0.600 27.00 100.0 8000.
P26 0.000 150.0 150.0 3.000 7.000 0.000 20.00 20.00 6.000 8.400
P27 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P28 15.00 .1151 0.000 0.000 0.000 0.000 0.000 6.000 6.000 34.00
P29 20.00 1000. 8000. 74.00 .0477 251.3 6.000 0.000 7.000 0.000
P30 1.000 .6700 .3300 .2200 1.000 .4000 .2500 .1800 0.000 0.000
P31 14.00 45.00 140.0 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P32 14.00 7.000 5.000 70.00 8000. .1151 0.000 0.000 0.000 0.000
P33 32.00 60.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P34 40.00 8.000 2.000 2.000 2.000 1000. 0.000 0.000 0.000 0.000
P35 0.000 0.000 0.000 0.000 0.750 1.250 0.750 1.250 60.00 100.0
P36 80.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P37 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P38 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P39 0.000 0.000 0.000 0.000 0.000 0.000  1660    24   100   977
```

Parameter Values

This is the data read into the M and P arrays from the disk file OPARAM.DAT. The first record of the file contains the first 10 parameter values of the M array, the second record gives the 11th to 20th values and so forth.The 11th record contains the first 10 parameter values of the P array, the 12th record gives the 11th to the 20th value and so forth.
The first column of the file indicates whether M or P values are contained in the record and also gives a line count.There are 100 M values and 400 P values.

APPENDIX B Table B4 Variables used in CATRUN program

Array C (I,J) = 40 x 2 Matrix of Observed Run-off
C (I,1) = Date
C (I,2) = Depth of observed daily-run-off (mm)

Array CLIMAT (I) = Meteorological Data for Month
where I = items 1 to 42
CLIMAT (1) to CLIMAT (31) = Daily rainfall for month
CLIMAT (32) = Mean daily maximum temperature (°C)
CLIMAT (33) = Mean daily minimum temperature (°C)
CLIMAT (34) = Mean daily evaporative demand (mm/day)
CLIMAT (38) = Total monthly rainfall (mm)
CLIMAT (39) = Number of rain days in month

Array D (I,J) = Observed and Predicted Soil Moisture Data
where I = items 1 to 200
and J = items 1 to 12
D (I,1) = Record number
D (I,2) = Date
D (I,3) = Project number
D (I,4) = Treatment number
D (I,5) = Mean observed soil moisture (mm) (0-10cm layer)
D (I,6) = Mean observed soil moisture (mm) (10-30cm layer)
D (I,7) = Mean observed soil moisture (mm) (30-90cm layer)
D (I,8) = Mean observed soil moisture (mm) (0-90cm layer)
D (I,9) = Predicted soil moisture (mm) (0-10cm layer)
D (I,10) = Predicted soil moisture (mm) (10-30cm layer)
D (I,11) = Predicted soil moisture (mm) (30-90cm layer)
D (I,12) = Predicted soil moisture (mm) (0-90cm layer)

Array IRUN (J) = Predicted Daily Run-off for month
where J = items 1 to 33
IRUN (1) to IRUN (31) = Depth of daily run-off for days 1 to 31 of month (mm)
IRUN (32) = Total monthly run-off (mm)
IRUN (33) = Number of run-off days in month

Array IRUNM (J) = Predicted Monthly Run-off for month J
where J = month number. (If month is January, February .... December then J is 1, 2 .... 12 respectively.)

Array M (I) = Integer Counter
where I = 1 to 100
M (1) and M (4) are used as counters
M (6), M (8), M (9), M (31), M (53), M (56) and M (57) are used to control output. They may have values of 0 or 1. If their value is set to 1 then output will occur.

Array P (J) = Parameter Values
where J = 1 to 300
Parameter values are read from the file C68CAT.DAT which is shown on page 368. Some values are:
P (1) = Simulation run number
P (2), P (3) and P (4) = Initial values of soil moisture in the 0-10, 10-30 and 30-90 cm soil layers respectively (mm)
P (208) and P (209) = Initial values of grass yield and litter yield (kg/ha)

Array R (I) where I = 1 to 100
R (11) = Predicted evapotranspiration rate (mm/day)
R (12) = Predicted soil moisture recharge rate (mm/day)
R (14) = Predicted run-off rate (mm/day)
R (15) = Predicted deep drainage rate (mm/day)
R (16) = Predicted soil moisture deficit (mm)
R (18) = Predicted evapotranspiration for grass growth (mm/day)

Array S (I) where I = 1 to 100
S (11) = Predicted water storage in 0-90cm soil layer (mm)
S (12) = Predicted water storage in 0-10cm soil layer (mm)
S (13) = Predicted water storage in 10-30cm soil layer (mm)
S (14) = Predicted water storage in 30-90cm soil layer (mm)
S (15) = Predicted grass yield (kg/ha)
S (16) = Predicted litter yield (kg/ha)
S (17) = Predicted pasture biomass (kg/ha)

DATE = Date (yymmdd)
DAY = Day of month (1 to 31)
SETPAS = Predicted monthly accumulation of evapotranspiration for grass growth (mm/month)

Variables used in water balance and pasture growth subroutines (WAC1 and AMBROS respectively are defined on pages 366 and 367.

APPENDIX B Table B5 FORTRAN listing of CATRUN program

```
C*********************************************************************     0001
C                                                                          0002
C       CATRUN ------ CATCHMENT RUNOFF MODEL                               0003
C       ******        ********************                                 0004
C                                                                          0005
C         FILENAME = CATRUN.FOR                                            0006
C                                                                          0007
C         CREATED FROM A63V16.F10 ON 5 OCT 83                              0008
C                                                                          0009
C*********************************************************************     0010
C                                                                          0011
C       M57=1 WRITE DAILY MET DATA & RUNOFF TO C103A.DAT                   0012
C       M57=1 WRITE MONTHLY SM,BIOMAS & DAILY RUNOFF TO C103.DAT           0013
C       M58=1 MODEL SM NOT SET TO OBS SM ON 14 JAN 70                      0014
      REAL S(100),R(100),P(300),T(100),D(200,12),CLIMAT(42),C(40,2)        0015
      INTEGER M(100),DAY,MTH,YR,IRAIN(33),IRUN(33),IRUNM(12)               0016
      OPEN(UNIT=20,FILE='C68CAT.DAT',ACCESS='SEQIN')                       0017
      OPEN(UNIT=21,FILE='B29RUN.DAT',ACCESS='SEQIN')                       0018
      OPEN(UNIT=23,FILE='C103.DAT',ACCESS='SEQOUT')                        0019
      OPEN(UNIT=24,FILE='C104.DAT',ACCESS='SEQOUT')                        0020
      OPEN(UNIT=22,FILE='C103A.DAT',ACCESS='SEQOUT')                       0021
C                                                                          0022
C                                                                          0023
      READ(20,1)M                                                          0024
    1 FORMAT(7X,10I6)                                                      0025
      READ(20,2)P                                                          0026
    2 FORMAT(7X,10F6.0)                                                    0027
        TYPE 21,P(2),P(3),P(4),P(208),P(209)                               0028
   21   FORMAT(' SOIL MOISTURE STARTING VALUES',3F6.1,/,                   0029
     1          ' GRASS/LITTER  STARTING VALUES',2F6)                      0030
      CLOSE(UNIT=20,FILE='C68CAT.DAT')                                     0031
C      READ CATCHMENT SM                                                   0032
        OPEN(UNIT=20,FILE='C100.DAT',ACCESS='SEQIN')                       0033
        DO 11 I=147,179                                                    0034
        READ(20,4)(D(I,J),J=2,9)                                           0035
    4   FORMAT(9X,8F)                                                      0036
         D(I,6)=D(I,6)+D(I,7)                                              0037
         D(I,7)=D(I,8)+D(I,9)                                              0038
         D(I,8)=D(I,5)+D(I,6)+D(I,7)                                       0039
         IF(D(I,9).EQ.0.)D(I,7)=0.                                         0040
         IF(D(I,9).EQ.0.)D(I,8)=0.                                         0041
         D(I,9)=0.                                                         0042
   11   CONTINUE                                                           0043
        DO 19 I=1,33                                                       0044
   19   READ(20,12)(C(I,J),J=1,2)                                          0045
   12      FORMAT(X,2F)                                                    0046
        CLOSE(UNIT=20,FILE='C100.DAT')                                     0047
C      CHANGE PARAMETER VALUES  ==========================                 0048
        IF(M(6).EQ.0)GOTO 10                                               0049
        OPEN(UNIT=20,FILE='C105.DAT',ACCESS='SEQOUT')                      0050
          M7=M(7)                                                          0051
    6   CONTINUE                                                           0052
        TYPE 18                                                            0053
        WRITE(20,18)                                                       0054
   18     FORMAT(X,'SET P/M VALUE')                                        0055
```

Comments in this column are to assist understanding of the adjacent program. CATRUN is an interactive FORTRAN program that executes in a way similiar to the program SSISMO (see page 331). Variables are stored in the arrays S, R, T, D, C and CLIMAT. Parameters are stored in the arrays M and P. The program advances through simulated time on a daily basis, however weather data is read at the beginning of each month with daily rainfall data for the month stored in the array CLIMAT. The catchment water balance is calculated daily but pasture biomas is calculated monthly.

The program was initially coded to compare observed and predicted soil moisture and run-off, and to optimize parameter values. While the subroutines performing these tasks have been deleted from this listing, some code for these tasks still remain in the main program segment.

Parameters of the arrays M and P are read at line 24, however parameter values may be changed interactively before the program starts to simulate the catchment water balance. The first prompt of CATRUN is 'SET P/M VALUE'. The procedure for replying to this prompt is the same as used in SSISMO (see page 334).

Further comments in this column refer to adjacent lines.

READ parameter values of the arrays M and P from the file C68CAT .DAT. (This file is listed at the end of the program).

READ observed soil moisture data from the file C100.DAT and store in array D.

READ observed run-off data from the file C100.DAT and store in array C.

Reset parameters of the M and P arrays interactively using the same procedure as used in SSISMO (see page 334).

```
       ACCEPT 13,SET,PARAM,NP,VAL
  13     FORMAT(A3,X,A1,I,F)
       WRITE(20,14)SET,PARAM,NP,VAL
  14     FORMAT(X,A3,X,A1,I3,F12.5)
       IF(SET.EQ.'END')GOTO 501
       IF(SET.NE.'TYP')GOTO 17
         IVAL=IFIX(VAL)
       IF(PARAM.EQ.'P')TYPE 15,NP,IVAL,(P(I),I=NP,IVAL)
       IF(PARAM.EQ.'P')WRITE(20,15)NP,IVAL,(P(I),I=NP,IVAL)
  15      FORMAT(/,X,'P',I3,' TO P',I3,2(5F12.5))
       IF(PARAM.EQ.'M')TYPE 16,NP,IVAL,(M(I),I=NP,IVAL)
       IF(PARAM.EQ.'M')WRITE(20,16)NP,IVAL,(M(I),I=NP,IVAL)
  16      FORMAT(X,'M',I3,' TO M',I3,10I6)
          GOTO 6
  17   IF(PARAM.EQ.'P')P(NP)=VAL
       IF(PARAM.EQ.'M')M(NP)=IFIX(VAL)
       IF(SET.EQ.'YES')GOTO 6
       REWIND 21
        M(4)=1
        M(5)=147
        DAY =99
```

Set initial values of soil moisture and pasture biomass.

```
       S(11)=P(2)+(3)+P(4)
       S(12)=P(2)
       S(13)=P(3)
       S(14)=P(4)
       S(15)=P(208)
       S(16)=P(209)
C     COMMENCE DAILY LOOP    ============================
       T(1)=0.
  10  CONTINUE
      DAY = DAY+1
      T(1)=T(1) + 1.0
      T(7)=T(7) + 1.0
      T(10)=T(10) + 1.0
       IF(DAY.LT.32.AND.CLIMAT(DAY).GE.0.)GOTO 40
       IF(M(57).NE.1)GOTO 25
       IF(DAY.EQ.100)GOTO 25
C------OUTPUT DAILY MET DATA ,SM4,BIOMAS AND DAILY RUNOFF
       IRUN(32)=0
       IRUN(33)=0
       DO 22 I=1,31
       IRAIN(I)=IFIX(CLIMAT(I))
       IRUN(32)=IRUN(32)+IRUN(I)
       IF(IRUN(I).GT.0)IRUN(33)=IRUN(33)+1
  22   CONTINUE
       IRAIN(32)=IFIX(CLIMAT(38))
       IRAIN(33)=IFIX(CLIMAT(39))
       IRUNM(MTH)=IRUN(32)
```

At the end of each month WRITE year, month, soil moisture (0-90 cm), pasture biomass and daily run-off for month to the disk file C103.DAT.

```
       WRITE(23,27)YR,MTH,S11,S17,(IRUN(I),I=1,33)
       IF(MTH.EQ.9)WRITE(24,28)YR,(IRUNM(I),I=10,12),(IRUNM(I),I=1,9)
  23   FORMAT(I3,I2,3F5.1,31I3,I5,I3)
  24   FORMAT(9X,F5,F6,31I3,I5,I3)
  27   FORMAT(I3,I2,4X,F5,F6,31I3,I5,I3)
  28   FORMAT(I3,12I5)
  25   CONTINUE
```

```
      IF(DAY.NE.100)CALL AMBROS(SETPAS,S(15),S(16),S(17))
      SETPAS=0.
      READ(21,26,END=500)YR,MTH,CLIMAT(32),CLIMAT(33),CLIMAT(34),
     1     (CLIMAT(I),I=1,31),CLIMAT(38),CLIMAT(39)
   26 FORMAT(I3,I2,3F5.1,31F3,F5,F3)
      DAY=1
      S11=S(11)
      S17=S(15)+S(16)
   40 CONTINUE
      DATE=FLOAT(YR*10000+MTH*100+DAY)
C    TEST ACTUAL & MODEL SOIL MOISTURES=======================
      CALL WAC 1(CLIMAT(DAY),CLIMAT(34),S(12),S(13),S(14),
     1  S(11),R(11),R(14),R(12),R(15),R(16),S(17),R(18),DATE)
      SETPAS=SETPAS+R(18)
      IRUN(DAY)=IFIX(R(14)+.5)
      IF(M(9).EQ.0)GOTO 46
     IF(DATE.GE.P(111).AND.DATE.LE.P(112))WRITE(20,811),DATE,(S(I),
     1 I=12,14),R(14),R(16),CLIMAT(DAY),CLIMAT(34)
  811 FORMAT(X,'DATE',F8,X,'SM123=',3F6.1,X,'RUN',2F6.1,' RAIN',
     1 F5.1,F5.1)
   46 CONTINUE
      IF(M(55).EQ.0)GOTO 48
      M4=M(4)
      TMP1=DATE
      TMP2=C(M4,1)
      TMP3=TMP1-TMP2
      IF(TMP3.GT.-3..AND.TMP3.LT.4.)TYPE 811,DATE,(S(I),I=12,14),
     5    R(14),R(16),CLIMAT(DAY),CLIMAT(34)
   48 CONTINUE
      IF(M(53).EQ.5)WRITE(20,481)DATE,T(1),S(12),S(13),S(14),S(11),
     1  R(11),CLIMAT(DAY),R(14),R(15),S(15),S(16),S(17)
  481 FORMAT(F9,F6,'   SM',3F5,' =',F5,'   ERRG',F5.1,3F5,
     1       '   PAS',3F6)
C     END OF DAILY CYCLE    =========================
      M4=M(4)
C    TEST END OF 10 DAY LOOP   =========================
      IF(T(7).LT.10.0)GOTO 49
      T(7)=0.0
      T(6)=T(6) + 10.0
C    TEST END OF YEARLY LOOP   =========================
   49 IF(DAY.EQ.30.AND.MTH.EQ.9)GOTO 50
      GOTO 10
      T(1)=0.0
      T(6)=0.0
      T(7)=0.0
      M(11)=0
      GOTO 10
C    END OF RUN      ==================================
  500 CONTINUE
      IF(M(6).EQ.1)TYPE 502,M(1),M(2),NP,VAL
      IF(M(6).EQ.1)WRITE(20,502)M(1),M(2),NP,VAL
  502    FORMAT(X,'RUN',I4,'   DATE =',I6,'  P',I3,' =',F12.5)
      IF(M(10).EQ.1)WRITE(23,502)M(1),M(2),NP,VAL
      IF(M(10).EQ.1)WRITE(23,503)((D(I,J),J=1,12),I=147,179)
      IF(M(10).EQ.1)WRITE(24,502)M(1),M(2),NP,VAL
```

Call the subroutine AMBROS to calculate pasture biomass at the end of each month.
READ next month's weather data from the file B29RUN.DAT .

Call daily water balance subroutine WAC1

```
 503   FORMAT(X,F6.0,F7.0,F4.0,F3.0,2X,8F6.1)
C      IF(M(54).EQ.1)CALL DATAN(4)
       IF(M(6).EQ.1)M(1)=M(1)+1
 600   CONTINUE
       IF(M(6).EQ.1)GOTO 6
 501   CONTINUE
       IF(M(31).EQ.1)WRITE(24,504)M,P
 504       FORMAT(10(/,X,10I6),20(/,X,10F6))
       STOP
       END
C***********************************************************************
C
      SUBROUTINE WAC1(RAIN,E0,S1,S2,S3,STORE,ET,Q,RECHA,G,
    1                RUNDEF,BIOMAS,ETG,DATE)
C     *************
C
C     WAC1 CALCULATES THE DAILY WATER BALANCE OF THE CATCHMENT
C
       REAL P(300)
       INTEGER M(100),DAY,MTH,YR
       COMMON DAY,MTH,YR,M,P
         S1MAX=P(11)
         S1MIN=P(12)
         S2MAX=P(13)
         S2MIN=P(14)
         S3MAX=P(15)
         S3MIN=P(16)
C---- EVAPOTRANSPIRATION MODEL -----------------------------------
C     CALCULATE ACTUAL ET FOR PASTURE
       ET1=AMIN1(1.,P(65)*EXP(P(66)*(S1-S1MIN)/(S1MAX-S1MIN)))*E0
       ET2=AMIN1(1.,P(68)*EXP(P(69)*(S2-S2MIN)/(S2MAX-S2MIN)))*E0
       ET3=AMIN1(1.,P(71)*EXP(P(72)*(S3-S3MIN)/(S3MAX-S3MIN)))*E0
       ET=ET1+ET2+ET3
C     TEST FOR ET>E0
       IF(ET.LE.E0)GOTO 30
       ET1=E0/ET*ET1
       ET2=E0/ET*ET2
       ET3=E0/ET*ET3
  30   CONTINUE
C     TEST FOR MIN SOIL MOISTURE
       ET1=AMIN1(S1-S1MIN,ET1)
       ET2=AMIN1(S2-S2MIN,ET2)
       ET3=AMIN1(S3-S3MIN,ET3)
       ET =ET1+ET2+ET3
C     CALCULATE ET FOR PASTURE GROWTH
       ETG=0.
       IF(S1.GT.P(205))ETG=ET1
       IF(S2.GT.P(206))ETG=ETG+ET2
       IF(S3.GT.P(207))ETG=ETG+ET3
C     ADJUST SOIL STORES
       S1=S1-ET1
       S2=S2-ET2
       S3=S3-ET3
       STORE=S1+S2+S3
C
```

Subroutine to calculate water balance of cathment.

RAIN = rainfall (mm/day), E0 = evaporative demand (mm/day)
Q = run-off (mm/day), F = infiltration (mm/day)
ET = evapotranspiration (mm/day), G = deep drainage (mm/day)
RECHA = recharge to soil moisture (i.e. RAIN - Q - G, mm/day)
S = equivalent ponded depth of soil moisture (mm)
Where the numbers 1,2 and 3 appear in variable names they indicate soil layers 1, 2 and 3 respectively. Similarly MAX and MIN indicate maximum and minimum values.
BIOMAS = pasture biomass (Kg/ha), ETG = cumulative ET for grass growth, DATE = current date (yymmdd)

see eq 3.16 in text

```
C---- INFILTRATION RUNOFF MODEL---------------------------------
      Q=0.
      G=0.
      RUNDEF=0.
      IF(RAIN.EQ.0.)GOTO 100
      F1=AMIN1(P(19)*RAIN,S1MAX-S1)                ! Infil to S1      see eq 3.18 in text
      F2=AMIN1((P(19)+P(20))*RAIN-F1,S2MAX-S2)     ! Infil to S2      see eq 3.19 in text
      XS=RAIN-F1-F2
      BI=.5-.5*TANH((BIOMAS-P(61))/P(62))          ! Biomas index     see eq 3.21 in text
      S3DEF=S3MAX-S3
      F3MAX=AMAX1(P(17),AMIN1(P(18),S3MAX-S3)-P(63)*BI-P(64))         see eq 3.22 in text
      F3=F3MAX*TANH(XS/F3MAX)                      ! Infil to S3      see eq 3.20 in text
      IF(XS-F3.LT..5)F3=XS
      Q =XS-F3                                     ! Runoff
      G =AMAX1(0.,S3+F3-S3MAX)                     ! Ground flow
      F =F1+F2+F3                                  ! Total infiln
      S1=AMIN1(S1+F1,S1MAX)                ! Change soil stores
      S2=AMIN1(S2+F2,S2MAX)
      S3=AMIN1(S3+F3,S3MAX)
      IF(M(59).EQ.1.AND.Q.GT.0.)TYPE 99,DATE,ET,RAIN,F1,F2,S3DEF,XS    Output water balanse data if M(59) = 1 and run-off > 0.
     1      ,BI,F3MAX,F3,Q,G
   99 FORMAT(F8,F5.1,F5,3F6.1,'  XS',F5,F5.2,'  MFQG',4F6.1)
  100 CONTINUE
      RECHA=S1+S2+S3-STORE
      STORE = S1 +S2 +S3
      RETURN
      END
C***********************************************************************
C
      SUBROUTINE AMBROS(ET,GRASS,LITTER,BIOMAS)                        Subrouine to calculate pasture biomass on catchment.
C     **********
C                                                                      ET = Cumulative evapotranspiration for month (mm).
C-------THIS SUB CALCULATES PASTURE DM YIELD OF CATCHMENT              GRASS = Above ground biomass of grass (kg/ha).
      REAL S(100),R(100),P(300),T(100),X(100),D(200,12),Y(100)         LITTER = Above ground biomass of litter (Kg/ha).
     1     ,CLIMAT(42),C(30,2),LITTER                                  BIOMASS = GRASS + LITTER
      INTEGER M(100),DAY,MTH,YR                                        TEMP = mean daily temperature (deg C), TX = temperature index
      COMMON DAY,MTH,YR,M,P,S,R,T,X,Y,D,CLIMAT                         GYX = grass yield index, GG = Grass growth (Kg/ha/month),
C                                                                      GI = grazing intake (kg/ha/month), PL = litter production
      RAIN=CLIMAT(38)                                                  (Kg/ha/month), DL = litter decomposition (Kg/ha/month).
      TEMP=(CLIMAT(32)+CLIMAT(33))/2.
C-------CALCULATE PASTURE BIOMAS CHANGES
      GYX=AMIN1(1.,P(191)+P(192)*GRASS)                                see eq 3.9 in text
      IF(GRASS.GT.P(210))GYX=AMAX1(0.,1.-(GRASS-P(210))/600.)
      IF(TEMP.GT.P(194))TEMP=AMAX1(P(194),TEMP-3.)
      TX=(1.-P(193)) + P(193)*EXP(-(TEMP-P(194))**2/P(195))            see eq 3.8 in text
      GG=P(196)*ET*GYX*TX                                              see eq 3.6 in text
      GI=P(198)*(1.-EXP(P(199)*GRASS))
      PL=P(200)*GRASS                                                  see eq 3.10 in text
      DL=P(202)*LITTER                                                 see eq 3.11 in text
      GRASS=GRASS+GG-GI-PL
      LITTER=LITTER+PL-DL
      BIOMAS=GRASS+LITTER                                              see eq 3.33 in text
C-------OUTPUT
      YRM=FLOAT(YR*100+MTH)
      IF(M(56).EQ.1)CALL PLOT(2,YRM,GRASS,LITTER,4000.,0.)
```

```
      IF(M(56).EQ.1)WRITE(22,10)YR,MTH,TEMP,RAIN,ET,
     1             GYX,TX,GG,GI,PL,DL,GRASS,LITTER,BIOMAS
   10 FORMAT(2I3,'  TRE',F5.1,2F5,'  GTX',2F5.2,
     1          '  GIPD',F6,F4,2F5,'  GLB',3F7)
      RETURN
      END
C*********************************************************************
```

If M(56)=1 then WRITE monthly pasture data to file C103A.DAT.

Parameter Values

This is the data read into the M and P arrays from the disk file C68CAT.DAT. The first record of the file contains the first 10 parameter values of the M array, the second record gives the 11th to 20th values and so forth.The 11th record contains the first 10 parameter values of the P array, the 12th record gives the 11th to the 20th values and so forth. The first column of the file indicates whether M or P values are contained in the record and also gives a line count.There are 100 M values and 300 P values.

```
M00     1250779     0     1   147     1    20     0     0     0
M01     0     1     1     0     0     0     0     0     0     0
M02     1     1     7     3     8     5     1     4     1     1
M03     0     0     0     0     0     1     0     0     0     0
M04     0     0     0     0     0     0     0     0     0     0
M05     1     0     0     1     0     0     0     1     0     0
M06     0     0     0     0     0     0     0     0     0     0
M07     1     1     1     1     1     1     1     1     1     1
M08     0     0     0     0     0     0     0     0     0     0
M09     1     2     3     4     5     6     7     8     9     0
P00 1.000 6.200 20.90 124.0 1.000 4.993 2.176 0.000 0.000 0.000
P01 38.00 3.900 78.00 18.10 215.0 81.90 10.00 100.0 0.700 0.150
P02  400.  162.    1. 1660.    .1    0.    0.    0.    0.    0.
P03    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P04  40.0   7.5  80.0  25.0 215.0 125.0    5.    0. 0.450 0.000
P05  200.  600. 1000. 1400. 1800. 2200. 3600.   2.5 24.27    0.
P06 700.0 300.0 40.00 5.000 .0107 5.400    0. P0107 5.100    0.
P07..0061 5.000    0.    0.    0. 5.000 0.800 173.0 15.00    0.
P08-6.386 50.52-.4524-11.33 123.0 0.000-25.50 335.8 0.000 0.000
P09-7.304 54.62 .3630-13.84 124.0 .2119-18.61 265.0 .4730 0.000
P10    0.    0.    0.    0.    .2    .4    .8    1.    1.    0.
P11800000810000    0.    0.    0.    0.    0.    0.    0.    0.
P12    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P13    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P14    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P15    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P16    5.   25.  125.   10.   7.5   25.  125.01001.    0.    0.
P17    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P18    0.    0.    0.    0.    0.    0.    0.    0.    0.    0.
P19 0.400 .0006 0.670 27.00 15.63 5.000 0.000 24.00-.0055 0.090
P20 0.000 0.200 0.000 0.000 14.00 40.00 130.0 1040.  330. 2000.
P21 0.000 400.0 800.0 .0000 .0000 .0000 .0000 .0000 10.00 .0000
P22 2000. 2500. 3000. .0000 .0000 .0000 .0000 .0000 .0000 .0000
P23 20.00 25.00 30.00 35.00 .0000 .0000 .0000 .0000 .0000 .0000
P24 12.50 15.00 17.50 20.00 .0000 .0000 .0000 .0000 .0000 .0000
P25 4.902 8.700 27.59 36.14 0.000 0.000 0.000 0.000 0.000 0.000
P26 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P27 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P28 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
P29 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
```

APPENDIX C: ADDITIONAL RESULTS FROM SIMULATION EXPERIMENT 1

Table C1 Estimated planting dates and time to half bloom in years of cropping on the irrigation-area. (Observed rainfall and simulated run-off before and during crop growth are also shown).

Table C2 Estimated daily run-off from Mitchell grass catchment for the period 1 October 1918 to 30 September 1978.

Table C3 End of year simulation output from SSISMO program. I. Attributes of grain sorghum production on irrigation-area (output disk file QDAT3.DAT).

Table C4 End of year simulation output from SSISMO program. II. Water storage and ponded-area crop production (output disk file QDAT4.DAT).

Table C5 End of year simulation output from SSISMO program. III. Costs and Profits of grain production on irrigation-area (output disk file QDAT2.DAT).

APPENDIX C Table C1 Estimated planting dates and time to half bloom in years of cropping on the irrigation-area. Observed rainfall and simulated run-off before planting (from 1st October) and during growth are also shown. (Data from SSISMO in simulation experiment 1.)

Year	Planting Date	Time to half bloom (days)	Rainfall (mm) and run-off (mm) (in brackets)		
			Before planting	Planting to half bloom	Half bloom to maturity
1921-22	6 Feb	59	333(5)	21	-
1923-24	21 Feb	61	222(8)	240(56)	78
1926-27	21 Feb	62	360(55)	96	-
1932-33	19 Feb	61	230(6)	-	-
1933-34	28 Feb	63	298(14)	20	10
1935-36	20 Feb	71	254(6)	7	151(1)
1936-37	17 Mar	70	329(4)	-	4
1937-38	22 Feb	62	309(6)	11	-
1939-40	15 Feb	60	282(21)	269(134)	-
1940-41	30 Jan	59	318(44)	201(55)	48
1944-45	15 Mar	72	366(22)	35	-
1949-50	22 Feb	66	378(41)	306(127)	13
1950-51	26 Dec	60	301(5)	274(97)	-
1952-53	17 Feb	62	361(48)	-	-
1953-54	8 Feb	62	305(45)	215(87)	3
1954-55	27 Feb	67	327(18)	120(3)	160(35)
1955-56	10 Feb	63	272(21)	118(20)	103
1956-57	28 Dec	58	295(97)	134(9)	92
1960-61	6 Jan	56	243(45)	71	2
1963-64	13 Feb	59	304(5)	16	-
1965-66	12 Jan	57	225(13)	103(1)	-
1967-68	21 Feb	60	207(32)	44	59
1969-70	8 Feb	60	280(20)	13	-
1970-71	12 Mar	74	328(89)	224(85)	9
1971-72	10 Mar	70	383(61)	-	-
1973-74	8 Feb	61	863(371)	100	-
1974-75	4 Feb	61	311(18)	184(26)	-
1975-76	14 Feb	60	530(41)	15	4
1976-77	25 Dec	56	188(15)	67	100

APPENDIX C Table C2 Estimated Daily Run-off (mm) from Mitchel Grass Catchment for the period 1 October 1918 to 30 September 1978. (Days on which run-off was zero are not shown.) (Data from CATRUN in simulation experiment 1.)

Date	Run-off	Date	Run-off	Date	Run-off
28 Jan 20	1	13 Feb 50	9	8 Jan 66	6
1 May 20	6	15 Feb 50	3	9 Jan 66	7
6 Apr 21	3	16 Feb 50	12	21 Jan 66	1
2 Feb 22	5	18 Feb 50	5	18 Feb 68	32
16 Feb 24	1	19 Feb 50	12	3 Feb 70	20
18 Feb 24	7	8 Mar 50	1	9 Mar 71	89
27 Feb 24	26	9 Mar 50	4	30 Mar 71	2
7 Mar 24	30	12 Mar 50	42	31 Mar 71	3
23 Mar 25	3	13 Mar 50	14	16 Apr 71	66
3 Feb 27	2	14 Mar 50	1	17 Apr 71	2
15 Feb 27	8	3 Apr 50	28	18 Apr 71	12
16 Feb 27	7	4 Apr 50	35	11 Jan 72	1
18 Feb 27	38	7 Apr 50	2	4 Mar 72	2
25 Mar 27	4	20 Dec 50	5	6 Mar 72	35
6 Jan 29	2	14 Jan 51	6	7 Mar 72	23
25 Feb 30	1	15 Jan 51	25	8 Feb 73	1
8 May 30	1	24 Jan 51	66	29 Mar 73	43
13 Feb 33	1	10 Feb 53	1	30 Mar 73	30
14 Feb 33	1	12 Feb 53	9	27 Nov 73	2
15 Feb 33	4	14 Feb 53	38	3 Jan 74	27
21 Feb 34	1	3 Feb 54	1	8 Jan 74	9
22 Feb 34	13	4 Feb 54	41	12 Jan 74	30
17 May 36	6	5 Feb 54	3	14 Jan 74	20
5 Jul 36	1	5 Mar 54	17	17 Jan 74	13
14 Mar 37	4	6 Mar 54	70	18 Jan 74	7
17 Feb 38	6	23 Feb 55	18	19 Jan 74	49
17 Feb 39	2	1 Mar 55	2	20 Jan 74	25
10 Feb 40	6	3 Mar 55	1	21 Jan 74	1
11 Feb 40	13	11 Mar 55	23	22 Jan 74	46
12 Feb 40	2	25 May 55	2	23 Jan 74	21
19 Feb 40	35	26 May 55	33	24 Jan 74	2
20 Feb 40	41	7 Feb 56	21	25 Jan 74	38
24 Feb 40	9	15 Feb 56	20	26 Jan 74	2
29 Feb 40	30	20 Dec 56	1	27 Jan 74	4
1 Mar 40	19	21 Dec 56	13	31 Jan 74	39
9 Jan 41	15	22 Dec 56	83	1 Feb 74	4
23 Jan 41	4	10 Jan 57	9	3 Feb 74	30
24 Jan 41	24	27 Dec 60	11	5 Feb 74	2
25 Jan 41	1	2 Jan 61	30	8 Jan 75	18
28 Feb 41	55	3 Jan 61	4	15 Feb 75	22
29 Dec 42	2	13 Jan 62	3	26 Feb 75	4
11 Mar 45	14	29 Mar 63	6	6 Feb 76	10
12 Mar 45	8	30 Mar 63	3	7 Feb 76	16
12 Jan 46	2	4 Apr 63	9	9 Feb 76	14
13 Jan 46	1	5 Apr 63	3	11 Feb 76	1
16 Feb 46	2	6 Feb 64	1	21 Dec 76	15
29 Mar 47	1	7 Feb 64	4		

APPENDIX C Table C3 End of year simulation output from SSISMO in simulation experiment 1. I. Attributes of grain sorghum production on irrigation-area. (Output disk file QDAT3.DAT) (Data is shown on next page).

Column Number	Output Mnemonic	Variable
1	PDAT	Planting date (year month day)
		Irrigation Strategy
2	T1	First irrigation (standard days after planting)
3	T2	Second irrigation (standard days after planting)
4	T3	Third irrigation (standard days after planting)
		Attributes of Grain Sorghum Number 1 Area
5	GNNO	Grain number (millions/ha)
6	GSIZ	Grain size (mg)
7	LL	Proportion of grain yield lost to lodging
8	YHA	Grain yield (kg/ha)
9	AREA	Area of crop (ha)
10	TOTY	Total grain production of crop (t)
11	WU	Volume of irrigation water use (ML)
		Attributes of Other Irrigated Grain Sorghum
12	YHA	Grain yield (kg/ha)
13	AREA	Area (ha)
14	TOTY	Total grain production (t)
		Attributes of all Irrigated Grain Sorghum
15	YHA	Grain yield (kg/ha)
16	AREA	Area (ha)
17	TOTY	Total grain production (t)
18	WU	Volume of irrigation water use (ML)
19	WUE	Water Use Efficiency (t/ML of water harvested)
20	COST	Cost of grain ($/t)
		Attributes of Dryland Grain Crops
21	N	Crop Number
22	YHA	Grain yield (kg/ha)
23	AREA	Area (ha)
24	TOTY	Total grain production (t)
25	COST	Cost of grain ($/t)

APPENDIX C

Table C3 (continued)

```
      ..IRRIG.I                CROP 1                I     OTHERS      I            ALL IRRIG            I        DRYLAND
   PDAT.T1.T2.T3I.GNNO.GSIZ.LL...YHA..AREA.TOTY...WU.I..YHA..AREA.TOTY.I..YHA..AREA.TOTY...WU..WUE..COSTI.N..YHA..AREA.TOTY..COST
220206.55.-1.-1.  119. 21.8 .06 2451.  17.    41.  20.     0.   0.     0.  2451.  17.   41.  20. 0.49  41.  2  172.  23.    4. 522.
240221.55.-1.-1.  156. 26.0 .01 4011.  40.   160.  35.     0.   0.     0.  4011.  40.  160.  35. 0.37  25.  0    0.   0.    0.   0.
270221.55.-1.-1.  146. 23.4 .03 3301.  40.   132.  40.     0.   0.     0.  3301.  40.  132.  40. 0.26  30.  0    0.   0.    0.   0.
330219.55.-1.-1.  110. 23.9 .03 2569.  19.    48.  23.     0.   0.     0.  2569.  19.   48.  23. 0.48  39.  2  160.  21.    3. 562.
340228.55.-1.-1.  114. 26.2 .01 2946.  40.   118.  46.     0.   0.     0.  2946.  40.  118.  46. 0.51  34.  0    0.   0.    0.   0.
360320.55.-1.-1.  115. 27.5 .01 3126.  20.    62.  24.     0.   0.     0.  3126.  20.   62.  24. 0.53  32.  2  369.  20.    7. 244.
370317.55.-1.-1.  112. 25.8 .01 2863.   9.    27.  12.     0.   0.     0.  2863.   9.   27.  12. 0.41  35.  2  591.  31.   18. 152.
380222.55.-1.-1.  114. 23.7 .03 2623.  20.    53.  24.     0.   0.     0.  2623.  20.   53.  24. 0.54  38.  2  279.  20.    5. 322.
400215.55.-1.-1.  139. 23.8 .03 3217.  40.   129.  42.     0.   0.     0.  3217.  40.  129.  42. 0.35  31.  0    0.   0.    0.   0.
410130.55.-1.-1.  156. 24.0 .03 3658.  40.   146.  36.     0.   0.     0.  3658.  40.  146.  36. 0.32  27.  0    0.   0.    0.   0.
450315.55.-1.-1.  129. 26.2 .01 3343.  40.   134.  44.     0.   0.     0.  3343.  40.  134.  44. 0.37  30.  0    0.   0.    0.   0.
500222.56.-1.-1.  152. 26.8 .01 4032.  40.   161.  29.     0.   0.     0.  4032.  40.  161.  29. 0.45  25.  0    0.   0.    0.   0.
501226.55.-1.-1.  154. 21.2 .08 3019.  40.   121.  35.     0.   0.     0.  3019.  40.  121.  35. 0.32  33.  0    0.   0.    0.   0.
530217.55.-1.-1.  121. 24.9 .02 2962.  40.   118.  49.     0.   0.     0.  2962.  40.  118.  49. 0.27  34.  0    0.   0.    0.   0.
540208.55.-1.-1.  144. 23.8 .03 3327.  40.   133.  40.     0.   0.     0.  3327.  40.  133.  40. 0.32  30.  0    0.   0.    0.   0.
550227.55.-1.-1.  132. 27.5 .01 3614.  40.   145.  38.     0.   0.     0.  3614.  40.  145.  38. 0.25  28.  0    0.   0.    0.   0.
560210.55.-1.-1.  152. 25.7 .01 3831.  40.   153.  34.     0.   0.     0.  3831.  40.  153.  34. 0.35  26.  0    0.   0.    0.   0.
561228.55.-1.-1.  156. 23.0 .04 3456.  40.   138.  39.     0.   0.     0.  3456.  40.  138.  39. 0.33  29.  0    0.   0.    0.   0.
610106.55.-1.-1.  131. 21.6 .06 2650.  40.   106.  38.     0.   0.     0.  2650.  40.  106.  38. 0.24  38.  0    0.   0.    0.   0.
640213.55.-1.-1.  115. 22.2 .05 2417.  13.    32.  14.     0.   0.     0.  2417.  13.   32.  14. 0.49  41.  2  179.  27.    5. 501.
660112.55.-1.-1.  147. 20.7 .09 2766.  40.   111.  46.     0.   0.     0.  2766.  40.  111.  46. 0.48  36.  0    0.   0.    0.   0.
680221.55.-1.-1.  120. 25.0 .02 2945.  40.   118.  47.     0.   0.     0.  2945.  40.  118.  47. 0.26  34.  0    0.   0.    0.   0.
700208.55.-1.-1.  117. 20.8 .08 2225.  40.    89.  49.     0.   0.     0.  2225.  40.   89.  49. 0.27  45.  0    0.   0.    0.   0.
710312.55.-1.-1.  156. 26.3 .01 4068.  40.   163.  37.     0.   0.     0.  4068.  40.  163.  37. 0.38  25.  0    0.   0.    0.   0.
720310.55.-1.-1.  117. 25.2 .02 2911.  40.   116.  49.     0.   0.     0.  2911.  40.  116.  49. 0.26  34.  0    0.   0.    0.   0.
740208.55.-1.-1.  138. 22.8 .04 3018.  40.   121.  30.     0.   0.     0.  3018.  40.  121.  30. 0.64  33.  0    0.   0.    0.   0.
750204.62.-1.-1.  156. 24.9 .02 3817.  40.   153.  29.     0.   0.     0.  3817.  40.  153.  29. 0.32  26.  0    0.   0.    0.   0.
760214.55.-1.-1.  128. 23.2 .04 2865.  40.   115.  45.     0.   0.     0.  2865.  40.  115.  45. 0.26  35.  0    0.   0.    0.   0.
761225.55.-1.-1.  155. 23.0 .04 3428.  40.   137.  48.     0.   0.     0.  3428.  40.  137.  48. 0.55  29.  0    0.   0.    0.   0.
```

APPENDIX C Table C4 End of year simulation output from SSISMO in simulation experiment 1. II. Water storage and ponded-area crop production (Output disk file QDAT4.DAT) (Data is shown on next page).

Column Number	Output Mnemonic	Variable
1	YR	Year
		Attributes of Water Storage and Irrigation
2	PLV	Volume of storage at planting (ML)
3	DAY	Day of last irrigation applied (standard days)
4	NO	Number of irrigations applied
5	VOL	Volume of water in dam before last irrigation (ML)
6	WA	Volume of water calculated as available for irrigation at last irrigation (ML)
7	S:D	Surplus : deficit of water at last irrigation (ML)
		Ponded Area Forage Sorghum Hay Production
8	NO	Total number of plantings on ponded area
9	AREA	Total area of land sown (ha)
10	NO	Number of crops harvested for hay
11	AREA	Area harvested (ha)
12	HAY	Total hay production (t)
13	$TON	Cost of hay ($/t)
		Forage Sorghum Production at the End of May
14	NO	Number of crops sown
15	AREA	Area of crops sown (ha)
16	KGHA	Average dry matter yield of crops (kg/ha)
17	AGE	Average age of crops (wks)
18	TYLD	Total dry matter production (t)
		Forage Sorghum Production at the End of July
19	NO	Number of crops sown
20	AREA	Area of crops sown (ha)
21	KGHA	Average dry matter yield of crops (kg/ha)
22	AGE	Average age of crops (wks)
23	TYLD	Total dry matter production (t)
		Forage Sorghum Production at the End of September
24	NO	Number of crops sown
25	AREA	Area of crops sown (ha)
26	KGHA	Average dry matter yield of crops (kg/ha)
27	AGE	Average age of crops (wks)
28	TYLD	Total dry matter production (t)

APPENDIX C Table C4 (continued)

```
   .PLV.DAY.NO...VOL..WA...S:D.NO.AREA.NO.AREA..HAY.$TON.NO.AREA..KGHA.AGE..T.YLD.NO.AREA..KGHA.AGE..T.YLD.NO.AREA..KGHA.AGE..T.YLD
22  61. 55. 1.  20.  20.  -28. 1.  13. 1.  13.  18.  22. 1.  13. 1102.  8.0  15. 1.  13. 1670. 16.0  22. 1.  13. 1759. 26.0  23.
24 105. 55. 1. 295. 295.  260. 2.  19. 2.  19.  28.  20. 1.  10.  322.  4.0   3. 2.  19.  925. 11.0  17. 2.  19. 2035. 17.8  38.
27 387. 55. 1. 300. 300.  260. 3.  26. 3.  26.  43.  19. 1.  10.  268.  4.0   3. 3.  26.  929. 10.9  24. 3.  26. 2001. 16.9  52.
33  76. 55. 1.  23.  23.  -27. 2.  16. 2.  16.  31.  17. 2.  16.  506.  6.5   8. 2.  16. 2621. 13.0  41. 2. .16. 3017. 23.0  48.
34 184. 55. 1.  85.  85.   36. 4.  27. 4.  27.  40.  20. 2.  18.  533.  5.2  10. 4.  27. 1268. 12.3  34. 4.  27. 1970. 19.9  52.
36  75. 55. 1.  24.  24.  -24. 2.  15. 2.  15.  44.  13. 2.  15.   24.  2.0   0. 2.  15. 2431.  8.8  38. 2.  15. 3567. 18.7  55.
37  48. 55. 1.  12.  12.  -38. 2.  11. 2.  11.  15.  22. 2.  11.   33.  2.0   0. 2.  11. 1109.  9.0  12. 2.  11. 1825. 18.9  20.
38  74. 55. 1.  24.  24.  -23. 2.  15. 2.  15.  20.  23. 2.  15.  398.  5.1   6. 2.  15. 1581. 12.7  24. 2.  15. 1846. 22.7  29.
40 298. 55. 1. 272. 272.  230. 3.  26. 3.  26.  34.  23. 2.  18.  397.  5.7   7. 3.  26. 1054. 11.9  28. 3.  26. 1735. 19.5  46.
41 382. 55. 1. 326. 326.  290. 2.  18. 2.  18.  32.  18. 1.   9.  253.  4.0   2. 2.  18. 1389. 11.3  25. 2.  18. 2310. 18.9  41.
45 312. 55. 1. 165. 165.  121. 3.  25. 3.  25.  46.  17. 2.  19.   36.  2.0   1. 3.  25. 1175.  9.1  29. 3.  25. 2479. 17.3  61.
50 389. 56. 1. 362. 362.  334. 2.  17. 2.  17.  27.  19. 0.   0.    0.  0.0   0. 2.  17.  348.  6.0   6. 2.  17. 1962. 13.5  33.
51  88. 55. 1. 328. 328.  293. 4.  36. 4.  36.  52.  21. 3.  30.  881.  9.0  26. 4.  36. 1478. 14.8  53. 4.  36. 1910. 23.1  68.
53 393. 55. 1. 205. 205.  156. 4.  38. 4.  38.  54.  21. 2.  23.  419.  5.5  10. 4.  38. 1024. 12.3  39. 4.  38. 1823. 18.7  70.
54 390. 55. 1. 305. 305.  265. 3.  25. 3.  25.  38.  20. 2.  18.  166.  4.0   3. 3.  25. 1080. 10.7  27. 3.  25. 1916. 18.2  48.
55 246. 55. 1. 291. 291.  253. 0.   9. 0.   0.   0.   0. 0.   0.    0.  0.0   0. 0.   0.    0.  0.0   0. 0.   0.    0.  0.0   0.
56 305. 55. 1. 290. 290.  256. 2.  16. 2.  16.  33.  16. 1.   8. 1154.  6.0  10. 2.  16. 1904. 12.2  31. 2.  16. 2802. 20.6  45.
57 381. 55. 1. 283. 283.  244. 4.  34. 4.  34.  62.  18. 3.  27. 1303. 10.9  35. 4.  34. 1758. 16.0  60. 4.  34. 2338. 23.8  80.
61 386. 55. 1. 222. 222.  184. 5.  43. 5.  43.  66.  20. 3.  32. 1405. 10.8  45. 5.  43. 1451. 17.1  62. 5.  43. 1907. 24.2  82.
64  49. 55. 1.  14.  14.  -28. 2.  11. 2.  11.  21.  17. 2.  11.  892.  7.1  10. 2.  11. 2263. 14.8  26. 2.  11. 2471. 24.8  28.
66 178. 55. 1. 100. 100.   54. 4.  28. 4.  28.  42.  20. 3.  25. 1196.  9.5  30. 4.  28. 1592. 16.4  44. 4.  28. 1994. 24.9  55.
68 389. 55. 1. 240. 240.  193. 3.  26. 3.  26.  49.  17. 2.  18.  782.  5.5  14. 3.  26. 1721. 12.6  45. 3.  26. 2424. 20.8  63.
70 269. 55. 1. 127. 127.   79. 4.  33. 4.  33.  46.  21. 3.  27.  836.  8.2  23. 4.  33. 1427. 14.5  46. 4.  33. 1853. 22.8  60.
71 392. 55. 1. 326. 326.  290. 2.  17. 2.  17.  31.  18. 0.   0.    0.  0.0   0. 2.  17.  261.  6.0   5. 2.  17. 2087. 12.9  36.
72 388. 55. 1. 202. 202.  154. 3.  32. 3.  28.  36.  24. 2.  20.  163.  3.6   3. 3.  28. 1015. 10.6  28. 3.  28. 1738. 18.8  49.
74 389. 55. 1. 288. 288.  259. 4.  32. 4.  32.  50.  20. 2.  18.  464.  5.7   8. 4.  32.  992. 12.0  32. 4.  32. 1970. 17.9  63.
75 207. 63. 1. 316. 316.  287. 3.  26. 3.  26.  39.  20. 2.  18.  157.  4.0   3. 3.  26.  954. 10.3  24. 3.  26. 1991. 17.3  51.
76 389. 55. 1. 221. 221.  176. 5.  38. 5.  38.  53.  21. 3.  25.  692.  7.0  18. 5.  38. 1126. 13.3  43. 5.  38. 1714. 20.2  65.
77 195. 55. 1.  66.  66.   17. 4.  32. 4.  32.  82.  14. 3.  31. 2658. 11.8  83. 4.  32. 2879. 19.4  92. 4.  32. 3020. 29.1  97.
   RUN       1   FLANNED IRRIGS  1    TIMING  55.  -1.  -1.   SM REQ 264.0  27.0
```

<u>APPENDIX C</u> <u>Table C5</u> End of year simulation output from SSISMO for simulation experiment 1. III. Costs and profits of grain production on irrigation-area (output disk file QDAT2.DAT((Data is shown on next page).

Column Number	Output Mnemonic	Variable
1	YR	Year
2	Aplo	Area of land ploughed (ha)
3	Alpa	Area of land planted (ha)
4	Airr	Area of land irrigated (ha)
5	Hrs	Hours of labour (hours)
6	Prod	Total Grain production (t)
7	WUE	Water Use Efficiency (t/ML of water harvested)
8	Cos$	Total Cost of production ($)
9	Inc$	Total Income ($)
10	C $t	Cost of grain ($/t)
11	P $t	Profit on grain ($/t)
12	P1$	Total profit from Irrigated Area ($)

<u>Semitivity of Total Profits ($) from Irrigated Area to Changes in Costs and Prices</u>

		Fixed Costs*	Operating Costs*	Price of Grain ($/t)
13	P2$	.75	.75	60
14	P3$	1.25	1.25	60
15	P4$	1.25	.75	60
16	P5$	1.25	1.25	60
17	P6$	.75	.75	100
18	P7$	.75	1.25	100
19	P8$	1.25	.75	100
20	P9$	1.25	1.25	100

* Total Fixed and operating costs multiplied by factor shown.

APPENDIX C Table C5 (continued)

	APLD	APLA	AIRR	HRS	YL$	VDE	COS$	INC$	C$T	P$T	P1$	P2$	P3$	P4$	P5$	P6$	P7$	P8$	P9$
19	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
20	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
21	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
22	40.	40.	17.	170.	45.	0.54	5366.	3574.	120.	-40.	-1792.	-1344.	-2777.	-2594.	-4027.	443.	-990.	-807.	-2240.
23	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
24	40.	40.	40.	195.	160.	0.37	5793.	12835.	36.	44.	7043.	5282.	3635.	4032.	2386.	11700.	10054.	10450.	8804.
25	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
26	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
27	40.	40.	40.	195.	132.	0.26	5722.	10563.	43.	37.	4841.	3631.	2019.	2381.	769.	8912.	7301.	7662.	6051.
28	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
29	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
30	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
31	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
32	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
33	40.	40.	19.	172.	51.	0.52	5395.	4107.	105.	-25.	-1288.	-966.	-2414.	-2216.	-3664.	1087.	-361.	-163.	-1611.
34	40.	40.	40.	195.	110.	0.51	5687.	9426.	48.	32.	3740.	2805.	1211.	1555.	-39.	7518.	5924.	6268.	4674.
35	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
36	40.	40.	20.	174.	69.	0.60	5448.	5557.	78.	2.	110.	82.	-1392.	-1168.	-2642.	2861.	1387.	1611.	137.
37	40.	40.	9.	163.	45.	0.68	5325.	3601.	118.	-38.	-1724.	-1293.	-2705.	-2543.	-3955.	508.	-905.	-742.	-2155.
38	40.	40.	20.	174.	59.	0.59	5424.	4712.	92.	-12.	-713.	-534.	-1997.	-1784.	-3247.	1021.	359.	571.	-891.
39	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
40	40.	40.	40.	195.	129.	0.35	5714.	10296.	44.	36.	4582.	3436.	1829.	2186.	579.	8504.	6977.	7334.	5727.
41	40.	40.	40.	195.	146.	0.32	5758.	11706.	39.	41.	5948.	4461.	2832.	3211.	1582.	10314.	8684.	9064.	7434.
42	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
43	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
44	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
45	40.	40.	40.	195.	134.	0.37	5727.	10697.	43.	37.	4970.	3728.	2114.	2478.	865.	9076.	7463.	7826.	6213.
46	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
47	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
48	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
49	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
50	40.	40.	40.	195.	161.	0.45	5795.	12902.	36.	44.	7106.	5330.	3682.	4080.	2432.	11781.	10133.	10531.	8883.
51	40.	40.	40.	195.	121.	0.32	5694.	9661.	47.	33.	3967.	2975.	1378.	1725.	128.	7805.	6208.	6555.	4958.
52	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
53	40.	40.	40.	195.	118.	0.27	5688.	9477.	48.	32.	3789.	2842.	1247.	1592.	-3.	7580.	5986.	6330.	4736.
54	40.	40.	40.	195.	133.	0.32	5725.	10646.	43.	37.	4921.	3691.	2078.	2441.	828.	9014.	7401.	7764.	6151.
55	40.	40.	40.	195.	145.	0.25	5754.	11564.	40.	40.	5810.	4358.	2731.	3108.	1481.	10140.	8513.	8890.	7263.
56	40.	40.	40.	195.	153.	0.35	5775.	12259.	38.	42.	6484.	4863.	3225.	3613.	1975.	10993.	9355.	9743.	8105.
57	40.	40.	40.	195.	138.	0.33	5738.	11059.	42.	38.	5321.	3991.	2372.	2741.	1122.	9520.	7901.	8270.	6651.
58	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
59	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
60	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
61	40.	40.	40.	195.	106.	0.24	5657.	8479.	53.	27.	2822.	2116.	538.	866.	-712.	6356.	4777.	5106.	3527.
62	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
63	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
64	40.	40.	13.	167.	37.	0.56	5328.	2961.	144.	-64.	-2367.	-1775.	-3189.	-3025.	-4439.	-294.	-1709.	-1544.	-2959.
65	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
66	40.	40.	40.	195.	111.	0.48	5669.	8851.	51.	29.	3182.	2387.	802.	1137.	-448.	6813.	5228.	5563.	3978.
67	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
68	40.	40.	40.	195.	118.	0.26	5687.	9425.	48.	32.	3738.	2804.	1210.	1554.	-40.	7516.	5923.	6266.	4673.
69	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
70	40.	40.	40.	195.	89.	0.27	5615.	7120.	63.	17.	1505.	1129.	-429.	-121.	-1679.	4688.	3131.	3438.	1881.
71	40.	40.	40.	195.	163.	0.38	5799.	13018.	36.	44.	7219.	5415.	3765.	4165.	2515.	11921.	10274.	10671.	9024.
72	40.	40.	40.	195.	116.	0.26	5683.	9315.	49.	31.	3531.	2723.	1132.	1474.	-118.	7381.	5789.	6131.	4539.
73	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.
74	40.	40.	40.	195.	121.	0.64	5694.	9659.	47.	33.	3965.	2973.	1376.	1723.	126.	7803.	6206.	6553.	4956.
75	40.	40.	40.	195.	153.	0.32	5774.	12213.	38.	42.	6439.	4830.	3193.	3580.	1943.	10936.	9299.	9686.	8049.
76	40.	40.	40.	195.	115.	0.26	5679.	9169.	50.	30.	3490.	2618.	1028.	1368.	-222.	7202.	5613.	5952.	4363.
77	40.	40.	40.	195.	137.	0.55	5735.	10969.	42.	38.	5234.	3926.	2308.	2676.	1058.	9410.	7793.	8160.	6543.
78	40.	0.	0.	67.	0.	0.00	3115.	0.	0.	0.	-3115.	-2336.	-2643.	-3586.	-3893.	-2336.	-2643.	-3586.	-3893.

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