Chapter 1

INTRODUCTION

1.1 Specification of the Problem

The fundamental issue in water resources management in New South Wales or Australia in general relates to the relative scarcity of the resource. Water resources readily accessible to centres of demand are already substantially committed and, on a local or regional basis, the availability of adequate water supplies is becoming a key factor in continuing economic development (Watson and Rose 1980). Researchers believe that the development of appropriate planning and management systems for existing irrigation supplies will be the primary irrigation issue for the eighties (Watson and Rose 1980). Current debate on water resources management therefore centres on issues of irrigation water allocation and pricing (ARAU 1982; Randall 1982). Various researchers, State water authority advisors and critics have advocated a much greater reliance on the market mechanism for allocating water (Moy 1981; Neilson and Associates 1981; Anon 1982; Dragun 1982).

Regardless of the outcome of the allocation debate, one can expect an increasing interest on the part of water administrators in alternative water allocation procedures. The preferred allocation procedure, among the available alternatives, would be the one that contributes most to the attainment of the authority's objectives. While knowledge of these objectives is slight, one might presume that the impact of policy on the level of farm income and its distribution between farms would be important. This is apparent from the criteria used by the Water Resources Commission in the allocation of water licenses. These criteria, as outlined by Davis (1968, p. 670) based on his studies of judicial appeals decisions, are:

> (1) A known advantage or benefit to one or more riparian landholder must be balanced against an apprehended or possible disadvantage or prejudice to other riparian landholders or to the public.

(2) A more equitable distribution and beneficial use of water should be promoted.

(3) The Commission's ability to control its own flow regulation works should not be affected prejudicially.

(4) Landholders should be encouraged to conserve water.

(5) The greater public interest or public benefit should be served.

There will, however, be trade-offs between these assumed objectives used by the Water Resources Commission. For example, allocating licenses to the most beneficial uses need not lead to the most equitable distribution of water.

An understanding of the actual and potential performance of alternative water distribution procedures, within the given system of water rights, and judged by the assumed objectives of the water authority should be helpful to the authority in handling the increasingly severe problems of water allocation. Particularly important among these allocation problems is the difficulty caused by higher frequency of water shortages as a result of the increasing pressure on supply. The nominated objectives of the authority lead, primarily, to the evaluation of the efficiency and equity consequences of the alternative procedures.

The current incidence of drought throughout much of New South Wales underlines the need for an assessment of water distribution during periods of droughts. Information on how alternative distribution procedures distribute the impact of seasonal drought between farms would presumably be useful to water authorities in determining their policies for such periods of water shortages.

Given this background, the study takes the NSW Water Resources Commission as the relevant irrigation authority and a part of the Gwydir Valley as the hypothetical irrigation area with its own discrete water supply, and analyses the impact on production and income, of a number of case farms, of alternative water distribution rules which could conceivably be used by the Commission to distribute water among irrigators in the valley.

The Water Resources Commission, which is the authority responsible for the control of distribution of supplies of water for irrigation in all the river valleys in New South Wales, at present uses a volumetric water allocation procedure to distribute water to farmers with licensed irrigation landholdings. Under this procedure, each irrigator is allocated six megalitres of water per hectare of licensed area during a season of full allocation. The Commission's intention with this procedure is to get a higher level of production from a given volume of water rather than maximise production from a given area of land (T.J. Dillon, personal communication, 1982).

The important question which is studied in this dissertation is whether the volumetric allocation procedure is more efficient in the sense that it generates more income per megalitre of water than other allocation procedures which could have been used by the Commission. A further question is whether volumetric allocation procedure generates the most regional income and distributes losses during a drought more equitably than other possible water distribution procedures. These questions are answered by analysing within the framework of a simulation model, the effects of different water supply levels and rules of water delivery as determined by the irrigation authority, on crop patterns, crop production and farm incomes in the ten case farms used in the study.

The major components of the irrigation system considered are: 1) the irrigation authority which determines the water distribution rules; 2) farmers who decide on watering schedules at the farm level in relation to the available water supply; and 3) the crops and their response to variable water applications which will determine the level of output. Results from the study will provide information on the attributes of alternative methods of distributing water among farms and so contribute to the understanding by water authorities of such alternative methods of distributing water.

1.2 Aims of the Study

The three main objectives of the study are:

1) to test, in terms of comparative efficiency, some alternative water distribution procedures that could be used in the agricultural environment considered in the study;

2) to analyse the effect of these alternative water distribution

procedures on the deviation in income per hectare and per megalitre among the farms considered in the study under a range of water supply conditions;

3) to draw some policy conclusions for water distribution based on the assessed performance of the alternative distribution procedures.

1.3 Hypotheses of the study

In line with the problem stated in section 1.1 and the objectives outlined in sectin 1.2, the key hypotheses of the study follow:

1) The demand-plan or volumetric allocation procedure generates more income per megalitre of water used in the area than any other form of water distribution procedure studies.

2) Different water distribution procedures lead to significantly different diviation in income per hectare and per megalitre between farms.

1.4 Major Assumptions of the Study

In order to limit the scope of the study and keep it to a manageable size a number of simplifying assumptions are made.

1) It is assumed that 10 model farms participate in a hypothetical irrigation system based on the Gwydir Valley which permits removal of water for irrigation from a hypothetical river with the hydrological characteristics of the Gwydir.

2) It is assumed that the stream flow pattern obtained from records at Pallamallowa recording station adequately represents the flow behaviour and seasonal availability of water on the portion of the Gwydir River aolng which the 10 model farms are located.

3) The irrigation sequences practised by the farmers in the area are taken as given. That is, no attempt is made to arrive at an

optimal irrigation sequence.

4) Only the benefits generated from different operating procedures simulated in the study are analysed. That is, the costs of implementing different procedures are assumed to be equal, and if different the difference is assumed to be small.

5) The simulation exercise does not examine design characteristics of the system, that is, it is assumed that irrigators have in place the necessary delivery system for the successful operation of the alternative distribution procedures.

6) It is assumed that the water distribution efficiency for each of the ten farms is the same. That is all the farms are equally efficient in their distribution of water to the various fields in their farms. Such an assumption is not too unrealistic as all the farms in the analysis use furrow irrigation and as such differences in distribution efficiency between farms will not be large.

More specific assumptions about the model used in the study are discussed in Chapter 3.

1.4 Outline of the Study

The dissertation is organised around six chapters. Chapter 2 commences with a review of water law and water distribution procedures in New South Wales. A review of work on crop response to water use and computer simulation of water resource systems is also included in that chapter. The choice of the method to study the problem is explained and justified together with a detailed examination of the simulation model in Chapter 3. Discussion of the data and farms chosen for the study are presented in Chapter 4. Chapter 5 contains the results and the discussion of the results. The summary and conclusions of the study, with particular emphasis on its limitations together with proposals for future work, form the content of the final chapter.

Chapter 2

WATER DISTRIBUTION RULES AND CROP RESPONSE TO IRRIGATION WATER - A REVIEW

2.1 Introduction

This chapter presents a brief review of the literature that deals with irrigation water distribution and the theory of crop-water response. Irrigation water distribution is discussed in relation to the existing water law in New South Wales. This will provide a background for analysing the alternative ways of distributing water among users within the framework of water law known as the riparian and appropriation doctrines.

Work on the theory of crop-water response is reviewed as a basis for developing yield loss functions which are a key component of the simulation model. The aim is to understand the nature of the production relationship between irrigation water as the input and crop production as the economically useful output.

The chapter is organised into eight main sections. The section that follows takes a brief look at water law in New South Wales. That section is followed by a discussion of water distribution rules. Attention is then focussed on soil moisture and plant growth relationships in the fourth section. Evapotranspiration and theories of evapotranspiration are examined in Section five. The empirical estimation of crop response to water is examined in Section six. That is followed by a brief survey of work on the optimal allocation of irrigation water. The final section of the chapter provides some conclusions about the works surveyed and sets the preamble for the methodology to be employed in the study which forms the subject matter of the third chapter.

2.2 Water Law in New South Wales

The water law in New South Wales has its historical foundations in the common law riparian doctrine which has worked well in England because of the bountiful flows in its rivers. In the Australian context with more frequent low stream flows and droughts, the riparian doctrine, which only allowed owners of land in lateral or vertical contact with a river, to use water proved to be completely inadequate (Clark 1982). In N.S.W., the system of riparian rights was abolished in 1896 when the Government introduced the Water Rights Act. This law came to be known as the 'Water Act' when it was broadened and strengthened in 1912. The Act transferred ownership of water to the Crown, thus giving 'the Government power to control available supplies in the most equitable fashion and to reduce costly litigation' (Water Conservation and Irrigation Commission 1971, p. 169). The legislation provided 'for the more equal distribution and beneficial use of all the water in the rivers and lakes of the State' (ibid. 1971, p. 169).

State property rights over water resources are enforced through a system of administered apportionment. Individual users are granted by the State the right to a specified amount of water for a given period of time. This right is attached to a designated landholding. Under this system of administered apportionment of surface waters, the licensing provisions deal comprehensively with all diversions other than those for the purpose of stock, small garden and domestic supply. The State Water Resources Commission has wide discretionary powers over the granting and renewal of licenses. Individual licensees can use only specified amounts of water and any use of water in excess of the amount specified can lead to revocation of the license. The licenses are granted for fixed periods and renewal is not automatic within the statutes. However, if the conditions of the license have been adhered to, renewal is seldom refused. The license is granted for and tied to a specified area of land within defined irrigation areas. Transfer of licenses between individual users is not allowed and reallocation occurs only through the State Authority allocation mechanism (Moy 1981).

The provisions for priority of use during periods of shortage can range from proportional restriction of all licenses, restrictions based on a seniority classification of licenses, to complete administrative discretion.

Irrigation development was rather sporadic and limited to a relatively small number of landholders during the first 50 years after the passing of the Water Act in 1896. In 1946 there were only 2863 licenses authorising the irrigation of an area of about 53 000 hectares in the State. Under an amendment to the Water Act in 1946, provisions were made for the development of joint water supply schemes which enabled the development of group irrigation or water supply projects. Little use, however, was made of the joint water supply scheme provision in the fifties and sixties. The number of individual licenses at the end of 1961 was 8030. By 1970, however, there were over 15 000 individual licenses and some 270 authorities for joint water supply schemes. About half a million hectares of land were brought into irrigation through these licenses and authorities (Water Conservation and Irrigation Commission 1971, p. 171).

With regard to the pricing of water, up to 1966, holders of licenses or authorities paid only for issue and renewal of those licenses or authorities. Since 1st July 1966 an irrigator, on any stream where public funds have been expended to augment, stabilise or assure flows, has had to instal a meter to measure the amount of water he takes from the stream. A small fee is levied to cover the operational and administrative costs of the metering scheme. In New South Wales, the license fee for 162 hectares, which is the maximum area normally permitted under license and which has an allocation of six megalitres per hectare each year, is $725.40 each five years. This works out to about 15 cents per megalitre used. The metering fee ranges from $4.80 to $7.10 per megalitre (Anon. 1982).

Given this legal framework for water distribution the Water Resources Commission could use a number of distribution procedures or rules to distribute water from the irrigation systems under its management. Each of the procedures will have its characteristic impact on farm income and its distribution between farms. The alternative procedures will also distribute the impacts of seasonal drought among farms differently. These different impacts will be of interest to the water authority in evaluating policies for water distribution especially during periods of shortage. The water distribution procedures to be considered in the study are presented in the next section.

2.3 Water Distribution Procedures

By water distribution procedures are meant the terms and conditions under which water from an irrigation system is made available to the beneficiaries of the system. The distribution procedures work within the framework of the water law that exists. Apart from economists' interest in transferable water rights and water pricing, the efficiency and equity implications of alternative water distribution procedures have received relatively little economic analysis.

Maass and Anderson (1978) analysed water distribution procedures for six irrigated areas, three in Spain and three in the United States. They compared several short-run operating procedures to determine how efficient the procedures were in terms of farm income realised per unit of water applied in the agricultural environments of Spain and the United States. They pointed out that the operating procedure used to distribute water in a shortage situation has a significant effect on irrigator income.

Hartman and Seastone (1970) carried out a comparative analysis of alternative institutional arrangements for the distribution and reallocation of water in the Northern Colorado Water Conservancy District of the United States. An extensive economic efficiency analysis of alternative ways of allocating surface flows among users in Colorado was done by Callaway (1979). The possibility of efficient water allocation under the appropriation doctrine through the competitive market process has been investigated by Burness and Quirk (1979). The appropriation doctrine is a modified form of riparian doctrine in conjunction with appropriation law. This is a legal system characterised in large part by the doctrine that water is not legally attached to the land adjacent to it (Hartman and Seastone 1970, p. 16). Howe and Alexander (1980) examined some of the problems arising from the Colorado water law during periods of drought and looked at the possibilities for improving the economic efficiency of response by irrigation authorities to drought. Howe et al. (1982) examined water allocation under the appropriation doctrine and identified the sources of inefficiency during drought and suggested fundamental institutional changes to improve efficiency in water allocation. Randall (1982) discussed the establishment of transferable property rights in Australia as a basis for the allocation of water. All these studies concentrated on alternative institutional arrangements for water transfer and water allocation. Since it is generally more difficult to bring about changes in the institutional and legal framework under which water is allocated, the present study takes the water law discussed in section 2.2 as given and tests a number of alternative water distribution procedures to evaluate their performance in terms of efficiency and equity.

Water distribution procedures or rules have been classified in the literature into three major types, that is water delivery on demand, rotation, and continuous flow (Hutchins et al. 1953; Hagan et al. 1967). The continuous flow procedure involves delivery of water into the head of each farm lateral continuously throughout the irrigation season. It does not mean that each irrigator takes the water incessantly, it means that he has the right to do so. With the rotation delivery system, water is delivered by turns to various portions of the service area. Water may be rotated among sections of the main canal, from one lateral to another, or among the users under each lateral. In the case of the demand procedure, deliveries of water are made when requested by a user in the quantities asked for. This three-part classification is, however, very limiting in that it does not include a range of other operating procedures that could be used by irrigation authorities. Consequently, the elaboration of the above three-part classification system suggested by Anderson and Maass (1974) is used in this study. The procedures are divided into two main groups, that is procedures based on regulated flow of water and procedures based on unregulated or stream flow.

2.3.1 Regulated flow procedures

The regulated flow procedures are based on the assumption that all the water for the season is in storage and the farmers can draw it on demand. It involves a process of ordering water in advance so that it will be available when needed. Usually it takes about ten days from the time water is first ordered to the time it is available for pumping into the fields. Among the regulated flow procedures are demand and demand-plan procedures.

Demand

In this regulated flow procedure the water supply for the full irrigation season is stored and available at the beginning of the season and each farm is allotted a fixed quantity for the season. Each farm receives in each irrigation period the quantity of water that the crops need up to the farm's seasonal allotment. In the simulations in the study, that water which is stored and available at the beginning of the season is 90 per cent, 75 per cent, 50 per cent, 25 per cent and 10 per cent of the full water requirement needed to achieve production without loss in yields. Each farm is given six megalitres per licensed hectare as the maximum allotment. This reflects the procedure used in the Gwydir irrigation system.

Demand-Plan

This is similar to the demand procedure except that farmers knowing at the beginning of the season what their seasonal water supplies will be, plan the areas of their crops which will give the highest possible returns from the available water. The plan subroutine in the simulation program is used to do this. The present volumetric allocation procedure used in the Gwydir irrigation system will reflect this procedure if farmers plan to maximise their returns from the six megalitres allocation given for each licensed hectare of land.

2.3.2 Unregulated flow procedures

These procedures assume minimal storage facilities. As a result continuous flow is assumed. The flow is based on the stream flow pattern of the given stream or river and the available irrigation water is distributed over the irrigation season in accordance with the stream flow data for the area. Irrigators can pump water from the river when they need it without having to go through a process of ordering water. They can, however, pump only that amount which is allotted to them in accordance with the distribution procedure in force. Among the unregulated or stream flow procedures are shares, shares with excess water returned to canal, rotation, turn, farm priorities, crop priorities and market. These unregulated procedures can also be used together with regulated procedures for distributing irrigation water. For example the demand procedures can be used in conjunction with farm priorities and crop priorities.

Shares procedure

Each farm receives in each period a fixed percentage of the water available for the period. A farm's percentage is based on the size of the farm. Water not used by a farm to which it is allotted is wasted. The shares procedure can also be used in conjunction with demand, crop priorities, and market procedures. For example, farmers can have a share of the season's stream flow water as well as demand water that is kept in storage. Alternatively water could be distributed by shares early in the season but when water shortages develop, farmers use their respective share water on priority crops only.

Shares with excess water returned to canal

This is the same as the shares procedures described in the previous section except that water not used by a farm is available to other farms should they have inadequate water during the period. Excess water is accounted for in each period and if it is not used during a period, it just runs off and is wasted. This procedure can also be used in conjunction with the crop priorities system. For example, during each period water not used by farmers whose shares exceed their requirements can be transferred to farmers whose shares fail to do so, subject to the constraint that the excess water is distributed by crop priorities. This means highest value crops are watered first in each of the farms facing a water shortage.

Rotation procedure

Each farm has a reserved time in which to irrigate in each period, but the water delivered in this time will vary within each rotation in accordance with the flow in the stream at that time. The time assigned to a farm is based on the farm's size. If a farmer fails to take water in his assigned time, that water is available to subsequent irrigators. This procedure can also be used in conjunction with crop and farm priorities. For example, if rotation is subjected to farm priorities, then in any period priority farms are given time to remove water first and subsequently to non-priority farms.

Turn procedure

Farms are served in order of their location along the river or canal. When water reaches a farmer, he takes all he needs for the period, before the next farmer is served. Water distribution in any period begins where it stopped in the previous period. This procedure can also be used in conjunction with farm and crop priorities.

Farm priorities

Farms are served in order of priority based on the time of settlement. When water reaches a farmer, he takes the water required for the period before the farmer next in order of priority is served. Water distribution in any period begins with the first priority farm. When water shortages develop, licensees would be cut off in inverse order of date of application, the holder of the most recent license being cut off first. The prior appropriation followed the rule 'first in time, first in right' by which licenses are given priority of right on the basis of date of application (Davis 1968, p. 661).

Crop priorities

Based on economic value, crops are assigned orders of priority. When water is sufficient all crops receive needed irrigations but, as water shortages develop, priority crops are watered first in all farms. If water remains, it is distributed to the non-priority crops on each farm by turn as in the turn procedure described previously.

Market procedure

In the case of this procedure the assumption is made that all water users bid in each period for the water needed to irrigate their crops. As a result water is allocated to the highest value uses in each period. The assumption is that farmers who have a higher value use for the water can outbid farmers with lower value uses for the same water. The value of using water on any crop at any time is assumed to be equal to the loss in income that would be sustained if the crop is not watered during that period. The simulation program used in the study calculates these values for each field of each crop on each farm for each period.

Having discussed the water distribution rules which are being tested in the study, the chapter now focuses on crop response to irrigation water. This is required because, central to the simulation of irrigation systems using various distribution rules, is the response of crops to particular irrigation sequences or regimes. Therefore the sections that follow trace some work on soil-water-plant relationships and the economic modelling of such input-output relationships between water as input and crop yield as the economically useful output.

2.4 Soil Moisture and Plant Growth

Water is basic to the life of plants as most of the biological activities in a plant take place in an aqueous medium (Slatyer 1967). The amount of water that will be available to a plant is dependent on the level of soil moisture. Thus the water input which directly influences plant growth is not irrigation or rainfall but soil moisture. Irrigation is of interest because, as an input, it enables the decision maker to manipulate the level of soil moisture so that desired plant growth can be achieved. As Flinn (1968) indicated in his survey of the literature, agronomists adhere to two schools of thought with regard to the theory of plant response to water. Viehmeyer and Hendrickson (1950), who typify the older school, claim that plants can successfully and uniformly utilise soil moisture in the soil over the range between parmanent wilting point and field capacity. Field capacity and permanent wilting point refer to the highest and lowest levels of soil moisture that may be accessible to a plant. The moisture that is actually available for intake by the roots of a plant is the soil moisture found between the field capacity and permanent wilting point of the soil.

Stanhill (1957), and Hagan, Vaadia and Russel (1959), provide an alternative theory by suggesting that the availability of soil moisture to the plant is not independent of the soil moisture level between permanent wilting point and field capacity. This, according to them is due to the fact that the plant's use of water for evapotranspiration decreases considerably as the permanent wilting point is approached. One or the other of these two theories on crop water response has been used in most studies as the basis for estimating yield response of crops to different levels and times of water application.

Plants require water for two essential purposes. These are the support of continuous metabolic activity within the plant tissues and the regulation of temperature so as to maintain the thermal balance required for sustaining life and growth. The maintenance of the thermal balance is where much of the water used by plants is directed (Minhas et al. 1974). A large number of studies have shown that plant growth is directly related to the water balance in plant tissues (Kramer 1944; Wadleigh and Ayers 1945; Kenworth 1949; Taylor 1952; Barrs 1962; Robins and Domingo 1953; Henkle 1964; Shaw and Laing 1966). These studies have shown that, as water deficits develop, physiological processes are disturbed, and growth and yield are subsequently reduced. The relative rates of water absorption and loss by plants determine their internal water balance and this reflects the plants' interaction with the environment. As mentioned earlier, a large portion of the water used by plants is directed towards maintaining thermal balance which the plant does by evaporating water. This process of evaporative loss of water from plants is called transpiration. The sum total of water lost through transpiration by crop plants and direct evaporation from fields is called evapotranspiration. The following section therefore takes a brief look at evapotranspiration and the theories relating to it.

2.5 Evapotranspiration and Theories of Evapotranspiration

Evapotranspiration is the sum total of water lost through transpiration by crop plants and direct evaporation from the field. The process is also referred to as consumptive use of water, although the term 'consumptive use' was not used to refer to evapotranspiration prior to 1900 (Jensen et al. 1973). For a given soil type, the evapotranspiration (ET) of water by crops is affected by climate, availability of water, growth stage of the crop, and plant characteristics (Minhas et al. 1974). The climatic factors which affect evaporation are sunlight - both its duration and intensity - temperature, humidity and wind velocity.

A number of theories have been postulated about the determinants of evapotranspiration (ET). The theory that the bigger the plant the higher the level of transpiration is perhaps the simplest of these theories. The work of Veihmeyer and Hendrickson (1950) tends to support this view that transpiration is a function of total leaf area. Penman (1956), however, highlighted the limitation of the theory as it is useful only in those cases where there is less than complete crop cover since crop cover affects ET. Later work by Penman, Blaney and Criddle, and Thornthwaite concentrated more on the meteorological rather than the biological determinants of evaporation. Penman (1963) considered ET more as a process involving energy transfer between the ground and the atmosphere. He concluded that, for any crop at full leaf cover and adequately supplied with water, transpiration is uniquely determined by meteorological factors. This implies that, given constant weather conditions, all crops will transpire the same amount of water per unit area. Penman (1956), however, qualified his conclusion as follows. Since different crops have different lengths of growing season and the growing seasons will be at different times of the year the crops will not transpire the same total amount of water per unit area over the growing season (Irvin 1973).

Blaney and Criddle (1950) and Thornthwaite (1948) worked on determining empirical formulae for estimating ET of particular crops over long periods of time. Like Penman, they also looked at climatic variables that affect ET under conditions of unlimited water supply. They related ET to temperature, relative humidity, and length of day. The formula developed by Thornthwaite is quite similar to that of Blaney and Criddle, but it includes fewer independent variables and it is generally more difficult to compute. The major limitations of the Blaney and Criddle, and Thornthwaite formulations of ET is that they do not account for advected energy, and differences in crop characteristics with respect to energy absorption. Also, these formulae only enable derivation of monthly total ET while it is often necessary for irrigation policy and design purposes to estimate potential ET for much shorter periods (Irvin 1973).

The central difficulty with all these theories lies in the inability of researchers to test effectively the results obtained. Direct measurements of evaporation are generally unreliable and therefore cannot be used to test the theories. It is also, on the whole, difficult to generalise from laboratory findings to the field (Irvin 1973). Evaporation can also be determined directly by observing moisture loss from an open water surface and relating this to a crop by adjusting the open water evaporation by the crop constant. The problem with this approach has been the relative lack of reliability of the estimates of the crop constant values, coupled with the problem of interpreting the observed values of evapotranspiration. This is so because evaporation from open surfaces is not independent of the size of the field plot as well as the type of surrounding (Irvin 1973). However, evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from a specific open water surface. As a result, where pan-evaporation readings are available, it is desirable to use these readings to estimate the water requirements of crops.

Jensen et al. (1973) in their evaluation of sixteen methods of estimating ET which represented most of the theories on ET based primarily on humidity, solar radiation, temperature and miscellaneous principles said that '... no single existing method using meteorological data is universally adequate under all climatic regimes, especially for tropical areas and for high elevations...' (Jensen et al. 1973). They concluded that 'the method selected for a particular use should depend on the accuracy of the available meteorological data, the training experience of the user, and the general acceptance of previous estimates.'

This brief excursion into ET and theories of its determination was considered necessary since ET data are used for estimating irrigation water requirements in this study. In this study the pan-evaporation method is used to determine potential ET as data on the US Class A pan evaporation at Moree is readily available. Details of how the values are obtained are given in Appendix F.

2.6 Empirical Estimation of Crop Response to Water

The literature on the empirical estimation of crop response to water reflects a clear line of evolution, from the simple concept of fixed water requirements to the development of more sophisticated models dealing with variable water inputs and time of application and the subsequent derivation of optimal patterns of resource use (Irvin 1975). The classification of the literature on plant-water-production relationships made by Flinn and Musgrave (1967) in their comprehensive survey of the literature is used in the present survey. Four broad approaches are seen to have been followed in the empirical estimation of plant-water production functions. The approaches are

1) plant-water-production functions based on single-valued crop water requirements,
2) functions based on physical input-output data,
3) synthetic functions based on physical criteria, and
4) simulated functions based on biological and physical relationships.

Each of these approaches will now be considered in detail.

2.6.1 Fixed crop-water requirements

Much of the earlier work on the empirical estimation of crop-water production functions assumed that every crop has a unique water requirement. Such an assumption takes its root from one of the alternative hypotheses concerning the availability of soil moisture and its effect on plant growth that says that plants extract soil moisture with equal facility between field capacity and close to the permanent wilting point. Unique crop-water requirements also tend to ignore the possibility of substitution between water and other inputs and **therefore is not appropriate** when water prices are varied in the analysis (Flinn and Musgrave 1967).

Philip (1956), in estimating the demand for irrigation water in the Burdekin River Irrigation Project, **assumed that the demand for water by the crop will be equal to the consumptive water use needs of the crop and it is the amount required to achieve maximum plant growth. The implication of such an assumption is that the price of water is zero or not significant in determining the amount of water to be used.**

A number of researchers have used the Blaney-Criddle method to estimate plant water requirements which are used as fixed water inputs for each crop. The work of Lee (1958), Clark (1960), and Hartman and Whittlesey (1960) are examples of such studies. Hartman and Whittlesey (1960) estimated crop yields from high, average and low levels of water use and with linear programming procedures estimated the marginal value product of water for monthly time periods during the growing season. Flinn (1968) in his survey of Hartman and Whittlesey's (1960) work noted that their results are likely to be biased as they programmed the high, average, and low crop yields separately. This resulted in the water use per unit area of output remaining constant even when water supply was varied (Flinn 1968). The work of Duane and Rowe (1960), Miller et al. (1965) and Dudley and McConnell (1967) also suffer from similar limitations.

The work of Lee (1958), McKean (1958) and Steiner (1964) which represent the analysis of water resource systems using simulation and mathematical programming techniques also assumes fixed water inputs to crops. The implicit assumptions of all these studies is that the demand for irrigation water is completely inelastic. Recognition of the inadequacies of the fixed water inputs approach to irrigation policy led to the development of more complex crop-moisture response functions which are discussed in the sections that follow.

2.6.2 Production functions based on physical yield data

The early work on the estimation of water production functions concentrated mainly on relating total seasonal water deliveries to yield. The main source of data for such empirical work has been physical yield data obtained from irrigation experiments conducted with varying levels of water on a given area of land. The crop yield data is then related to rainfall and irrigation inputs. The work of Clyde et al. (1923) is probably the earliest of the works which use a production function approach. Using the production factors of land and water they estimated input-output relationships for irrigation, where output was in the form of a single crop. Yaron (1966) used results from a series of field experiments carried out in Israel to estimate a production function for irrigation water. He related the yield of cotton per land unit to the depth of wetting of soil in metres per application and the effective total quantity of water applied per land unit. Yaron fitted the observations on total water deliveries and depth of wetting by least squares to linear transformations of three non-linear forms of the response relationship. The statistical quality of his results was high but the narrow range of observations for each of the variables and the limited number of observations made it difficult to draw useful conclusions from the exercise.

Dorfman (1963) in his work on the determination of optimal cropping patterns for small peasant holdings in the Punjab, India assumed a sigmoid form of relationship between soil moisture availability and crop yield. The quadratic expression he used to approximate the relationship was

$$Y = M[1 - b(s - x)^2]$$

where:

- Y is the crop yield per land unit,
- M is the yield when there is ample soil moisture,
- s is the saturation depth of irrigation,
- x is the total quantity of irrigation water applied in metres, and
- b is an empirically determined constant.

The uniqueness of Dorfman's formulation is that the relationship is in terms of seasonal moisture availability. As a result, the estimated parameter values of the expression are specific to a particular pattern of water delivery through time. In his estimation, Dorfman used both time-series and cross-sectional farm data.

A number of researchers also tried to estimate the productivity of irrigation water by using whole farm production functions. Dawson (1957), Hickey (1964), Hopper (1965), Naik (1965) and Ruttan (1961) are examples. In most studies, the quantity of irrigation water received at the farm headgate was used to specify the water input for the whole farm production function. The results obtained therefore gave no direct information on the productivity of water in relation to individual crops.

Beringer (1959) emphasised the important idea that the value of water is due to its impact on soil moisture and that the timing of application of water is important in determining final crop yield. He therefore argued that there is little point in using total seasonal water delivery as the independent variable in the estimation of a production function for irrigation water. Building on the work of Wadleigh (1946) and Taylor (1952) he suggested the use of an 'Integrated Moisture Stress Index' as the most suitable variable to distinguish between irrigation inputs and the availability of soil moisture to the plant through time. Accounting for moisture stress alone does not solve the problem because stress at different points in the growing season does not have the same retarding effect on growth. There is therefore a need for some procedure to weight the integrated moisture stress index. Even that, as Beringer has noted, cannot solve the problem completely since crop growth at any stage of crop development is not independent of growth at any other stage. This problem of sequential interdependence of growth retarding effects implies that a unique set of weights would be unrealistic. Beringer's main contribution to the estimation of water response functions has been to recognise the key difficulties in estimation of the response function and in introducing to economists the concepts of moisture deficiency (Flinn 1968).

Using experimental results, Reutlinger and Seagraves (1962) related crop yield to soil moisture deficiency indices for tobacco and obtained estimates of the expected yield and variance of yield resulting from different irrigation policies. Their method was novel in the sense that they derived from weather records long-term estimates of soil moisture deficiency and combined a probability distribution of moisture deficits with their estimated function to obtain the expected yields and variance of yields resulting from different irrigation policies. The major limitation of their technique is their failure to allow for the effect of the time of occurrence of the moisture deficit.

Young and Martin (1967) related harvested yield of sorghum to the time pattern in which irrigation was applied and showed that considerably better yields could be obtained for a given total water input if certain patterns of water application were followed. Minhas et al. (1974) examined the question of the extent to which the ratio of actual ET and potential ET depends on the level of soil moisture. They analysed, within a unified framework, the relationship between the rate of water use by the crop plant and the supply of moisture in the soil. They examined the relationship between water used at different points in time and the effect of these relationships on the timing of irrigation and the quantities of water used by the crop plant and its yields. They contend that there is a need to know the nature of the function relating actual ET and potential ET to soil moisture content. This, they say, will then enable one to compute actual soil moisture content on any subsequent day by using the knowledge of initial soil moisture content and subsequent potential ET. They estimated relative ET functions using data from fifteen field experiments in Delhi, India and approximated potential ET at 0.6 times pan evaporation. Using the estimated relative ET functions they went on to estimate a production function for wheat yields and dated inputs of water. Carruthers and Clark (1981) commenting on Minhas et al. (1974) study felt it to be one of the most refined mathematical interpretations in the development of economic models of crop response to irrigation. The limitation of the Minhas et al. (1974) study is that they used only one functional form and had limited data to test their model.

More recently Hexem and Heady (1978) in their book 'Water Production Functions for Irrigated Agriculture' present a number of estimations and applications of water production functions based on a large number of controlled experiments in the Western States of the U.S.A. Among the several crops they considered were corn, wheat, sugar beet, and cotton. They also aggregated the experimental data at each site, thus making it possible for them to estimate generalised production functions for each of those crops. The functions are called generalised because coefficients are estimated for the effect of water, nitrogen, soil and weather factors in the aggregated experiments (Hexem and Heady 1978). The generalised production function they derived from production functions that were estimated from data obtained from sites displaying a wide variation in weather, soil and spatial location characteristics had reasonably accurate predictive power. Further work on crop-water-soil relationships moved towards synthesising crop-water production relationships.

2.6.3 Synthetic function based on physical criteria

Further relevant contributions to the literature of the crop-water production function deal with attempts to synthesise crop-water relationships. These essentially involve development of models which utilise hypotheses about the plant, water and soil relationships. The models are then fed with weather data and conclusions on plant growth are made from the results obtained. Flinn (1968) noted that such models are more suited to estimation of crop water use rather than crop production. Moore (1961) presented one such synthetic crop-water soil relationship. His model of crop-water-soil relationship consists of three main elements: 1) a potential growth curve which relates the percentage of total final growth achieved by the plant at any point in the growing season when moisture stress is absent; 2) an hypothesised relationship between moisture stress and the percentage of potential growth actually achieved in any one period; and 3) a set of calculations on terminal levels of moisture depletion for each interval in the growing season. The model is developed for a hypothetical crop and the assumptions made on the key elements of the model are discussed in section 2.7.

Moore's major contribution is in illustrating, more clearly than his predecessors, that growth is related to moisture stress rather than actual water applications. This brought into the picture climatological variables, soil moisture retention characteristics and plant rooting behaviour as variables to be considered in the crop-water response functions.

An important limitation of Moore's model is that the moisture response relationship he hypothesised did not account for the impact of a moisture stress in one period on the growth in a subsequent period. Flinn (1968) argued that Moore's work is limited on plant physiological grounds and that the moisture release curve he developed is too site specific. As a result, in real world situations, an array of such moisture release curves will be required for different irrigation areas with different climates. A further difficulty Flinn (1968) had with Moore's model was the assumption that plant evapotranspiration will always be at the potential rate. This Flinn (1968) felt to be unrealistic and would result in underestimation of the soil moisture level (Flinn 1968, p. 41).

The next major development in the estimation of a crop-water production function consisted of a move to a more complex representation of moisture response with the help of mathematical programming and simulation.

2.6.4 Simulated functions based on biological and physical relationships

The limited success encountered in attempts to estimate plant-water response functions which incorporate in a realistic manner both biological and economic features led to attempts to synthesise such functions by simulating bioeconomic systems. One significant contribution is that of Flinn (1968). He developed a simulation model of the plant-soil-atmosphere system. In his model, crop growth depends on the interaction between the soil moisture level and the atmospheric demand for moisture from the plant. Flinn's main assumption is derived from the work of Denmead and Shaw (1962) which suggested that for any day, plant growth ceases whenever the daily potential ET rate exceeds the daily water intake rate, i.e. when the plant is subject to moisture stress. In a later model Flinn (1971) considered both the incidence and severity of stress in determining crop yield. Plant growth in each time period was related to the incidence and severity of moisture stress in that period and the growth was assumed to decline in a linear fashion from the maximum rate of growth to no growth as the ratio of actual to potential ET (relative transpiration rate) declines from one to zero. The input data for the simulation model expressed in daily terms consisted of the water retaining characteristics of the soil; crop parameters; expected daily values of rainfall and evapotranspiration; and a specified irrigation criterion, e.g. to irrigate when soil moisture in the crop root zone falls to a pre-determined level.

Flinn found that the productivity of irrigation water is strongly related to the time of application. He also derived production functions relating terminal soil moisture level to growth for thirty day intervals in the growing season. A further part of Flinn's study concentrated on the water allocation problem and is surveyed in Section 2.7 of this review. One of the limitations of Flinn's plant growth model is the rather rigid rule that growth ceases completely on any day in which the plant is exposed to moisture stress. The normal lag between transpiration rate and absorption rate could cause stress for short periods even when conditions of full water availability exist (Irvin 1973). Also, as in the previous studies, the model assumes the relationship between potential growth defined in any one stage to be independent of growth actually realised in previous stages. Another major limitation is the lack of validation of the results obtained from the simulation model with actual values of crop growth measured in the field. In spite of these limitations, Flinn's model combined considerable technical ingenuity in the formulation of water response relationships by taking into account a wide range of variables and in the formulation of an operational allocation model (Irvin 1973).

Mapp et al. (1975) developed a model for estimating the effect of a water deficiency on crop yield. The model consists of two parts. The first part computes a daily soil water balance while, in the second part, the critical stages of plant development for each individual crop are identified and the effects of soil water and atmospheric stress on yield during each of those stages are evaluated. In the first part of the model daily computations of soil water are made by allowing for daily changes in soil-water level due to addition through rainfall and irrigation, and subtraction through evapotranspiration. Net additions of soil water occur on any day when rainfall exceeds actual ET and depletion takes place when the opposite is true. In the second part of the model the authors assumed that the combined effect of soil water and atmospheric stress on yield per acre to be additive and expressed it as follows:

$$YR^{k}_{ij} = \theta SMD_{ij} + b^{k}_{j}(P_{ij} - P_{A})$$

where

YR^{k}_{ij} = yield reduction on day i for stage j and crop k,

θ = a coefficient reflecting yield reduction in units per day resulting from adverse soil-water conditions for stage j and crop k,

SMD_{ij} = soil water depletion in inches on day i for stage j,

b_j^k = the coefficient reflecting yield reduction in units per day due to severe atmospheric demands upon the plant for stage j and crop k,

P_{ij} = pan evaporation in inches on day i for stage j, and

P_A = critical pan evaporation level at or below which no yield reductions occur which are directly attributable to atmospheric conditions.

They verified their model by placing particular emphasis on the logical consistency of its relationships and on its ability to produce crops' yields and water-use rates consistent with those expected in the field. A series of simulation runs were made with each run concentrating on a particular crop and a number of irrigation application alternatives. From the results obtained and the opinions of agronomists, agricultural engineers and irrigation and farm management specialists, they concluded that the model successfully simulates crop yields and water use rates in the study area.

In a more recent work, Mapp and Eidman (1976) report the use of this bioeconomic simulation model to evaluate three methods of regulating ground water irrigation in the central basin of the Ogallala Formation in the Great Plains of the U.S.A. The alternative ways of regulating water use which they considered were: a no restriction situation; a quantity limitation situation; and a graduated tax per unit used above the quantity limitation situation. The results they obtained emphasised the need to educate farmers on the importance of timing of irrigation application to maximise net farm income.

The model of Mapp et al. (1975) is novel in the sense that yields of a number of crops, i.e. irrigated wheat, grain sorghum and corn are determined on the basis of length and severity of both soil moisture and atmospheric stress in relation to critical stages of plant development. The major limitation of their work perhaps is in the linear specification of the functional relationship between yield reduction and the variables of soil-water depletion, pan evaporation and critical pan evaporation. In spite of that, the bioeconomic simulation model developed by Mapp et al. (1975) has improved on earlier studies and has approximated to a greater extent the actual physical and biological relationships inherent in the crop-water-atmosphere system. Their model also shows promise for evaluating optimal irrigation strategies in combination with linear programming, dynamic programming or statistical decision theory techniques.

Anderson and Maass (1974) developed a model to simulate the effects of temporary water shortages within the crop year on the final yield of several irrigated crops. They divided the crop growing season into fourteen two-week periods and calculated the quantities of water required by each crop during each period for a given irrigation sequence. They then avoided the problem of having to model the soil-water-atmosphere-crop yield relationship by estimating the percentage reduction in crop yield that will occur if specified irrigation is not applied. Although the estimates of yield reduction are said to have been obtained from numerous experimental studies, no clear explanation is given as to how they were obtained. The model is used to determine the best allocation of irrigation water among crops and among farms participating in a water distribution system under conditions of limited water supply.

The Anderson and Maass (1974) model is therefore a whole farm model and concentrates on water requirements for each crop and computes the percentage loss in yield associated with a missed irrigation during various stages of the crop growing season. It also encompasses within a single model the three main components of an irrigation system, that is the water delivering authority, the farmers, and the crop-response to irrigation water. It is used in preference to the Mapp et al. model because the latter model is less flexible. The crop yield part of their model is more site specific and they have only developed the yield reduction model for sorghum, wheat and corn. Since a larger number of crops have to be considered for the present study the Anderson and Maass (1974) model is chosen. The Anderson and Maass (1974) model is also capable of simulating a larger number of water distribution procedures than that of Mapp et al. (1975). Given that the present study is concerned with water distribution rules, the Anderson and Maass (1974) model is used to simulate the effect of different water supply situations and distribution rules on farm crop production. This model and its limitations are discussed in greater detail in Chapter 3.

Having reviewed the work on the empirical estimation of water response functions, the next section consists of a brief examination of the work that has been done on optimal allocation of water at the farm level.

2.7 Models of Optimal Allocation of Irrigation Water

A logical consequence of the empirical estimation of water production functions was a move towards developing operational allocation models which were then used to derive optimal allocation policies at the farm level. Moore (1961) developed an analytical methodology to estimate the production function for crops using irrigation water and to impute a value to the irrigation water applied within any one irrigation cycle. He then determined an optimal irrigation policy which would account for varying water prices and changing commodity prices during the growing season. Using the moisture release curve as an indicator of the relative growth rate he derived an index of relative plant growth. By multiplying the index with the estimates of potential yield, Moore obtained actual yields under specified irrigation practices. The labour and water requirements for the crop for each specified irrigation practice is then obtained. Prices were then attached to these inputs and outputs thus enabling the establishment of value for the water used in the irrigation cycle (Moore 1961).

The results Moore obtained showed that the level of terminal soil moisture depletion will not be the same when the economic criterion of marginal cost equals marginal revenue holds for each irrigation cycle. It varies over a wide range and depends on the cost of pumping water and the expected commodity price during the season.

Moore's work can be said to be only an approximation to the problem of optimal allocation of water. Many assumptions were made in order to make the model operational. Included were the assumptions that: 1) the farmer has perfect knowledge of the moisture status of the soil at any time; 2) the effect of soil moisture stress on total relative growth is the same between irrigation cycles irrespective of the evapotranspiration rate; 3) soil moisture stress will have an equal effect upon plants that are harvested for their green weight, dry weight or fruit weight and size; and 4) the assumption of linearity of growth over time.

More sophistication is seen in the model developed by Flinn and Musgrave (1967) and Flinn (1968). The main part of their study was devoted to the problem of optimal allocation of irrigation water over the irrigation season. They handled the problem by first quantifying crop growth in relation to irrigation and weather inputs. The effect of moisture stress at different stages of crop growth on harvested yield was then quantified. They were then able to develop net revenue functions after knowing the value of output and the cost of irrigation for the eight stages of irrigation season considered. By using the net revenue functions of the eight stages of the irrigation season and applying dynamic programming they were able to determine the optimal allocation of water for each stage of the irrigation season.

The major limitations of the Flinn and Musgrave (1967) and Flinn (1968) models are that they used a single state variable, i.e. the quantity of water available for distribution over the remainder of the season to describe the state of the system at any stage. They therefore ignored the effect of the level of soil moisture at the start of a stage and its response to applied water during that stage. Dudley (1970) felt this to be unrealistic. The dynamic programming model developed by Flinn and Musgrave (1967) was also deterministic as they used single-valued estimates of return for each quantity of irrigation water applied at each stage.

Dudley et al. (1971) developing the work of Flinn (1968), incorporated the soil-moisture plant growth simulation model into a two-state stochastic dynamic programming model to derive optimal irrigation and timing under limited seasonal water supply. The states in their model were soil moisture and storage. Using simulation they were able to derive associated transition probabilities of soil moisture. They investigated the problem of allocating a given quantity of water over a growing season to a predetermined crop when rainfall and water requirements for the crop vary stochastically. The results of their study indicated that irrigators should keep soil moisture level at the root zone at a high level even at the risk of exhausting the available water supply early in the season. Dudley (1970) argued that such a result made sense because water remaining in the reservoir at the end of the season will have little or no value.

The major limitations of the Dudley et al. (1971) study stem from the assumptions made for the soil-moisture plant growth simulation model. It was assumed that the quantity of water applied at each irrigation will always be the amount that will return the whole root zone to field capacity. Also, the plant growth at any stage of development was assumed to be independent of past growth patterns of the crop.

The study also assumed that there was no substitution between irrigation water and other inputs since all inputs except water were assumed to be fixed. However, this work, which incorporated simulation and stochastic dynamic programming, demonstrated the usefulness of dynamic programming as a technique for analysing water allocation problems.

Hall and Butcher (1968) in their study of the optimal allocation of water over an irrigation season, used a two-state variable deterministic dynamic programming model. The state variables were the quantity of water available for allocation over the rest of the season and the soil moisture. A multiplicative relationship between the sequential steps, as opposed to an additive one in Dudley's (1970) study, was used in their formulation of the dynamic programming model. They found such a formulation to be an accurate representation of soil-moisture-plant growth relationships and validated their findings with experimental information. Two limiting assumptions of the study were that evapotranspiration in each stage was assumed to be independent of changes in soil moisture levels, and that irrigation costs were assumed not to affect optimal policies (Aron 1969).

Flinn (1968) also demonstrated the use of a linear programming model in which the choice of timing and quantity of water applied to a particular crop is related to a wide variety of other on-farm choice variables and subject to multiple constraints. His work demonstrated a procedure for approximating a non-linear irrigation response function in linear terms by a series of steps in which the solution to the program is used to identify the critical area in which the specification of the response function in greater detail is possible. Irvin (1973) also used linear programming to estimate an irrigation response function. Through an iterative procedure he approximated a non-linear irrigation function in linear terms so that an overall solution to the irrigation allocation problem is achieved. He applied the method in determining the optimal allocation of water in an Israeli kibbutz.

Rhenals and Bras (1981) presented an optimising stochastic dynamic programming model for irrigation scheduling. They were interested in testing how sensitive in qualitative terms the measure of performance of irrigation scheduling is to uncertainty in potential evapotranspiration.

Sub-models for potential and actual evapotranspiration, average soil moisture, crop yield and percolation were also developed. Their work is novel in that they chose to treat potential evapotranspiration as a random variable and to include its main characteristics in the scheduling problem. They applied their model to the South Platte river irrigation area in Colorado. The results of their study showed that the inclusion of potential evapotranspiration uncertainty in the modelling of irrigation scheduling does not bring any significant improvement in the expected net benefits in comparison to a model in which potential evapotranspiration is taken to be deterministic. The major limitations of their study are that the crop yield model used was not field tested and they assumed rainfall to be deterministic.

2.8 Conclusion

The review of literature of crop water response and its relation to the optimal allocation of water has shown that programming and simulation models can provide an operational framework for dealing with the complex allocation decision of the farm planning environment. However, the interactions between water, soil, the environment, biological production, and the economic system are very complex and there is a need to abstract from these complex relationships some simple observable relationships which can then be modelled.

In most studies researchers have seen the need to develop an empirical relationship between irrigation inputs, and plant production as the useful output, as the first step prior to including it in a model of water allocation. Much controversy still exists over the quantification of the relationship between available soil moisture and plant growth. An important part of this controversy is concerned with the nature of the growth-retarding effects of a given degree of stress at a given point in time. Knowledge is also lacking on the effect of growth retardation in one period on potential growth in later periods. Complex modelling exercises also tend to give small benefits in relation to the extra precision achieved or in their practical use to water institutions (e.g. Dudley 1970; Rhenals and Bras 1981). Simpler models of crop response may enable the treatment of a larger set of crops and may approximate real farm situations to a greater degree than complex models of single crop farm situations. The chapter that follows discusses in detail the model and technique used in the study.