THE ECONOMIC EVALUATION OF IRRIGATION WITH PARTICULAR REFERENCE TO WATER HARVESTING SYSTEMS

A thesis presented in partial fulfilment of the requirements for the degree of Master of Agricultural Science in Agricultural Economics and Farm Management at Massey University

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CHAPTER 1.

INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

This study is concerned with *ex ante* economic evaluations of irrigation systems, particularly those based on water harvesting.

While problems associated with the development of irrigation projects and allocation of irrigation water are usually diverse and complex, it is well recognised that these problems can be usefully studied within the framework of economic theory. This is well illustrated by the widespread adoption of cost-benefit analysis since the 1950's in New Zealand (N.Z.) and many other countries, in evaluating public investment in irrigation and other water resource development projects.

The continuing expansion of irrigation and increasing competition for water between urban, industrial and rural users, indicate that economists should play an important role in evaluating irrigation systems. Economic investigations of water harvesting irrigation systems are of particular importance in this context since water harvesting may provide the only, or cheapest, source of water to an area, and also because water that may otherwise be lost, primarily to the sea, is harvested and utilised.

The quantification of benefits in evaluating irrigation presents a number of challenges. Firstly, plant response to irrigation is largely dependent on meteorological conditions and irrigation benefits can therefore vary considerably over time and space. Secondly, interaction between the level of soil water and plant response (and consequent animal response in animal production systems) is such that the timing of an irrigation can

be more critical than the amount of water applied. Thirdly, the fact that most irrigation projects provide benefits over a number of years, and for large projects over an extended geographical area, necessitates that benefits must be estimated over time and space. The methodology applied in this study represents an attempt to at least partly overcome these challenges.

A number of irrigation studies have been carried out using plant-soil water simulation models. These modeals have been used primarily to generate plant-irrigation response functions. These studies appeared sufficiently encouraging to the author, that the major objective of this study was to investigate and evaluate the potential role of these simulation models in ex ante economic evaluations of irrigation projects, especially in relation to those carried out in N.Z. by the Ministry of Agriculture and Fisheries. To satisfy this objective, it was necessary to review the methods that have been used to determine irrigation benefits in ex ante evaluations of irrigation projects, particularly those carried out in N.Z.

Increasing demand for water from agriculture and other sectors of the economy, forces users to become more efficient in the use of their limited supplies of water. Information on various plant responses to irrigation can assist a farmer in allocating water between competing crops and in improving the time of application to individual crops. Mathematical optimising techniques have been used in conjunction with plant-soil water simulation models to allow estimates to be made, at the farm level, of the optimum allocation of water for any combination of water supplies and other limited resources, and price conditions. Another objective of this study was to investigate the intra-seasonal and inter-seasonal problems of optimising the allocation of a limited supply of water between crops. A linear programming (L.P.) model was developed in an attempt to satisfy this objective.

A further objective, complementary to the first two, was to use results obtained from the simulation and L.P. models to carry out positive and normative ex ante evaluations of a case study

irrigation proposal, viz. the Massey No. 4 Dairy Unit water harvesting irrigation proposal.

1.2 THESIS OUTLINE

Following a discussion of the technology of water harvesting and a description of the Massey No.4 Dairy Unit water harvesting irrigation system in Chapter 2, economic evaluations of irrigation systems are reviewed in Chapter 3. In Chapter 4, basic plant-soil water relationships are reviewed, together with comments on relevant N.Z. research in this field. The simulation model is described in Chapter 5 and the results obtained from applying the model to the case study project are presented and discussed. In Chapter 6, the L.P. model is presented together with the results for the case study project. Economic evaluations of the case study project are detailed in Chapter 7 and finally the summary and conclusions of the study are presented in Chapter 8.

CHAPTER 2

WATER HARVESTING FOR IRRIGATION

2.1 INTRODUCTION

In Chapter 2 the technology of water harvesting for irrigation is introduced. The current adoption and future potential of water harvesting for irrigation in New Zealand is briefly discussed. A number of irrigation projects in New Zealand, based on water harvesting, are discussed and finally the Massey water harvesting system is expanded on.

2.2 WATER HARVESTING TECHNOLOGY

Water harvesting is commonly defined as the process of collecting, conveying and storing surplus water from an area that has been treated to increase the runoff of rainwater or snowmelt (Myers, 1963). Treatment of a catchment to encourage surface runoff varies from leaving the catchment area in its natural or unimproved state, to rolling and compacting the soil, to using bituminous materials or plastic sheeting (Bowler, 1975).

Water harvesting is not a new technology. However, during the last 20 years, renewed interest in it has been apparent (Bowler, 1975). This interest has been generated principally as a result of an increasing demand for water and/or a reduction in the supply of formerly acceptable sources of water (due to pollution).

Although water harvesting has traditionally involved the storage of surface rainwater runoff, subsurface surplus water may also be collected by a subsurface drainage system, which effectively increases the amount of water harvested. (1)

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(1) The collection of subsurface surplus water is a distinguishing feature of the Massey water harvesting project which is expanded on in Section 2.4.

The objective of storing harvested water during periods of seasonal surpluses may be for drinking by animals or humans, but more commonly it is for irrigation during periods of seasonal moisture deficits (Bowler, 1975).[2] Other objectives, normally complementary to an irrigation objective, which may be fulfilled by a water harvesting project include flood control and soil conservation during seasonal water surpluses, and in the case of subsurface water collection, reducing or eliminating seasonal water-logging of soil.

Probably the best recent example of water harvesting is that developed at the University of Sydney Badgery's Creek farm (Bowler, 1975). This project was initiated in 1952, some results of which have been presented by Crofts et al. (1963) and Carter (1970). The soil and vegetation of the catchment areas were left in their unimproved states as these conditions on the Badgery Creek farm produce maximum surface runoff. Only surface water runoff is collected. In New Zealand there are numerous examples of water harvesting for irrigation, most of which also rely on the collection of surface rainwater runoff. Some of these projects are discussed in Section 2.3.

Although the objectives of storing surplus water, and the sources of water, may vary with different water harvesting projects, all water harvesting projects have in common a water storage facility. This storage facility is referred to as a storage pond, tank, dam or reservoir. They have been classified by Wiesner (1970) as follows according to the nature of the topography where they are constructed. The two basic types of dam are natural storage dams and artificial storage dams.

Natural storage dams are further subdivided according to the shape of the site, into gully storage dams and hillside dams. These dams are built on sloping land where water 'backs-up' from a man-made embankment, generally over a natural ground surface.

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[2] Irrigation is defined as the process of supplementing natural precipitation so as to maintain moisture within the root zone of plants above permanent wilting point (PWP) and up to field capacity (FC).

Gully storage dams are formed in a gully by building an embankment at the down-hill end. If the slope is uniform, the dam is formed by building a hillside dam.

Artificial storage dams are built on flat ground and are characterised by man-made walls. These dams are further subdivided according to whether the bulk of the water is stored above the natural ground surface (ring tank or turkey nest dams) or below it (excavated tanks). Ring tanks are the most common type of artificial storage dam.

Dams are constructed to suit the conditions of a particular location and many variations to the basic types exist. Wiesner (1970) has listed the most important factors that determine the type of storage dam built at a particular location as: the nature of the catchment; climate; rainfall; runoff; land utilisation of the irrigable area; and available capital.

2.3 WATER HARVESTING FOR IRRIGATION IN NEW ZEALAND

2.3.1 Its 'need' from a technical or physical viewpoint

In New Zealand, water shortages and consequential soil moisture deficits [3] are a common farming problem, a problem which has been accentuated by more intensive farming practices. Coulter (1973a) estimated by a simple water balance analysis of New Zealand daily rainfall data (which provided an approximation to the distribution of water surpluses and deficiencies, with respect to average seasonal water need) that most of the South Island, except for Westland and Buller, and much of the North Island, have soil moisture deficits at

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[3] A soil moisture deficit is defined as the amount by which water available to plants falls short of meeting plant water requirements (i.e. evapotranspiration). It is a measure of irrigation water requirement. Periods of soil moisture deficit are referred to as 'days of soil dryness' or 'days of agricultural drought' (Rickard, 1960).

some time in 50% to 100% of years, with deficits of 100 millimetres or more in parts of Canterbury, Otago, Marlborough and eastern areas of the North Island in more than 50% of years.

Coulter also estimated average irrigation 'needs' which ranged from zero in the west of the South Island and in high rainfall areas of the North Island, to nearly 200 millimetres in the driest parts of the North Island and to nearly 300 millimetres near Alexandra in Central Otago. (4) On average, deficits occurred largely between December to March inclusive.

Annual water surpluses or runoff (5) were also estimated by Coulter (1973a). They ranged from just above zero in parts of Central Otago to 6400 millimetres in the Southern Alps. North Island values were more uniform, falling to less than 400 millimetres in the Manawatu, Wairarapa and Hawkes Bay. On average, runoff was estimated to occur largely between May to September inclusive.

Coulter's estimates of monthly runoff show appreciably greater variation than the corresponding variability of rainfall, especially in low and medium rainfall areas. In all seasons (for 1940–72) in high rainfall areas, and in most places during the winter period, monthly rainfall statistics, less potential evapotranspiration estimates, gave an adequate representation of the frequency distribution of runoff (Coulter, 1973a).

For all areas of N.Z. apart from Blenheim, average annual water surpluses (i.e. runoff) were estimated by Coulter to far exceed average annual water deficits (i.e. irrigation 'needs').

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(4) Coulter (1973a) used the Thornthwaite method to estimate evapotranspiration. In a subsequent paper (Coulter, 1973b) it was shown that the Thornthwaite method probably underestimates evapotranspiration, particularly in the summer. Thus irrigation 'needs' are probably greater than the figures quoted above suggest.

(5) Runoff is a measure of surplus water above plant and soil root zone requirements and occurs when soil moisture levels exceed FC.

Coulter's water balance model is basically very simple. It is of necessity highly simplified as it was designed for application in a broad-scale climatological survey to provide a moisture stress or drought index for application in inter-year and inter-district pasture production comparisons. The major simplifications of the model are: it ignores variations from day to day (and from year to year in monthly mean values) of potential evapotranspiration; the assignment of a fixed value of 75 mm as the available soil moisture level for plants. However, Coulter mentioned that detailed water balance studies (as is illustrated in Chapter 5 of this thesis, where a 'site-specific' water balance model for the Massey water harvesting project is applied) can make use of more realistic models.

Despite the simplicity of Coulter's water balance model, it does provide the best available indication as to physical or technical 'needs' for irrigation in New Zealand and as to the potential for water harvesting as a source of irrigation water.

2.3.2 The Current Situation

The current extent of adoption of water harvesting for irrigation in New Zealand is not known by the author.(6) However, according to Heiler (pers.comm.) there has been a "fairly rapid acceptance" of water harvesting in various parts of the South Island since 1968, with supplemental irrigation water being provided to a range of agricultural and horticultural crops from storage dams of varying sizes.(7)

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(6) No quantitative published data indicating the extent of adoption of water harvesting as a method of providing irrigation water has been sighted by the author, and probably does not exist.

(7) The largest storage dam which is in the South Island, is approximately 160,000 m^3.

Storage dams in New Zealand are mainly of the gully storage or ring tank types. Gully storage dams (apart from the Massey system) collect normal surface rainwater runoff in wet periods and ring tank storage dams are filled either by pumping water from rivers or streams, or by natural gravitational diversion of water from streams.

New Zealand water harvesting irrigation projects that have been documented are all in the South Island apart from the Massey University project which is sited on the University's No.4 Dairy Unit two miles south of Palmerston North.

(a) Documented South Island Water Harvesting Projects

In 1975, of the four projects which are briefly discussed here, two were operational, with each involving only one farm, and the other two were proposed only, but each of these will involve a number of farms.

Heiler (1972) and Carran and Painter (1974) have detailed the proposed Glenmark Irrigation Scheme to be sited in Waipara, North Canterbury. This project proposal has been the subject of research carried out by the New Zealand Agricultural Engineering Institute.(8) The objectives of this research were: firstly, to examine the technical and economic feasibility of using water resources previously not considered suitable for irrigation purposes; and secondly, to examine techniques for obtaining estimates of water resource performance in areas where scant data only exists. The proposal involves pumping water (which would normally be lost to the sea), from a stream during the winter-spring period, into an open channel reticulation system delivering water to 18 farms. At each farm, water will be pumped into a storage dam, a gully storage dam or ring tank, with a capacity of approximately 90,000 cubic metres. On-farm irrigation will involve mechanical shift sprinkler systems capable of applying 76 millimetres gross application to 24 hectares per farm every 16.5 days, using two sprayline shifts per day. However, it is thought that the quantity of water provided and the system design could be capable of meeting plant water requirements of up to

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(8) This study is the first of its kind attempted in N.Z. (Heiler, 1972).

48 hectares of mixed crops. A farm management appraisal has been carried out on two representative farms and is reported in Heiler (1972). One group of farms are large units on light soils specialising in fat lamb production and the other group are smaller farms on more fertile soils with cash cropping providing a substantial proportion of income. The major conclusion of this research programme is that developments of this type can be shown to be economically and technically viable.

Plank et al. reported the results of a research programme designed to investigate the feasibility of an irrigation project based on farm storage dams and automatic watering through border dykes on a 216 hectare property in Waiau, North Canterbury. This property had alternative methods for obtaining irrigation water. However, the availability of suitable gully storage dam sites led to the adoption of water harvesting and also the technical feasibility of border dyking led to the adoption of this method of applying water (Plank et al.). Approximately 85,000 cubic metres of surface rain-water runoff will be stored in two gully storage dams during the winter-spring period and released during the summer to supply four irrigations on 29 hectares each of 76 millimetres. The property is predominantly a sheep fat lamb production unit with the irrigable area being light and stony. Land utilisation alternatives of the irrigable area are restricted even with irrigation, as intensive cash cropping is not feasible.

Rennie (1975) described a property in North Canterbury that relies on water harvesting for irrigation. A spray irrigation system (a mechanical shift side roll unit) is used to distribute the water. Water is pumped from a river largely during the river's winter flow, with a small amount being pumped during the summer to offset evaporation water losses from the dam surface. The dam is of the excavated tank type with a capacity of 160,000 cubic metres covering an area of approximately 5.5 hectares. The irrigable area is 49 hectares and the sprinkler system is designed to provide a gross application of 394 millimetres per annum. Land utilisation of the irrigable area consists of one half lucerne and one half cash crops.

McBryde et al. (1975) outlined initial proposals for a multi-purpose soil conservation-flood control-irrigation project for the Moutere Valley catchment. This proposal is based on the concept of water harvesting where storage of surface rainwater runoff will be effected by some 18 storage dams (gully storage and ring tank dams) from which water will be channelled and piped gravitationally to some 120 farms for irrigation during the summer. The irrigation design criterion involved an application of 375 millimetres over a three month period, which was estimated to meet crop requirements 98% of the time. In general, the placement of the dams will be in afforested catchment areas with arable land down stream. Present levels of cropping in the Moutere Valley has resulted in total use of natural water in the southern part of the catchment and maximum productive potential (from a technical or physical viewpoint) of this Valley is dependent on the implementation of a comprehensive irrigation and flood control scheme based on water harvesting.(9) The whole Valley catchment area is approximately 13,500 hectares, of which 70% is steep to rolling and 30% is flat. Of the flat area, approximately half is subject to flooding usually during the winter. A ratio of 1.5 to 1.0, of harvest area to irrigable area, provided the basis of the design of the project based on a detailed analysis of rainfall and stream flow records (McBryde et al.1975). The project was planned to be implemented over a number of years.

2.3.3 The potential of water harvesting for irrigation in N.Z.

The adoption of water harvesting for irrigation in New Zealand will depend essentially on the 'need' for irrigation (defined in terms of a technical, economic and/or personal sense) and on whether or not there are alternative sources of irrigation water. A physical or technical 'need' which was discussed in Section 2.3.1 is dependent on climatic factors such as rainfall, evapotranspiration and soil

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(9) The Moutere catchment is impervious with little or no ground water. Stream flow is directly related to rainfall, with the quantity of flowing water being very low in the summer. The development of a water resource thus depends solely on a water harvesting system (McBryde et al. 1975).

factors, such as the water holding capacity of the soil. An economic 'need' is dependent on economic factors which partly determine the profitability of irrigation. Personal factors of farmers, such as their aversion towards risk, a more peaceful 'state of mind' due to reduced worry through having sufficient feed, etc. may also be important in establishing a 'need' for irrigation. If alternative sources of irrigation water exist, careful consideration of the alternatives should be undertaken. Generally the most economic source of irrigation water, whether it be from a bore, a stream, or is harvested, should be utilised. In some situations, water harvesting may provide the only source of irrigation water, such as in the Moutere Valley.

The major irrigation projects operative in and planned for the South Island (especially in Canterbury) obtain (or will obtain) water from snow fed rivers which run to the sea and have their greatest flow during the spring and early summer (Plank et al.). These projects do not require storage and will cover approximately 405,000 hectares. Plank et al. estimated that at least another 1,620,000 hectares affected by drought in the South Island (Marlborough, Canterbury, North Otago and Central Otago) will not be able to obtain water from snow fed rivers because of their location. They see the concept of water harvesting providing a source of irrigation water to this area.

According to Massey water harvesting researchers (Evening Standard, 1973) water harvesting is potentially applicable to large areas in the North Island also, as well as the South Island. The North Island areas include parts of the Manawatu, Wanganui, Poverty Bay, Hawkes Bay and the Wairarapa.

In 1974 farmer interest in the Moutere Valley Scheme proposal was very high (McBryde et al., 1975). In August 1974 a questionnaire was sent to 120 farmers seeking their attitude to irrigation. One hundred replies were received all in favour of irrigation. The need for water harvesting in the Moutere Valley area is evidenced by the fact that a number of farmers have already constructed their own water storage dams to provide irrigation water, the largest dam having a capacity of 64,000 cubic metres.

Heiler (pers.comm.) believes that there is considerable potential for water harvesting in New Zealand. If the Glenmark project proves successful, ready acceptance by at least adjoining areas is likely (Heiler, pers.comm.). The successful development of individual farm projects and community projects involving a number of farms, designed largely by the New Zealand Institute of Agricultural Engineering and the Ministry of Agriculture & Fisheries, has been a first step in the development of water harvesting in New Zealand.

2.4 THE MASSEY WATER HARVESTING SYSTEM

2.4.1 The dams and catchment area

The 'No.1 Dam' was built in 1973 as part of a water harvesting research project funded by the New Zealand Water Resources Council. Objectives of this research project included the assessment of the feasibility of storing excess water, analysis of pasture responses to irrigation and analysis of nutrient recycling.(10) At the time this thesis was written, only very limited technical results of this research programme were available.

The 'No.1 Dam' has a storage capacity of 15000 cubic metres. In Table 2.1 the depth, surface area and storage capacity parameters pertaining to the 'No.1 Dam' are tabulated. These parameters have been estimated by depth gauge recording and aerial photography.

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(10) Research on the recycling of nutrients may have implications with respect to the efficiency of use of nutrients and water quality (Evening Standard, 1973).

TABLE 2.1 Depth, surface area and storage capacity of the 'No.1 Dam'.

Depth (metres)	Surface area (square metres)	Storage capacity (cubic metres)
1.0	900*	1100*
2.0	2750	2750
3.0	7500	5250
4.0	13700	7750
4.2 (top water level)	14990	8200

*Tentative estimates only.

(Source: Report, Department of Soil Science, Massey 1975).

In Figure 2.1 the parameters of Table 2.1 are graphed in a storage behavioural graph.

During April of 1975 two more dams (the 'No.2 Dam' and 'No.3 Dam') were constructed. The three dams are all gully-storage type dams constructed in the same gully to give a 'staircase' system of dams. A plan sketch and a longitudinal sketch of the three dams are presented in Figures 2.2 and 2.3 respectively. Detailed depth, surface area and storage volume parameters for the 'No.2 Dam' and the 'No.3 Dam' were not available at the time this thesis was written. However, total storage volume of the three dams was estimated to be 40,000 cubic metres (D. Bowler, pers.comm.).

The total catchment area for the three dams is approximately 20 hectares. This area is extensively drained. For example, the catchment area for the 'No.1 Dam' (which is approximately 12 hectares) has been drained by 55000 metres of mole drains and 2100 metres of field tiles. This drainage network distinguishes the water harvesting concept developed at Massey University from all other water harvesting projects in New Zealand. The Massey project is the first large scale attempt in New Zealand to transport water to a storage area by a subsurface drainage system (Evening Standard, 1973).

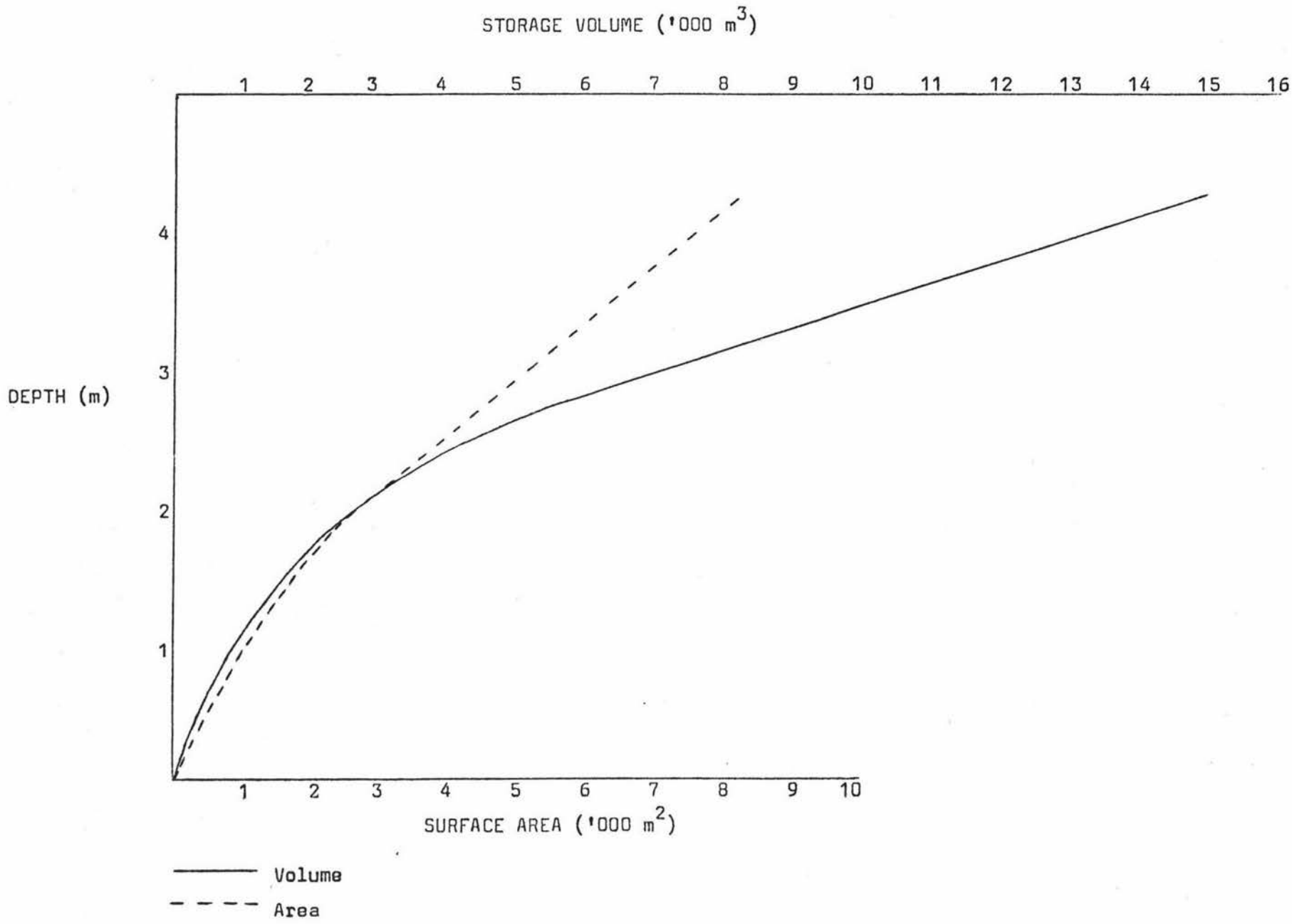

FIGURE 2.1 Storage behavioural graph for the 'No.1 Dam'

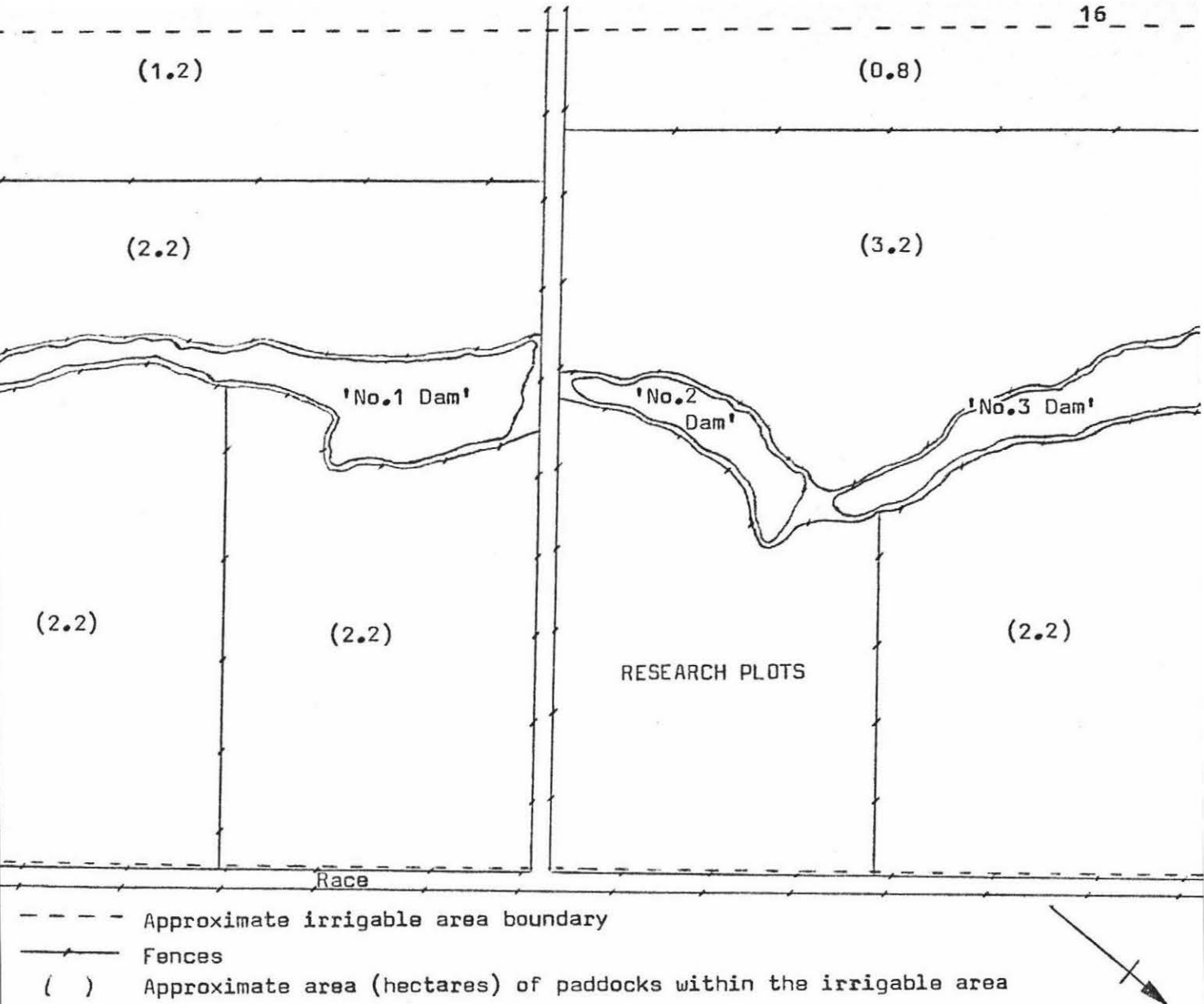

FIGURE 2.2 Plan sketch of the Massey No.4 Dairy Unit water harvesting dam system

FIGURE 2.3 Longitudinal sketch of the Massey No.4 Dairy Unit water harvesting dam system

Tentative results [11] for 1974 indicated that approximately 64% of the water that entered the 'No.1 Dam' entered via the drainage system. Also, 45% of this 64% entered during July and approximately 40% of the total rainfall appeared as tile discharge (Report, Department of Soil Science, Massey, 1975). These tentative results were extrapolated from water flow recordings obtained from drainage tile recorders on the Department of Soil Science's research plots.

2.4.2 The Massey No.2 Dairy Unit

The soil type on this 162 hectare property is a Tokomaru silt loam, which is a yellow grey earth characterised by reasonable fertility and poor natural drainage (requiring extensive drainage to minimise pugging during the winter). The property during 1975 was still undergoing development following purchase by Massey University some three years before. There were approximately 65 hectares of improved pasture and the balance of the pasture was browntop dominant (K.I. Lowe, pers.comm.).

The property during 1975 was being used as a seasonal supply dairy unit carrying 330 cows and 80 yearlings (K.I. Lowe, pers.comm.).

2.4.3 The Massey No.4 Dairy Unit proposed irrigation system

During 1975 a sprinkler irrigation system was designed by the Agricultural Engineering Department, Massey University, to irrigate 14 hectares within the catchment of the dams.[12]

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[11] These results in 1975 were considered to be tentative only. Additional data collected over a number of years will be necessary to verify them (Report, Department of Soil Science, Massey, 1975).

[12] Irrigating land within the dam catchment area facilitates a return to the dam of surplus water in the event of 'over-watering'.

This irrigation system was not designed as an integral component of the water harvesting research project. The design gross application of water at each irrigation is 50 millimetres every 14 days (R.M.Clarke, pers.comm.). The system is a hand-move sprinkler pipe type with a diesel engine driven mobile pump unit. Although 14 hectares are proposed to be irrigated initially, the engine and pump unit have the capacity to irrigate up to 28 hectares with the same gross irrigation application rate and frequency, although additional mainline and sprinkler line piping would be required (R.M. Clarke, pers.comm.).

The estimated costs of the proposed irrigation system (including the estimated costs of constructing the dams) are detailed in Appendices 4 and 5.

CHAPTER 3

ECONOMIC EVALUATION OF IRRIGATION SYSTEMS

3.1 INTRODUCTION

In this chapter, the components of economic evaluation that are applied in this study are explained. Models and techniques of analysis used in project evaluation and project design are discussed, and aspects of project design are elaborated on. Economic evaluations of N.Z. irrigation proposals are reviewed, and finally, methods of evaluating plant-irrigation responses are discussed.

3.2 COMPONENTS OF ECONOMIC EVALUATION APPLIED

3.2.1 Definitions

Definitions of most of the economic terms used in this study follow those provided by Jansen (1970). The remaining terms are defined below.

Project evaluation - the economic evaluation of a single project design, intended to estimate its economic worth.

Project design - the economic evaluation (usually from a public or national viewpoint) of more than a single design alternative of a project, intended to identify the alternative that maximises net economic returns and human satisfactions from the scarce resources employed in the project (The 'Green Book', 1958).

Positive evaluations - economic evaluations of projects which include an assessment of what farmers are likely to do, or will do.

Normative evaluations - economic evaluations which include an assessment of what farmers can potentially do, or should do.

Cost benefit analysis (CBA) - a technique used by economists to describe and quantify the social benefits and social costs of a policy in terms of a common monetary unit (Pearce, 1971).

'Conventional' CBA - CBA which employs only comparative techniques of analysis.

System - an identifiable grouping of components performing some function.

Systems research - the study of agricultural production systems. It incorporates aspects of systems synthesis and systems analysis, and is characterised by systems orientation, an inter-disciplinary approach and the use of systems modelling (Wright, 1973).

3.2.2 Components of economic evaluation considered and their inter-relationships

Although economic evaluation encompasses a wide spectrum of applied economics, this study is concerned with only a few components of economic evaluation. Specifically, economic evaluations of irrigation projects, with respect to a single objective, viz. economic efficiency, were considered. However, this incorporated aspects of project evaluation and project design. Although only ex ante evaluations were carried out, attention was concentrated on only one aspect of these, viz. the estimation of the physical impact of irrigation. Consideration of other aspects of ex ante evaluations of irrigation projects, such as the choice of economic criteria and discount rate, the handling of risk and uncertainty, the incorporation of multiple objectives, etc., while of extreme importance, was outside the scope of this study. In addition, both positive and normative evaluations, involving discounted cash flow analyses (investment analysis and CBA), were carried out using comparative and numerical techniques.

A schematic representation of the components of economic evaluation that were considered and their inter-relationships, is presented in Figure 3.1.

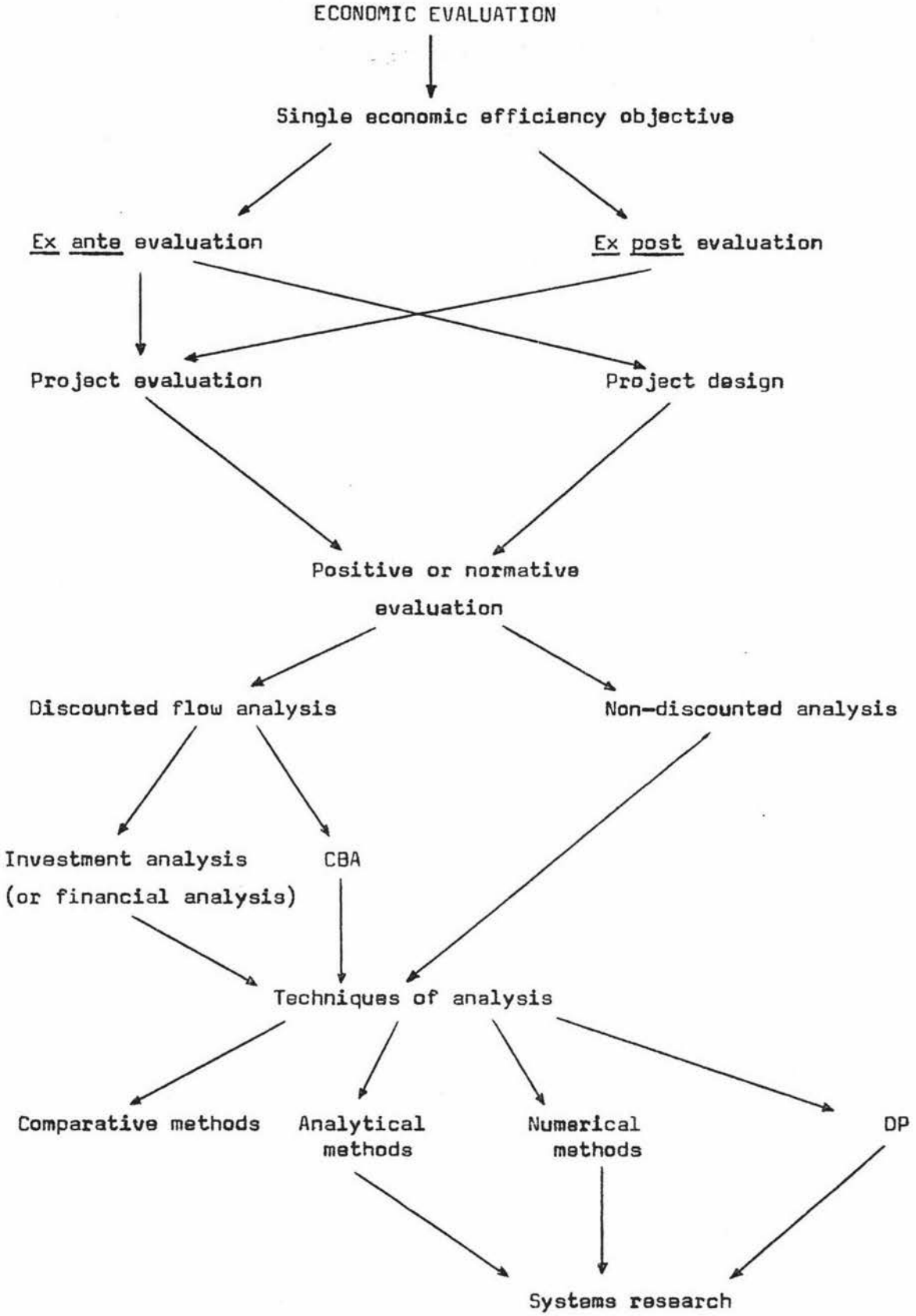

FIGURE 3.1 A schematic representation of the components of economic evaluation considered and their inter-relationships

3.3 MODELS AND TECHNIQUES OF ANALYSIS USED IN PROJECT EVALUATION AND PROJECT DESIGN

Given an adequate mathematical model of the agricultural system of interest, solution to decision making (management) problems (at a national, regional and/or farm level) can proceed by comparative, analytical, or numerical techniques. The decision problem being analysed should dictate the technique and hence the model to be used. However, the same problem could be solved by any technique, although the value of the solution will be largely determined by the adequacy of the model used.

Comparative techniques used in the analysis of agricultural decision problems involve budgeting. A budget is a description (statement of the inputs and outputs) of a system operated over some time period and is used as a means of solving a problem. The answers obtained are usually non-optimal.

Analytical techniques usually involve calculus. However, although most agricultural decision problems are amenable to solution by calculus, the model has to be very simple and therefore the solution may not be particularly useful.

There are two types of numerical techniques, viz. programming and simulation. Programming methods have a built-in optimising algorithm, whereas the simulation methods do not and an optimum solution to a problem is only approached by experimentation with the decision rules incorporated in the model.

Dynamic programming (DP) is a special type of modelling technique which provides a framework for solving multistage decision problems. DP may involve budgeting, calculus or numerical techniques. Although irrigation decision problems are typically multistage, dimensionality problems caused by computer size have restricted the application of DP to single-crop irrigation systems (Flinn, 1968; Dudley, et al., 1971; Salcedo,1972).

Irrigation project evaluations have almost exclusively used comparative modelling techniques, which usually involve gross margins and partial budgeting. Positive project evaluations of irrigation proposals have typically applied 'conventional' CBA, although normative project evaluations have applied programming (usually L P) and/or simulation methods to determine optimum, or suboptimum, land use patterns (Bergmann, 1973).

In 'conventional' project design, only comparative modelling techniques have been used.

In recent years, numerical techniques have been applied in the analysis of water resource project design problems in 'overseas' countries, but have not yet been applied in this field in N.Z. Applications of numerical techniques can be considered as exercises in systems research.

3.4 PROJECT DESIGN

3.4.1 'Conventional' methods

'Conventional' methods of project design used in the U.S.A. have been discussed by Reedy (1962). In brief, "necessary" information is collected, a tentative plan is prepared based on analysis of this information and a search for an optimal plan is carried out by incremental analysis of the tentative plan.(1) Project objectives are usually stated in physical terms only. Subsequent engineering analysis is then carried out to provide the physical goals at least cost. Finally, an economic evaluation (which really involves project evaluation, as defined in Section 3.2.1) of the least cost design alternative is carried out to test its economic worth using comparative techniques of analysis.

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(1) In incremental analysis, a series of alternative project plans are developed. An increment involves a separable unit of a plan, or a separable purpose.

In N.Z., economists have been traditionally involved at the final stage of 'conventional' irrigation project design using 'conventional' CBA. If a project proposal is not approved, either it is rejected, or its objectives are changed and the proposal is revised. However, subsequent incremental analysis by the engineer, in physical terms, is again limited without an accompanying economic evaluation.

The major limitations of 'conventional' project design of water resource systems are: firstly, the objectives for development, such as economic efficiency or income redistribution, are often not specified correctly and translated into adequate design criteria for water resource planners;(2) secondly, the techniques of project design may be ineffective in determining the 'optimal' design because (i) too few of the many technically feasible designs that may have economic merit are analysed, (ii) alternatives may be eliminated without full consideration of their benefits and costs, and (iii) the technique of selecting a tentative plan and applying incremental analysis to it is inadequate.

The principal objective of the Harvard Water Resources Program (HWRP), was to improve the methodology of water resource system design, by co-ordinating engineering and economics more effectively than had been done previously in the U.S.A. (Maass, et al., 1962). The HWRP is discussed in Section 3.4.2. (3)

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(2) Presumably the establishment of the National Water and Soil Conservation Authority in N.Z. and its two constituent councils, the Soil Conservation and Rivers Control Council and the Water Resources Council, and the publication of Water and Soil Management Guide Lines (1975), represent attempts to define the objectives of water resource development in N.Z. more precisely.

(3) Federal Register 36 (1971) of the Water Resources Council of the U.S.A. appears to have taken cognizance of the principal objective of Maass et al., (1962). However, the author did not know at the time this thesis was written, if the recommendations of Register 36 had been accepted by the U.S.A. Senate.

3.4.2 A literature review on systems research applications in water resource project design

(a) Programming models

The majority of programming models have been concerned with only a part of a river system,or with one or more of a river's important features.

Castle (1961) used LP in three simple water resource situations. The first dealt with structure capacity and water usage. The second with interdependent structures and the third with alternative water use relationships.

LP was used by Castle (1964) to evaluate changes in irrigation structures, cropping patterns and intensities of water application,for an assumed irrigation area.

'Conventional' CBA and LP were used by Pavelis (1961) in small watershed planning. Maximum net benefits were estimated for a specific watershed subject to land area, structure size and expenditure constraints.

Heady and Dorfman have discussed programming models of an entire river basin. Heady (1961), after formulating a complete mathematical welfare model, outlined a simplified programming version for river basin planning and development. However, no empirical application was carried out. A very simple programming model of a river basin project was developed by Dorfman (1961). Dorfman (1962) developed a very sophisticated programming model of a hypothetical river basin designed to maximise net benefits. However, the model had to be simplified to solve the problem and the resultant design was only optimal for the simplified problem.

(b) Simulation models including simulation models used in tandem with programming and/or DP models

Hydrologists have been developing simulation models of catchment behaviour for approximately 60 years (Halter and Miller, 1966). Comprehensive modelling of the physical and economic

environments of a water resource system commenced in the U.S.A. approximately 20 years ago with the HWRP. The HWRP attempted to establish an interdisciplinary approach by the involvement of engineers, economists and political scientists at all stages. (4)

The major objective of the HWRP was to improve the methodology of project design. This involved identifying the optimal design (5) of a river project, or, if this was not practicable, evaluating a "sufficiently" large number of possible alternative designs to assure that the best of these approximated the theoretical optimum (Maass, et al., 1962, P.6). Both a programming and a simulation approach were used. In the simulation approach, steepest accent statistical procedures were used to facilitate the search for maximised net benefits from the many combinations of design variables.

Maass et al., (1962) suggested the use of programming and simulation modelling techniques in tandem. The problem was initially divided into a set of manageable mathematical relationships that could be solved to give an approximation of the optimal design and then the range of plausible variation around the tentative solution was explored by a sequence of simulations. However, to quote the authors:

> "we cannot say that we have found the best combination of techniques, or that this combination is applicable to systems that differ significantly from that we have examined."

A comprehensive simulation model of the Susquehanna River Basin was developed by the Battelle Memorial Institute and has been detailed by Hamilton et al. (1969). The economic relationships of the river basin were studied by subdividing the entire basin into sub-regions, in an attempt to ascertain factors affecting economic growth in the area. The major purpose of the study was to explore how systems simulation could be applied in regional analysis.

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(4) The HWRP was detailed by Maass et al. (1962).

(5) Maass et al. (1962) defined an optimal design as that combination of system units, output and operating procedures that fulfil development objectives better than any other.

Anderson (1968) simulated a multifarm-multicrop system in which farmers could allocate an assumed supply of water at different periods throughout the growing season. However, the approach is limited as it did not consider the stochastic effects of rainfall and evapotranspiration.

Dudley et al. (1971) used the output of a simulation - DP model to determine the optimal area of a single crop irrigated from a reservoir.

DP was used by Hall and Buras (1961) to project expected irrigation water requirements throughout a growing season. These requirements were then used to allocate various resources over crops as well as time.

Flinn (1968) used simulation to generate crop-irrigation water response functions. Output from the simulation model was used in a DP model to establish the optimal allocation of a limited quantity of water to a single crop during a growing season, and also in a LP model of representative farms to derive normative regional irrigation water demand schedules.

The final stage of a three-stage research project, aimed at the development of a computer-oriented planning system for use in the planning of large multipurpose reservoir systems, was reported by Salcedo (1972). The final stage built on previous stages (where programming and simulation models were applied to simulate and optimise the water capture and transfer system) by relating irrigation water demand to the available water supply. A DP model was used which yielded optimal returns and decisions for scheduling the irrigation of a single crop on a single soil type. A LP model that selected optimal cropping patterns for various amounts of water availability, using the return information generated by the DP model, was also used. The output from the DP and LP models provided input to a dynamic simulation model which modelled farmers' "rational" decisions and changing status of their crops throughout a season.

3.5 A REVIEW OF ECONOMIC EVALUATIONS OF N.Z. IRRIGATION PROJECTS

Economic evaluations of N.Z. irrigation projects are reviewed with special emphasis on the types of evaluations that have been carried out and the methods by which the physical impacts of irrigation have been assessed in ex ante evaluations.

All of the M.A.F. irrigation investigations have involved multiple farm projects (i.e. projects which each supply water to a number of farms). The investigations prepared outside of the M.A.F. have involved multiple and single farm projects.

3.5.1 M.A.F. irrigation economic evaluations

Some 63 irrigation project economic reports were prepared by the M.A.F. during the period 1952 to 1975 (see Appendix I for details). For the purposes of this review, they have been divided into four categories. Reports that are similar in their methodology and presentation are reviewed together.

(a) The four categories

(i) Feasibility Studies

Feasibility studies have involved evaluating the economic impact of irrigation for a defined irrigation area. All are limited, though, in that they have assumed a fixed demand for irrigation water and a fixed irrigation response. An attempt has been made in these studies to determine the economic feasibility of irrigation and they have usually been prepared following initial project planning, prior to the estimation by engineers of detailed off-farm costs.

The Maniototo (1952) was the first irrigation economic report prepared by the M.A.F. The impact of irrigation was assessed in physical terms only and financial details of the surveyed farms provide the only economic content of the report.

The second report, the Cromwell-Ripponvale (1954), detailed what was essentially a physical study. The only economic content of it is a qualitative economic statement made by the author in his recommendations about the proposal.

All reports from 1957 to 1964, with the exception of the Hawea (1960) and the Upper Aparima (1963) reports, are reviewed together. These investigations all involved a farm survey (usually of the total farm population) and were aimed at : (i) assessing farm physical and financial structures at the time of the surveys; and (ii) assessing (by partial budgeting) increases in gross farm income attributable to irrigation. However, it is not made clear in these reports exactly what dryland situation the irrigation potential situation is compared to. Clearly, irrigation potentials should be compared to dryland potentials, not the dryland levels of production attained at the time farms are surveyed. Johnson (1970) also made note of this point.

Three separate project alternatives (involving different irrigable areas) were evaluated in the Hawea (1960) report. The methodology and report presentation were essentially the same as other reports prepared from 1957 to 1964.

The investigation described in the Upper Aparima (1963) report did not involve a farm survey. Instead, an attempt was made to estimate the difference between irrigation and dryland potential stocking rates, using two alternative methods. These methods, the 'Storie Rating Method' and the 'Evapotranspiration Method' were described in detail in the report. The estimates obtained, although significantly different, were used as upper and lower limits within which the "probable" stocking rate increment due to irrigation was considered to lie. Although obviously crude, it is unfortunate that the validity of these approaches cannot be tested, as the Upper Aparima project has not been implemented.

Feasibility studies prepared from 1969 to 1975 have all employed discounted cash flows analysis. The national viewpoint has always been analysed using 'conventional' CBA, although some of the investigations have also considered the farmer viewpoint (e.g. the Awatere, 1974). In all of these investigations, the maximum off-farm costs that could be sustained, so that the projects could meet Treasury guidelines for public funding, have been estimated.

(ii) Project Evaluations

The Maniototo (1961) report is the first M.A.F. irrigation economic report in which off-farm and on-farm costs were included. The report detailed the physical results obtained from a farm survey, as well as the dryland and irrigation stocking rate potentials, subjectively estimated from limited irrigation research data and the experience of farm advisory personnel. Also estimated was the additional number of stock required to "justify" the project.

The above report was revised (the Maniototo, 1962, report) to account for an increase in on-farm costs and a new (increased) estimate of the stocking rate increment attributed to irrigation.

One alternative project design of the Hawea project was re-evaluated in detail in the Hawea (1963) report. Estimated off-farm capital and associated costs were included in the evaluation.

The Maniototo (1965) report is the first M.A.F. irrigation report to have incorporated cash flows and discounting in a CBA framework. Physical data of the Maniototo (1962) report were used together with up-dated engineering costs. The results were presented in terms of the Present Worth (PW) criterion. A discount rate of five percent was used.

The remaining project evaluation reports are reviewed together. All of these reports were categorised as project evaluations as they were all concerned with the evaluation of a single project design. A CBA framework was used in these reports and results from the national viewpoint were presented in terms of PW, Benefit Cost Ratio and/or Internal Rate of Return criteria. The evaluations are all positive and used partial budgeting (i.e. marginal analysis). The reports differed in some methodological aspects (e.g. the discount rate used, the handling of risk and uncertainty). Of importance to this study are the methods that were used to assess the physical impacts of irrigation. A fixed, or single valued, response to irrigation water was assumed in all of the reports apart from the Hautere (1974) and the Inaha (1974) reports. This is a subjective approach based primarily on farm survey

data. This method, as well as that used in the Hautere (1974) and Inaha (1974) reports, are outlined in Section 3.5.

(iii) Project Design

Only two M.A.F. irrigation reports (the Maniototo, Dec. 1967) and the Teviot (1973)) have evaluated more than one project design alternative. Conventional techniques of analysis (viz. comparative techniques using gross margins and partial budgeting, in a CBA framework) were used. Only the national point of view was analysed and the PW and IRR criteria were correctly used. Sensitivity analyses which involved variations of the discount rate, development period and product prices, were carried out. Since conventional techniques of analysis were used, a large number of manual computations were involved in the preparation of these reports.

The Teviot report is more comprehensive than the Maniototo report.[6] Distinguishing features of the Teviot report include the method used of assessing the physical impact of irrigation. Use was made of quantitative feed budgeting to assess the impact of irrigation on stocking rates, rather than the subjective method more commonly used by the M.A.F. A cost effectiveness analysis was carried out for the orcharding component, since for all six project designs, orchardists could obtain irrigation water via an individual, or a community, irrigation system. The method of analysis used and presentation of the results allowed the design alternatives to be ranked and also their "true economic worth" to the nation, to be estimated.

(iv) Other

This category contains reports that could not be included in the previous categories.

Farm management and financial details obtained from a farm survey were presented in the Valetta (1968) report.

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(6) Six alternative designs of the Teviot project were analysed vis a vis only two of the Maniototo project.

The results of an ex post evaluation of the Hawea irrigation project were detailed in the Hawea (1968) report. All farms in the project area were surveyed to fulfil three objectives: (i) to determine what development had taken place since the project was implemented; (ii) to compare actual development with the development predicted ex ante in the Hawea (1963) report; and (iii) to determine the economic worth of the project to the nation as at 1968.

The Upper Waitaki (1969) report is similar to the Hawea (1968) report with respect to the objectives and presentation of the results.

Results obtained from a survey of a sample of farms in the Maniototo Basin that had private irrigation systems, were presented in the Maniototo (1969) report. At the time of this survey, six reports had previously been prepared by the M.A.F. on irrigation proposals in the Maniototo Basin for which public funds had been requested. However, these proposals had been rejected on the basis of being uneconomic (to the nation). In the Maniototo (1969) report, the results of a multiple regression analysis (in which an irrigation production function based on physical input-output data was derived) were also presented so that "future irrigation investigations in the Maniototo Basin could be dealt with a greater degree of confidence of the input parameters." However, subsequent reports on irrigation proposals in the Maniototo Basin (Maniototo, 1970, 1971 and 1974 reports) have not employed the potentially useful results of the 1969 report.

The impact of a shift to orcharding in the Upper Waitaki irrigation project area was evaluated in the Upper Waitaki (1972) report. The orcharding development (which was not predicted ex ante) had a significant impact on the economic worth of the project.

The Canterbury (1973) report detailed the results of a study aimed at providing information on the physical and economic consequences of irrigating the Rakaia area of Mid Canterbury. Nine representative farms (selected by a random sampling procedure stratified according to soil type and farm size) were analysed. Three levels of water application were evaluated and for each level of water application, fixed plant responses were assumed. Crop rotations were defined and stocking rate increments due to irrigation were assessed subjectively.

M.A.F. economic reports of irrigation projects in Otago were reviewed in the Otago (1974) report. An attempt was made to subjectively rank reassessment proposals and new proposals, on the basis of these reports and from information obtained from the M.O.W. and local farm advisory officers. Four parameters were used to rank the proposals, viz. farmer support, engineering feasibility, water resources and economic benefit. Each parameter was rated individually and an overall ranking was obtained by summing the ratings. It was pointed out in the report, that a time constraint limited the ranking procedure used to being subjective, and that the ranking was not to be considered as a final assessment.

(b) An overview of the M.A.F. reports

(i) Feasibility studies

Thirty-three percent of the M.A.F. irrigation reports reviewed have been categorised as feasibility studies. These reports are of limited use, since, although they are aimed at involving the economist at the design stage of projects, they have been largely ineffective in achieving this, because: (i) with the exception of one report, only a single defined irrigation area was evaluated; (ii) engineers and economists have not been closely associated in the investigations, but in fact have worked separately. Despite their disadvantages, feasibility studies may be useful for ex post evaluations of projects that have been implemented.

(ii) Project evaluations

Fifty-three percent of the reports reviewed were described as project evaluations. The methodology used in these reports is well developed. Each report has provided decision makers with a yes/no economic answer for a single project design alternative. The economists exercise can be described as merely a 'rubber stamp' one. The potential contribution of economics is severely limited, as no guarantee can be given that the proposal evaluated is the 'best' design alternative. Project evaluation reports may also be useful in ex post evaluations of approved proposals.

(iii) Project design reports

Only three percent of the reports fit into this category. This may in part be due to the fact that only comparative techniques were used. The use of computer techniques of analysis, such as LP and simulation, could facilitate the evaluation of project design alternatives. It is the author's opinion that had simulation been used in the preparation of the Teviot (1973) report, the same number of design alternatives could have been evaluated in less time than was the case using conventional techniques. Alternatively, it is likely that more than six design alternatives could have been evaluated in the same time had simulation been used.

(iv) Other reports

These reports account for 11 percent of the M.A.F. irrigation reports reviewed. The ex post evaluations were useful in checking ex ante methodology. The Canterbury (1973) and Otago (1974) reports have a potentially useful application in broad-order regional irrigation planning, prior to detailed project design. Methodological limitations of these two reports have already been outlined.

3.5.2 Non-M.A.F. irrigation economic evaluations

In this section, economic evaluations prepared in N.Z. by analysts other than those employed by the M.A.F. are reviewed.

(a) Single farm evaluations

Haslam (1965) presented a LP study of a single irrigation farm in Mid Canterbury. The objective of the study was to outline the most profitable management policies under different sets of price and physical production parameters. The analysis was non-discounted.

The physical and financial returns of an automatic irrigation system at Tara Hills in North Otago were detailed by Calder and Weston (1966). This ex post analysis was non-discounted.

The costings of an automatic irrigation system on a farm in North Otago were detailed by Koller (1967). Also presented was a non-discounted breakeven analysis which determined (at 1967 prices) the breakeven stocking rate increment due to irrigation. In a subsequent study, Koller and Crump (1968) carried out a non-discounted financial analysis (at 1968 price levels) to determine the economics of irrigation. Results were presented as a percentage rate of return to irrigation capital and as additional cash farm surplus per irrigable acre.

The financial results (expressed as gross income per acre) of a farm at Lyndhurst in Mid Canterbury were presented by "Cantuar" (1967). Unfortunately, no capital and associated irrigation costs were presented.

Plank et al. have detailed an ex ante evaluation of a water harvesting irrigation proposal for a farm in Waiau, North Canterbury.(7) The methodology used in this evaluation is similar to that used by Heiler (1972) for the Glenmark proposal. The only methodological difference between these evaluations is that the non-irrigated situation assumed in the Waiau evaluation was theoretical (as an increase in dryland productivity was assumed); whereas in the Glenmark evaluation, the non-irrigated productivity level was assumed to equal the level attained at the time of the evaluation.

A very simple farmer viewpoint ex ante evaluation of a North Canterbury water harvesting proposal has been presented by Rennie (1975). Irrigation benefits were quantified as additional lucerne hay sales. The measure of profitability used was additional annual gross income.

(b) Multiple farm evaluations

A survey of farms in the Ashburton-Lyndhurst area of Mid Canterbury, designed to obtain information on the comparative profitability of irrigated farms within the Ashburton-Lyndhurst

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(7) Physical and management details of this proposal were outlined in Section 2.3.2.

project, and comparable dryland farms, was detailed by Stewart (1963). The report emphasised that information was sought as a basis for negotiation of water charges and not an economic appraisal of irrigation on light soils in Canterbury. A sample of farms were surveyed for which physical and financial data for the years 1959/60, 1960/61 and 1961/62 were obtained. Owners' surplus was used as a measure of profitability. A further investigation of the results of this survey were presented by Stewart and Haslam (1964).

A discounted investment analysis of two farms using automatic irrigation systems was used by Lawson (1967).

A farmer viewpoint ex ante evaluation of the Glenmark irrigation proposal was included in Heiler (1972).[8] The evaluation was based on a study of two representative farms. The analysis was non-discounted and additional cash farm surplus attributable to irrigation was used as a measure of profitability. The partial budgeting method used to estimate the "best use" of the limited quantity of irrigation water can be criticised. A LP formulation of the problem, for example, that incorporated more management (of water, feed and stock) options than can be conveniently handled using partial budgeting, should result in a more confident "best use" water policy.

3.6 EVALUATION OF PLANT-IRRIGATION RESPONSES

Economists evaluate plant-irrigation responses by the use of production functions. Flinn and Musgrave (1967) have discerned four broad approaches used to estimate plant-irrigation production functions. These are discussed below.

(a) A single-valued plant water response

This is the simplest of the four approaches. A fixed plant irrigation requirement and a fixed plant(or consequential animal) response are assumed. The plant water production function is assumed to be represented by a single point. This approach has been most commonly used in the evaluations reviewed in Section 3.5. Limitations

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(8) This proposal was also discussed in Section 2.3.2.

include its simplistic representation of a biologically complex phenomenon and its subjective derivation.

(b) A function based on physical input-output data

In this approach a production function is derived, based on experimental data, using statistical methods. By application of standard production economics theory, the optimal level of irrigation input can be derived. However, the use of a total irrigation input parameter has limited practical usefulness as the optimal allocation of water over an irrigation season is not determined. This problem could be partly overcome by specification of a response function that relates plant production to irrigation inputs over time. However, there have been no empirical attempts to do this. Also, response functions derived from experimental data are unlikely to be useful in predicting plant responses to irrigation for climatic conditions, soil types or irrigation systems other than those for which the data were collected. One further limitation is that soil moisture stress influences plant growth rather than irrigation or rainfall per se. Therefore, the yield of a plant should be related to soil moisture tension, and only indirectly to water quantity, when plant water production functions are formulated. Of the evaluations reviewed in Section 3.5, only one employed this approach (viz. the Maniototo, 1969 report), although a number of attempts have been made in the literature (Flinn and Musgrave, 1967).

(c) A synthetic function based on physical criteria

In this approach, crop yields are related to soil moisture deficiency indices over both time and space. Climatological and irrigation data are used as soil moisture inputs. Agricultural production field data are also used. Moore (1961), Nix and Fitzpatrick (1969) and Dean (1975) have all used this method, which has evolved from soil water budgets of soil scientists and climatologists. A major criticism is that plant water use is better estimated than resulting agricultural production. Only two N.Z. irrigation evaluations (Hautere, 1974 and the Inaha, 1974) used this approach, details of which have been presented by Dean (1975).

(d) A simulated function based on biological and physical relationships

This approach relies on the use of plant-soil water simulation models. A model used to generate plant-irrigation response functions must provide a rational accounting method to estimate periodic (preferably daily) soil moisture levels, and also be able to relate daily soil moisture levels to evaporative parameters to derive an index of plant growth. In Chapter 5, a simulation model which was adapted from one developed by Flinn (1968), is used to estimate plant-irrigation response functions which are applied in Chapters 6 and 7 in the evaluation of the Massey case study irrigation proposal. Although this approach is new and has not been applied widely in irrigation evaluations, it is theoretically the most realistic approach for synthesising plant-irrigation production functions.

3.7 CONCLUSIONS

It has been shown in Chapter 3 that the major contribution economists can make in the evaluation of irrigation projects (and indeed other water resource projects) is at the design or planning stage. A review of N.Z. irrigation evaluations indicated that economists have not been involved to a large extent in project design. It was indicated that this may in part be due to the fact that only 'conventional' comparative techniques of analysis have been used in N.Z. This view is substantiated by a review of overseas literature concerned with the evaluation of water resources, which indicated that involvement of economists in water resource project design in recent years appears to have been largely dependent on the application of modern techniques of analysis (numerical and/or DP), which implies the application of systems research.

Irrigation production functions must be formulated when evaluating irrigation. The review of M.A.F. irrigation evaluations indicated that a single valued function (i.e. fixed demand and response), subjectively estimated, has been almost exclusively used. A review of the approaches that have been used to determine these functions indicated that a simulation approach holds the most promise.

CHAPTER 4

PLANT WATER RELATIONS

4.1 INTRODUCTION

In this chapter, a brief description is given of the soil moisture - plant - atmosphere relationships on which the simulation model used in Chapter 5 is based. A resume and exposition of N.Z. research on plant irrigation responses are also presented. Some comments are made on the utility of a systems experimentation approach for providing plant irrigation response functions and data on strategic allocations of water. Finally,it is suggested that the application of systems research, using mathematical models (i.e. systems modelling), could be the best systems experimentation method to use.

4.2 MAJOR SOIL MOISTURE - PLANT - ATMOSPHERE RELATIONSHIPS

A comprehensive review of literature on soil moisture - plant - atmosphere relationships was carried out during this study to gain confidence as to the biological validity of the simulation model used in Chapter 5. However, this review is not reported in this thesis. A similar review has been carried out by Flinn (1968). Also, Kramer (1963), Salter and Goode (1967), Slatyer (1967) and Chang (1971) have reviewed literature on the functions of water in plants, as well as on water stress and plant growth.

Soil moisture influences plant growth, not irrigation or rainfall *per se*. Irrigation water, though, is an input that augments soil moisture and furthermore it is an input that can be controlled by a decision maker (i.e. the irrigator or farmer).

In this study, soil moisture is the variable of interest and is varied. All other factors that affect plant production were assumed *ceteris paribus*. Although it would have been desirable,

incorporating substitution of other inputs for soil moisture, for example nitrogen fertiliser, was found to be beyond the scope of this study.

Two concepts require careful consideration when an attempt is made to estimate the productivity of irrigation water (Flinn, 1968). These two concepts, plant - atmospheric relationships and plant - soil relationships are discussed briefly in Sections 4.2.1 and 4.2.2 respectively, with respect to the simulation model used in Chapter 5.

4.2.1 Plant - atmospheric relationships

(a) Potential evapotranspiration (Ep)

Ep is the combined evaporation of water from soil and plant surfaces exposed to the atmosphere and the transpiration of plants. The methods that are available for measuring Ep have been reviewed by Oliver (1961) and Chang (1971). Accurate measuring methods are complicated and require extensive climatological data. As a consequence, less accurate but practical measurement methods have been developed by Penman (1948) and others, which empirically relate Ep to relatively easily measured and available climatic parameters.

Penman (1948) used a crop factor (F) to relate Ep to the evaporation rate from a 'free water' surface, Eo, in the relationship:

$$Ep = F * Eo \qquad (4.1)$$

The factor F has theoretical limitations. For example, research has indicated that at any instant it can only be approximated. Also, it varies according to plant species, stage of crop development, the time of the year and latitude. However, researchers have agreed that the use of such a factor is reasonable.

The simulation model described in Chapter 5 was applied to two crops, viz. pasture and maize. The F-factors are presented in

Table 4.1 [1]:

TABLE 4.1 Crop factors used for pasture and maize

Month	Crop factors (F)	
	Pasture	Maize
July	0.6	
August	0.7	
September	0.7	
October	0.7	
November	0.8	0.2
December	0.8	0.3
January	0.8	0.5
February	0.7	0.9
March	0.7	0.8
April	0.7	0.8
May	0.6	0.7
June	0.6	0.6

(b) Free water evaporation (Eo)

Since the ratio Ep/Eo has been shown by Penman (1948), Finkelstein (1961) and others to be constant at any time of the year for any particular crop, if Eo can be estimated, then Ep can in turn be estimated (refer to equation 4.1).

Actual measurements of Eo are limited in number and specific to location. A common method of indirectly estimating Eo involves the use of evaporimeters.[2] Conversion factors have been estimated

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[1] F factors for pasture are based on Wiesner (1970, Table 12, p.74) and those for maize were derived following a method suggested by P.Gander (pers.comm.) in which the months Nov. to Mar. inclusive were based on data obtained from Kerr (1973), and Apr. to June inclusive were based on Wiesner (op.cit.).

[2] An evaporimeter is an instrument which measures water evaporation. There are two basic types of evaporimeters: open water evaporation pans (raised and sunken pans); and porous surface-type atmometers.

that allow measurements from evaporimeters to be converted into estimates of Eo. Finkelstein (1973) analysed N.Z. tank evaporation records and updated previous conversion factors reported by Finkelstein (1961). The updated estimates are 0.69 for standard raised pan evaporimeters and 0.86 for standard sunken pan evaporimeters. These conversion factors were incorporated in the simulation model.

4.2.2 Plant - soil relationships

Water demanded by a plant must be supplied from the soil reservoir via the plant's root system. The capacity of the soil to absorb and retain water enables plants to survive (and grow) between periods of rainfall and/or irrigation. The volume of soil being explored by the root system, and the availability of water in that volume, are important characteristics to know and must be incorporated in a realistic plant - soil water model. These soil characteristics for a Tokomaru silt loam were estimated by D. Bowler (pers. comm.) and are presented in Table 4.2. The effective root zone water holding capacity estimates were incorporated in the simulation model.

TABLE 4.2 Effective crop root depth and water holding capacity of a Tokomaru silt loam

Crop	Effective crop root depth		Water holding capacity - Tokomaru silt loam			
	Metres (m)	Feet	mm per dm* depth of soil Up to 0.3 m	Below 0.3 m	mm per effective root zone (3)	
			22	15	A horizon	B horizon
Pasture	.4572	1.5			66	23
Maize	.6096	2.0			66	45

*dm = decimetre

(3) Available water holding capacity of a Tokomaru silt loam is probably larger than indicated in Table (4.2) (R.Jackson pers.comm.). However, no data have yet been published.

4.2.3 Actual evapotranspiration (Ea)

Evapotranspiration studies have shown that when soils are sufficiently moist, the evapotranspiration rate is dependent on external atmospheric conditions only. At low soil moisture levels though, evapotranspiration rates are independent of the evaporative power of the atmosphere and depend only on soil moisture conditions, with the rate of evapotranspiration declining as the soil dries.

Considerable controversy has existed as to the effect of available soil moisture [4] (sometimes referred to as soil moisture tension) on the depletion rate of evapotranspiration. Conflicting research results exist. For example, in Figure 4.1 three different relationships between relative evapotranspiration rate and soil moisture tension are depicted.

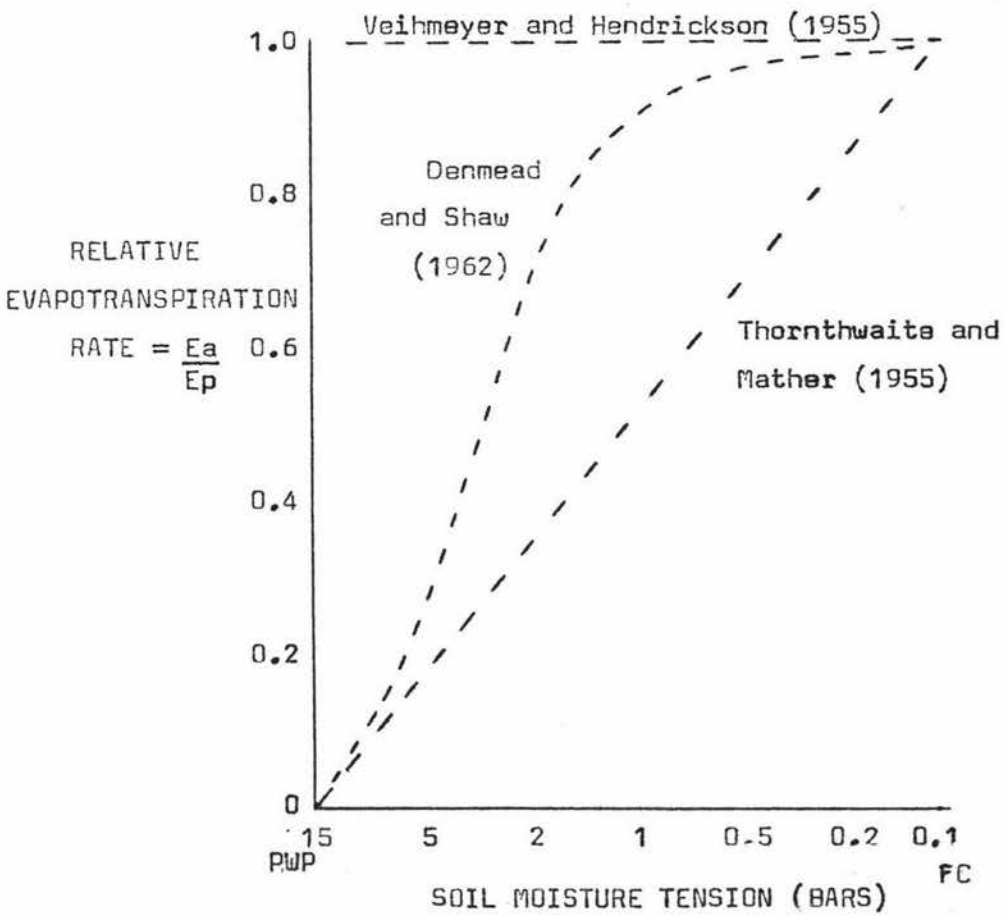

Figure 4.1 Various relationships between relative evapotranspiration rate and soil moisture tension

[4] Available soil moisture refers to the amount of water available to a plant and is held in the soil above PWP and below FC.

The concept of maximum water intake (Em) has helped clarify the controversy between evapotranspiration rates and soil moisture levels. Em is basically dependent on the prevailing soil moisture content, whereas Ep is dependent on meteorological conditions and not soil conditions. Because there is a maximum intake rate at each level of soil moisture, there is always a possibility that this maximum will be less than the potential evapotranspiration rate and hence Ea will be less than Ep. In fact, a plant loses water at the potential rate (Ep) only if Ep is less than Em. This condition is most likely to be satisfied when Ep is low, but will not be satisfied if Em declines sufficiently due to soil dryness. Once Em has fallen below Ep, than Ea will equal Em rather than Ep.

In Figure 4.2, the relationships between relative evapotranspiration rate (Ea/Ep) and soil moisture level, for various levels of Eo, which were incorporated in the plant - soil water simulation model, are presented. These relationships, which are used in the model to estimate P, were based on Denmead and Shaw (1962). Unfortunately, the author did not sight any N.Z. research on which these relationships could be based, so that this is a limitation of the model used in this study.

4.2.4 Evapotranspiration and growth

In this section, the relationships between evapotranspiration and plant growth that were incorporated in the simulation model, are discussed.

(a) Maize

Denmead and Shaw (1962) determined a relationship between soil moisture, climatic conditions and growth rates for maize. Ea and Ep were measured, and days during which Ea was less than Ep were defined as "days below turgor loss point". According to Denmead and Shaw, their measurements of dry matter production suggested that once the soil moisture content was less than turgor loss point the plants virtually ceased to assimilate. Their evidence therefore suggested

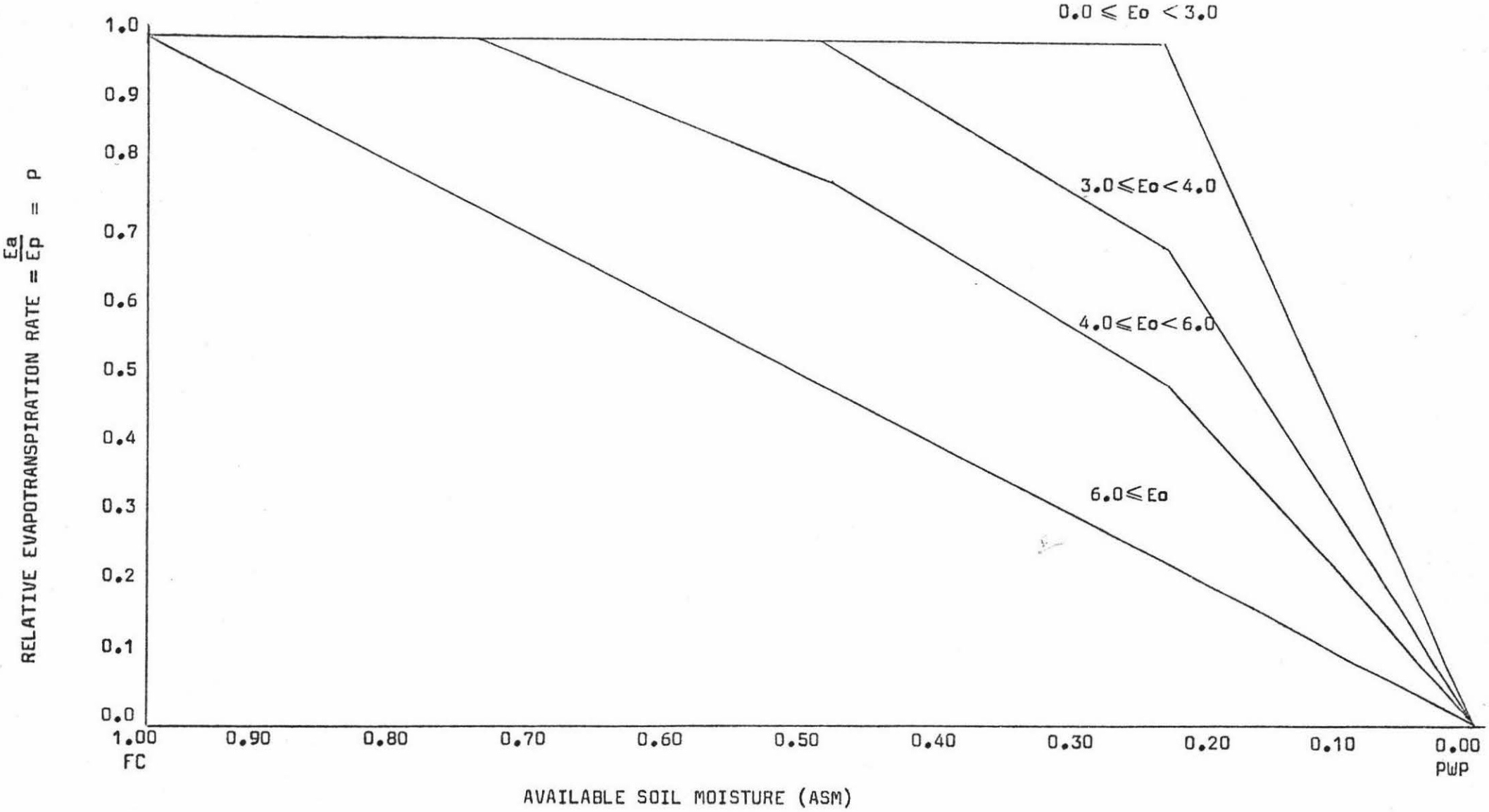

FIGURE 4.2 Relationships between ASM, Eo, soil moisture factor (P)

that maize growth (measured in terms of dry matter) ceases whenever Ep exceeds Em. (5)

Dale and Shaw (1965) determined a relationship between corn yields and number of moisture stress days (defined as days in which Ea was less than Ep). Their research supported the postulation that there is little or no growth during moisture stress days, and that corn yields are directly proportional to the number of non stress days accumulated during corn development. (6)

Research that has supported the growth - no growth effect has been largely carried out in situations of higher rates of Ep than those experienced in the Manawatu. However, of interest is a comparison of the Ep rates measured by Denmead and Shaw (1962) during a five week period commencing just prior to tasselling, with rates estimated (from the simulation model) during the corresponding development stage of maize in the Manawatu (January to February) for the year 1974. The highest rate measured by Denmead and Shaw was 6.4 millimetres per day (compared to 5.3 millimetres per day for the Manawatu) and the average rate was approximately 3.5 millimetres per day (compared to 3.7 millimetres per day for the Manawatu).

The growth - no growth effect was accepted as an approximation of the relationship between evapotranspiration and plant growth for maize (greenfeed, silage and grain) in Chapter 5. Actual growth, on days when P (= Ea/Ep) was equal to 1.0, was assumed to equal an estimated potential daily growth rate (the derivation of which is explained in Chapter 5) and was assumed to be zero when P was less than 1.0.

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(5) A number of other researchers have reported similar relationships between moisture stress and plant growth (in terms of dry matter production). Flinn (1968) has reviewed some of these studies.

(6) Several other researchers have demonstrated that the assumption of zero growth, when Ea is less than Ep, is reasonable for estimating the yield of annual grain crops subjected to moisture stress at some stage of their development.

This same approach was taken by Flinn (1968) for all of the crops he analysed for the Murrumbidgee region of New South Wales, Australia.

(b) Pasture

The relationship between evapotranspiration and growth assumed for pasture, involved multiplication of an estimated potential daily growth rate (the derivation of which is detailed in Chapter 5) by the growth or soil moisture factor P (= Ea/Ep, the relative evapotranspiration rate). The resultant is an estimate of actual daily pasture growth. A similar relationship has been incorporated in the pasture models of Brockington (1969), Freer et al. (1970), Wright (1970), Vickerey and Hedges (1972) and Wright and Baars (1976).

The theoretical basis of this approach has not, as far as the author is aware, been substantiated by plant physiological research. Despite this, the pasture models developed by Brockington and others, as well as that used in this study, have all yielded realistic pasture production results.

Salter and Goode (1967) have extensively reviewed literature on the effects of soil moisture on pasture production and sward composition. However, none of this literature considered the relationship between relative evapotranspiration rate (P) and pasture growth.

4.3 NEW ZEALAND RESEARCH ON PLANT IRRIGATION RESPONSES

In this section, N.Z. research on plant responses to irrigation is briefly discussed. No attempt is made to discuss the quantitative results of this research. Rather, the aim of this section is to discuss briefly the following: (i) locations at which irrigation research has been carried out; (ii) the crops researched; (iii) the limitations of applying real world irrigation research data in economic evaluations of irrigation proposals; (iv) the utility of irrigation systems experimentation and the role of systems modelling.

The majority of past plant irrigation response research in N.Z. has been carried out by the Research Division of the Ministry of Agriculture and Fisheries (M.A.F.) at the Winchmore Irrigation Research Station situated in Mid Canterbury. Research has been centred primarily on pasture responses and has been fairly well documented (e.g. Rickard and Fitzgerald, 1970). Recently, research by the M.A.F. has also been carried out at the Templeton Agricultural Research Station, which is also situated in Mid Canterbury, but is located on a soil type more suitable for intensive cropping. In addition to pasture, other experimental crops have been grown which include lucerne, wheat, barley, garden peas, dwarf beans and maize grain (Annual Reports of Research Division, M.A.F., 1972-73 and 1973-74). Research at Winchmore and Templeton, as well as being concerned with plant irrigation responses, has also involved: (i) the effects of irrigation on pasture composition and animal production; (ii) the interaction effects between irrigation and fertilisers on plant and animal production; and (iii) the development of more efficient systems of irrigation (Annual Report of Research Division, M.A.F., 1973-74).[7]

Detailed pasture responses to irrigation have been researched over approximately 25 years by the Research Division, M.A.F., at the Rukuhia Soil Research Station in Waikato (J.A. Baars, pers.comm.). However, only limited results have been published by Noble (1953), Annett & Noble (1950) and Annett (1951). Also, Weeda (1965) and (1970) has published results from Rukuhia on the effects of cattle grazing severity and frequency, on the production of irrigated pasture plus interaction effects between irrigated pasture (with and without clover) and nitrogen fertiliser. Weeda and During (1974) published the results of a ten year experiment at Rukuhia in which the physical impacts of irrigation, on farmlets carrying dairy beef bulls, were measured.

In addition, limited irrigation research has been carried out at a number of other locations in N.Z. At Ruakura, pasture responses to irrigation have been measured recently in an experiment designed to

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[7] It was not stated in this report from what viewpoint(s) efficiency was being studied, i.e. technical and/or economic.

measure the effects of irrigation and high stocking rates on seasonal dairy production (Hutton, 1974). At Massey University, pasture growth has been measured with and without irrigation, and irrigation plus nitrogen fertiliser, at the No.1 and No.3 Dairy Units over the last three seasons. Also, limited basic plant physiological research on the effects of water stress on plant yield and development, for various crops, has been carried out at Lincoln College (e.g. Dougherty, 1973) and by the Plant Physiology Division of the D.S.I.R.

Vartha (1974) has criticised N.Z. irrigation research on the basis that only limited attention has been given to the strategic use of water between pasture and other crops. Vartha also commented that although physical crop water requirements are being "adequately" researched, systems experimentation in irrigation should be fostered so that the inter-relationships between cropping, pasture and livestock production may be better understood. The author is in full agreement that there is a real need for irrigation systems experimentation to be carried out in N.Z.

The use of irrigation response data obtained from past (real world) irrigation research in N.Z. is of limited utility in economic evaluations of irrigation proposals and in analysing inter- and intra-seasonal water allocation problems, because: (i) although for pasture, and to some extent for other forage crops, total dry matter response data (monthly and seasonal) have been fairly well documented, no attempt has been made to derive growth rate functions. Similarly, for the various cash crops researched, no attempt has been made to derive growth rate functions; (ii) limited data appears to have been recorded on soil moisture levels during the irrigation season; and (iii) research has been confined to a small number of locations and hence the response data obtained is directly applicable only to crops experimented with, the irrigation strategy used, the soil types and the climatic conditions of the research areas, and for the years the research was conducted.

The method used in this study (which can be described as systems modelling) of using mathematical models in irrigation systems experimentation, sets out a methodology which the author believes has

advantages over experimentation with real world irrigation systems (via. field trials). The author is not suggesting here that systems modelling should replace irrigation field experiments, as field experimentation will still be necessary to provide essential data to construct and test (validate) the models. The systems modelling methodology provides a means for generating plant irrigation response data for a wide range of irrigation and grazing management (for forage crops) strategies and for a wide range of localities (including localities for which no field experimental data are available) over, if desired, long periods of time for which relevant climatological data are available. This response data can then be used, also within a systems modelling framework, for evaluating the economics of irrigation proposals, and for providing information to aid in: (i) defining irrigation treatments for field experiments; and (ii) farm management decision making problems concerning inter- and intra-seasonal allocations of irrigation water (as is illustrated in Chapters 6 and 7). As Baars et al. (1976, in press) have stated, it is likely that conclusions regarding the most profitable allocation of irrigation water can only be reached using systems modelling.

CHAPTER 5

THE SIMULATION MODEL

5.1 INTRODUCTION

The plant - soil water simulation model that was applied in this study, is discussed in Chapter 5. The model was adapted from one developed by Flinn (1968) and was programmed for operation on a Burroughs 6700 computer. Following a description of the model, testing and validation of it are discussed. Experimentation with the model and a summary of the results are outlined, followed by a discussion on the limitations of the model. Finally, possible applications of plant - soil water simulation models in the evaluation of irrigation systems, are further elaborated on.

5.2 DESCRIPTION OF THE MODEL

A diagrammatic illustration of the model is shown in Figure 5.1. The model can be seen to have three components: a soil moisture component; a pasture growth component; and a maize component.

5.2.1 Soil Moisture component

This component of the model was adapted by Dr A. Wright from a model developed by Flinn (1968). It is also similar to models used by Brockington (1969) and Wright and Baars (1976).

This component simulates soil moisture conditions in the root zone, on a daily basis, using a water budgeting technique. Daily rainfall and open-pan evaporation data provide the input

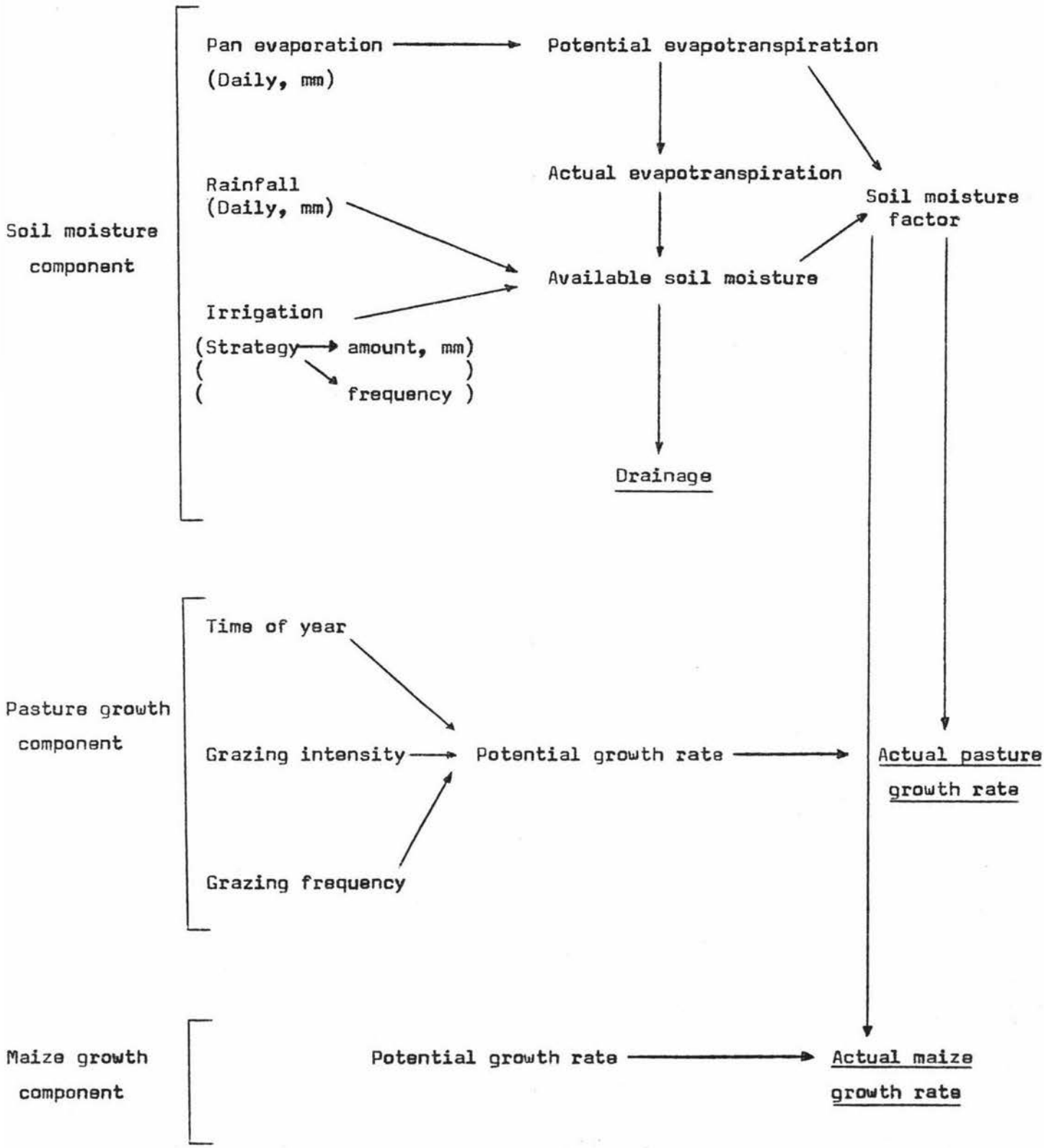

FIGURE 5.1 Diagrammatic illustration of the simulation model

when the Penman method for calculating evapotranspiration is used (as it was in this study).[1] The model can be run with or without irrigation. It was programmed so that various types of irrigation strategies could be evaluated.

The procedure for estimating the soil moisture content in the root zone is basically simple. At the end of any day (t), the level of soil moisture (SM_t) is estimated by subtracting the amount of water lost by evapotranspiration (Ea_t), adding the amount of effective rainfall (R_t), and irrigation (I_t), since the previous day. Any surplus moisture, i.e. drainage during day t (D_t), is also estimated (it is the amount of soil moisture above FC). The procedure can be represented as:

$$SM_t = SM_{t-1} - Ea_t - D_t + R_t + I_t$$

Subject to $PWP \leq SM_t \leq FC$

SM_t then becomes the soil moisture level at the start of the next day.

The soil was assumed to have two layers in relation to moisture holding capacity. These layers were defined on the basis of plant root distribution. The root depths assumed for pasture and maize, and the assumed soil moisture holding capacities, were presented in Table 4.2.

5.2.2 Pasture growth component

A set of relationships, in which potential daily pasture growth was assumed to be a function of the amount of pasture present (which is also dependent on grazing intensity and frequency), form the agronomic basis of this component. Average temperatures and non-limiting soil moisture were also assumed. There are 12 quadratic

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[1] The model has an option for estimating evapotranspiration using the Thornthwaite method, which requires daily rainfall, and daily maximum and minimum temperatures, as inputs. The Penman method was thought to be more accurate for the system modelled (D.Bowler, pers.comm.).

relationships (which were assumed to pass through the origin), one defined for the mid-point of each month. They were estimated by A. Wright and J. Baars (pers.comm.). Potential growth rates for intermediate days are obtained by linear interpolation. The theoretical basis for this treatment of potential pasture growth has been described by Wright and Baars (1976).

The method used to estimate actual pasture growth, from potential growth and P, was described in Section 4.2.4.

5.2.3 Maize growth component

Separate maize greenfeed and maize grain components were defined. Maize silage growth was derived from the maize grain component. The maize crop factors (F) were presented in Section 4.2.1, and in Section 4.2.4 the relationship between maize growth and the soil moisture factor (P) was described.

The theoretical basis for the treatment of a constant potential growth rate of maize greenfeed was provided by Edmeades (1972). The growth model can be represented as:

$$TY = \sum_{m=1}^{3} d_m \, PG$$

where TY is the total greenfeed yield in kg DM/ha.

d_m is the number of days of growth (days when Ea = Ep) in month m, where m represents Nov., Dec., or Jan.

PG is the potential growth rate (constant) in kg DM/ha/day (= total potential yield/92).

The work of Denmead and Shaw (1960) provided the theoretical basis of the maize grain model. Based on this paper, moisture stress yield reductions were obtained. These reductions were weighted to account for local (Manawatu) development timings (averaged for KC3, W415 and PX610 varieties). Weighting factors

were obtained from Menalda and Kerr (1973), and Edmeades (1972). The yield reduction factors used are presented in Table 5.1.

TABLE 5.1 Weighted yield reduction factors for maize grain in the Manawatu

Month	Weighted factors
Nov.	11
Dec.	17
Jan.	53
Feb.	7
Mar.	7
Apr.	5
May - July	0
	100

The maize grain growth model used can be represented as:

$$TY = \sum_{m=1}^{6} \frac{d_m}{t_m} W_m \; PY \qquad (5.1)$$

where TY is the total yield in bu/ac

d_m is the number of days of growth (days when $E_a = E_p$) in month m, where m represents any month from Nov. to Apr.

t_m is the number of days in month m

W_m is the weight assigned to month m (Table 5.1)

PY is the potential annual yield (bu/ac)

The potential yields of maize greenfeed and grain can be specified at any level.

Maize silage yields were estimated from grain yields according to the relationship (Menalda et al., 1972) :

1 bu/ac grain = 123 kg DM/ha silage (5.2)

5.3 TESTING AND VALIDATION

The model was tested by simulating the years for which dam inflow, pasture production and maize production data were available. The model was run using the meteorological data for the appropriate years as input. Unfortunately, only a limited amount of suitable field data were available for comparative purposes.

The measured inflow of water into the 'No.1 Dam' for the period 12 July to 1 November 1974 was 35,590 cubic metres (Report, Department of Soil Science, Massey Univ., 1975). Inflow into the 'No.1 Dam', estimated by the simulation model for the same period, was 38,164 cubic metres, which represented 106 per cent of the measured inflow. Both measurements accounted for evaporation losses from the dam surface and rainfall input on to the surface.

Pasture production data were not available for the No.4 Dairy Unit. It was noted in Chapter 2 that the No.4 Dairy unit was, at the time of this study, undergoing development. Existing levels of pasture production would therefore not be appropriate in evaluating a long term investment such as an irrigation proposal, at No.4. Present levels of pasture production at the No.1 and No.3 Dairy Units were considered to be more indicative of future production at No.4 (K. Lowe, pers.comm.). Data were used from the No.1 and No.3 Dairy Units, as well as the D.S.I.R. (Palmerston North). Only non-irrigated pasture data were used despite the fact that irrigated pasture data were available for the No.1 Dairy Unit. Insufficient information was available on the amount and frequency of irrigation for the irrigated pasture data to be used to test the model.

The monthly pasture growth rates for the years 1972/73, 1973/74 and the average monthly growth rates for the periods 1967/68 to 1972/73, 1971/72 to 1972/73 are illustrated in Figures 5.2, 5.3, 5.4 and 5.5 respectively. Overall, the model can be seen to predict pasture growth reasonably accurately. For 1973/74, the degree of difference between the simulated and measured growth rates

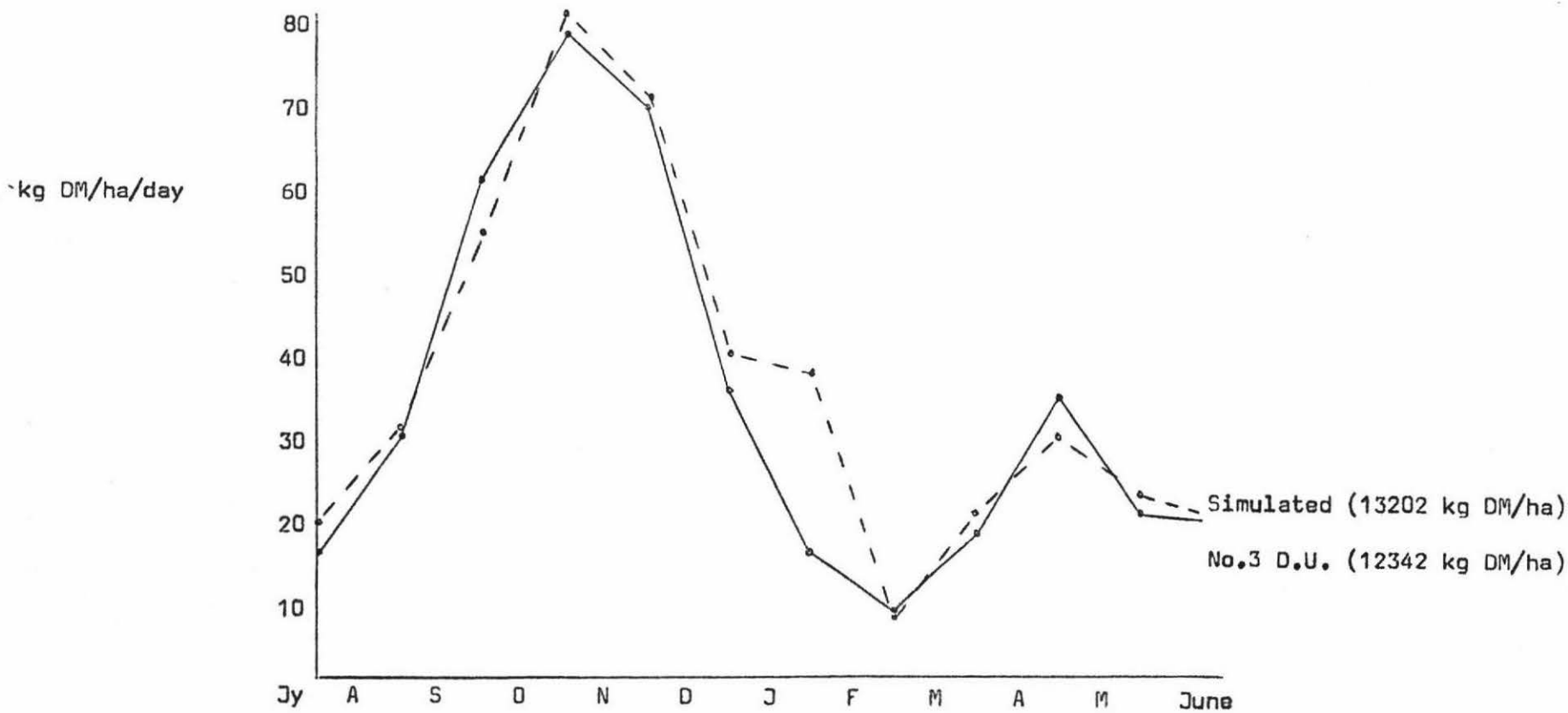

FIGURE 5.2 Pasture Growth Rates 1972/73

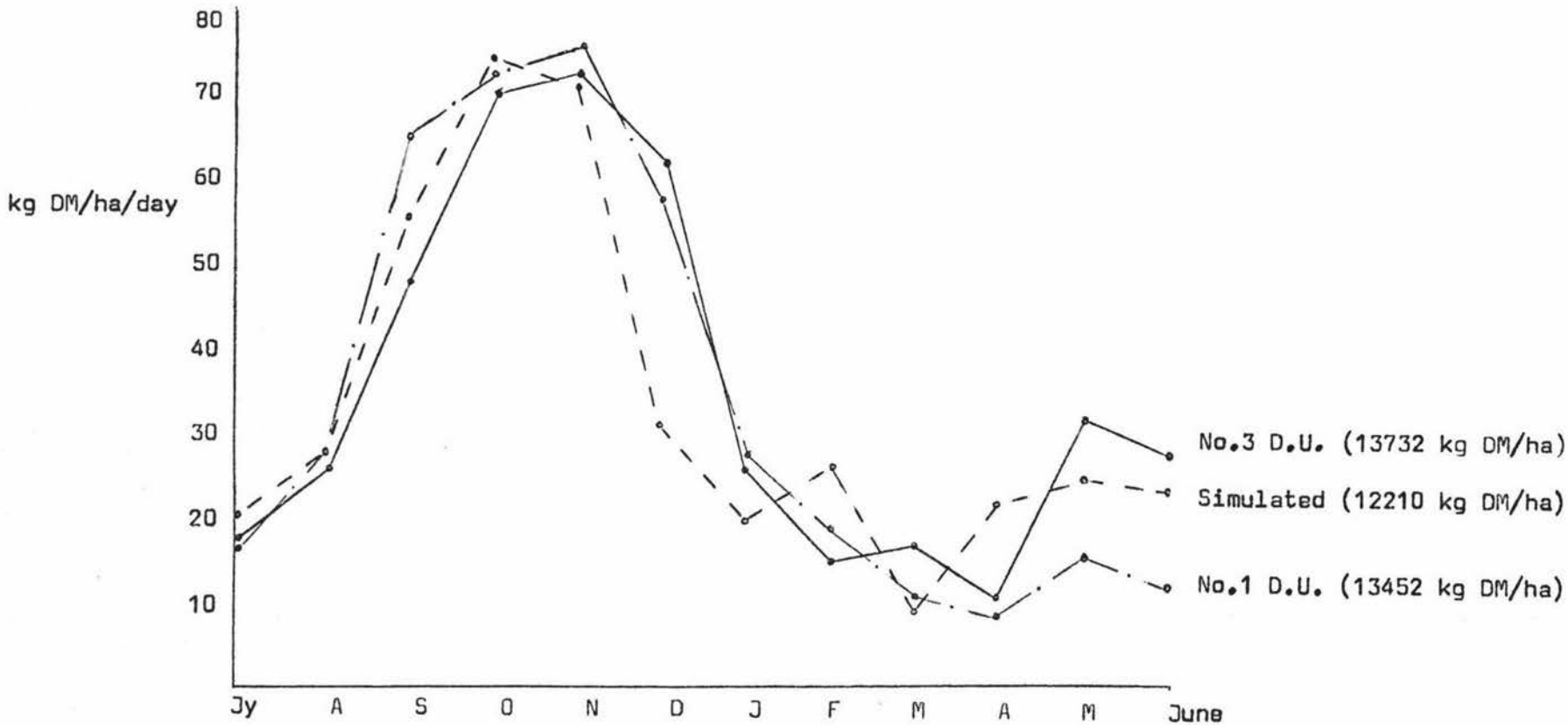

FIGURE 5.3 Pasture Growth Rates 1973/74

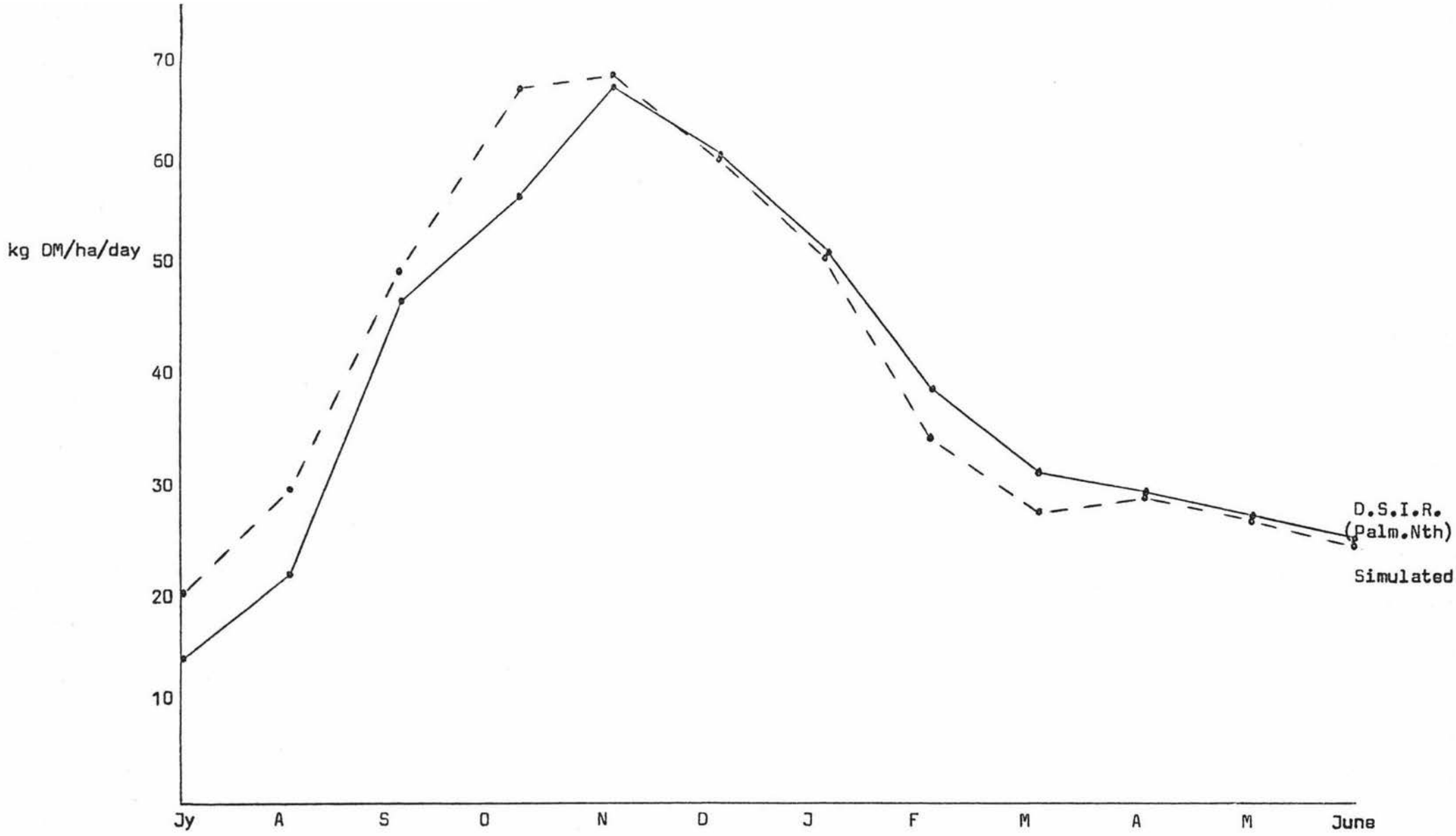

FIGURE 5.4 Pasture Growth Rates ; Average 1967/68 to 1972/73.

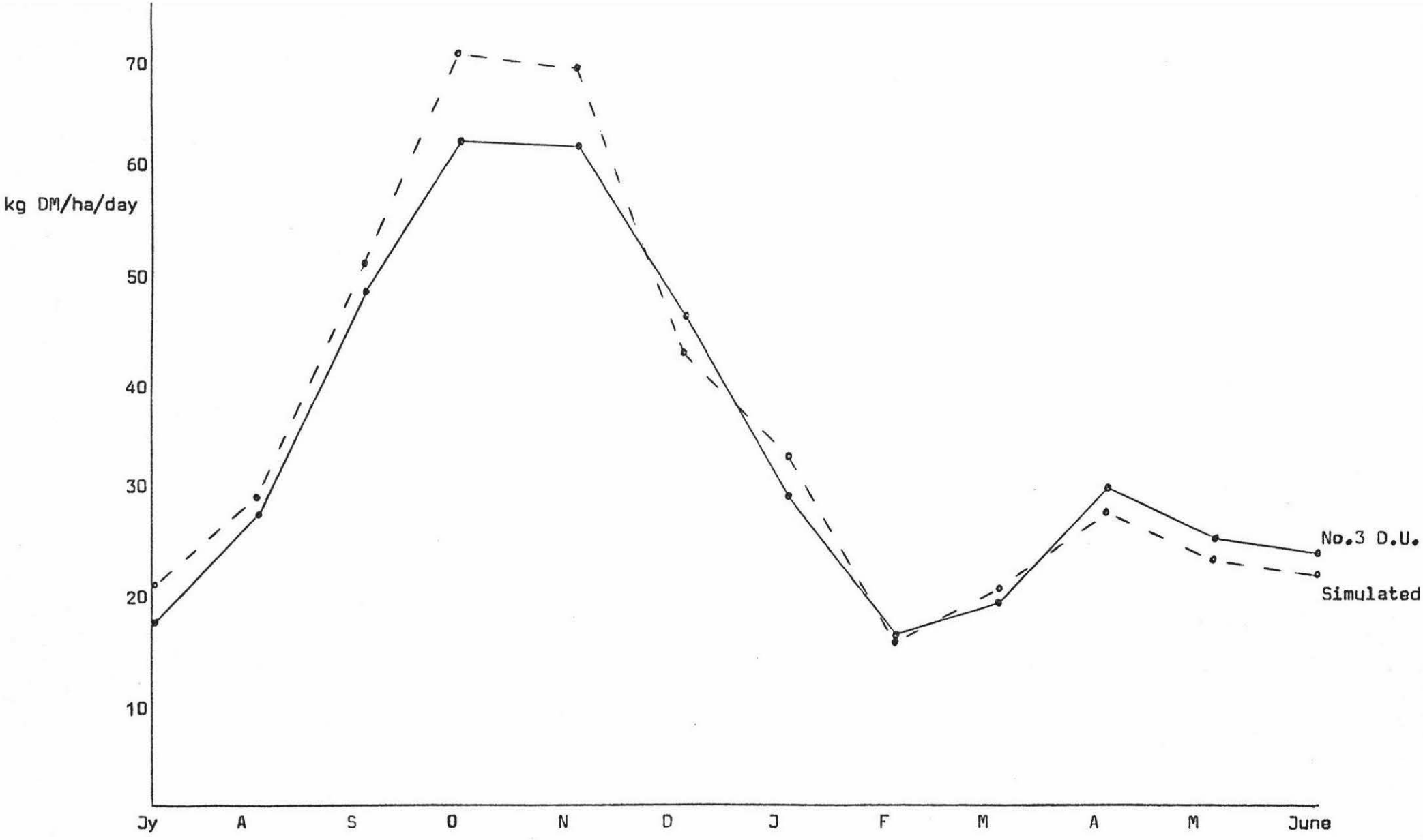

FIGURE 5.5 Pasture Growth Rates ; Average 1971/72 to 1972/73

appears to be no greater than between measured growth rates on the No.1 and No.3 Dairy Units. When averaged over a period of years, the model appears to over-estimate spring production. The same trend was noted by Wright and Baars (1976).

Difficulties were imposed by variable soil types and grazing frequencies and intensities. The No.1 and No.3 Dairy Units, as well as the D.S.I.R. (Palmerston North), are all situated on slightly different soil types. In addition, these soils are also slightly different to the No.4 Dairy Unit soil. Also, there were no data on the grazing frequencies and intensities that accompanied the measured growth rates. For the simulation model, a grazing intensity of 1100 kg DM/ha and a grazing frequency of eight weeks for the months June, July and August, and six weeks for September to May, were assumed (R. Halford pers.comm.).

The only data that could be used satisfactorily to test the maize component was provided by Menalda and Kerr (1973) for 1972/73. Also, only the maize grain and silage models could be tested. Late October sowings of three varieties (PX610, W415 and KC3) non-irrigated, yielded a mean grain yield at the end of March of 7600 kg DM/ha (i.e. 143 bu/acre). The model was run with the relevant meteorological input data to obtain d_m of equation 5.1. By substitution of the measured yield in equation 5.1, the potential yield of maize grain estimated by the model was 173 bu/acre, which for early harvesting is a realistic potential yield. The estimated silage yield of 17,589 kg DM/ha (143 x 123), compared to a measured yield of 16,530 kg DM/ha (Menalda and Kerr, 1973) indicated that the model overestimated the yield by 6 per cent. A potential yield of maize silage of 21,279 kg DM/ha (173 x 123) is also a realistic potential yield.

5.4 EXPERIMENTATION AND RESULTS

Experimentation with the simulation model was carried out primarily to provide pasture growth data (non-irrigated and irrigated) for application in Chapters 6 and 7. Additional experimentation was performed to illustrate other uses of the model.

Fifteen years of historical meteorological input data (daily rainfall and pan evaporation) for the simulation model were prepared. Seven years (1968/69 to 1973/74) of data collected at Massey University and nine years (1958/59 to 1967/68) of data collected at the D.S.I.R. Palmerston North, were used.(2) Weather data have been collected at Massey only since 1968/69 and were used in preference to D.S.I.R. data due to its collection point being closer to the No.4 Dairy Unit than the D.S.I.R.collection point.(3)

5.4.1 Pasture growth relationships applied in Chapters 6 and 7

The 15 years of data were used to simulate monthly pasture growth, non-irrigated and irrigated, for various grazing intensities and frequencies. The results obtained were used to represent long term pasture growth for specified grazing and irrigation management strategies, at the No.4 Dairy Unit. The degree to which these 15 years of historical climatological data are representative of longer term historical data is illustrated in Figure 5.6. In this figure, mean monthly rainfall and monthly standard deviations are plotted for the 15 years historical data used, and for 42 years (1928 to 1969) data for the D.S.I.R., Palmerston North (Met. Ser. Publ. 141, 1973). Of major interest

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(2) A sunken pan evaporimeter was used to measure the evaporation at the D.S.I.R. and a raised pan one was used at Massey. The correction factors used to estimate Eo were 0.86 and 0.69 respectively (as outlined in Section 4.2.1).

(3) In fact, very little discrepancy exists, for the same years, between the Massey and D.S.I.R. data

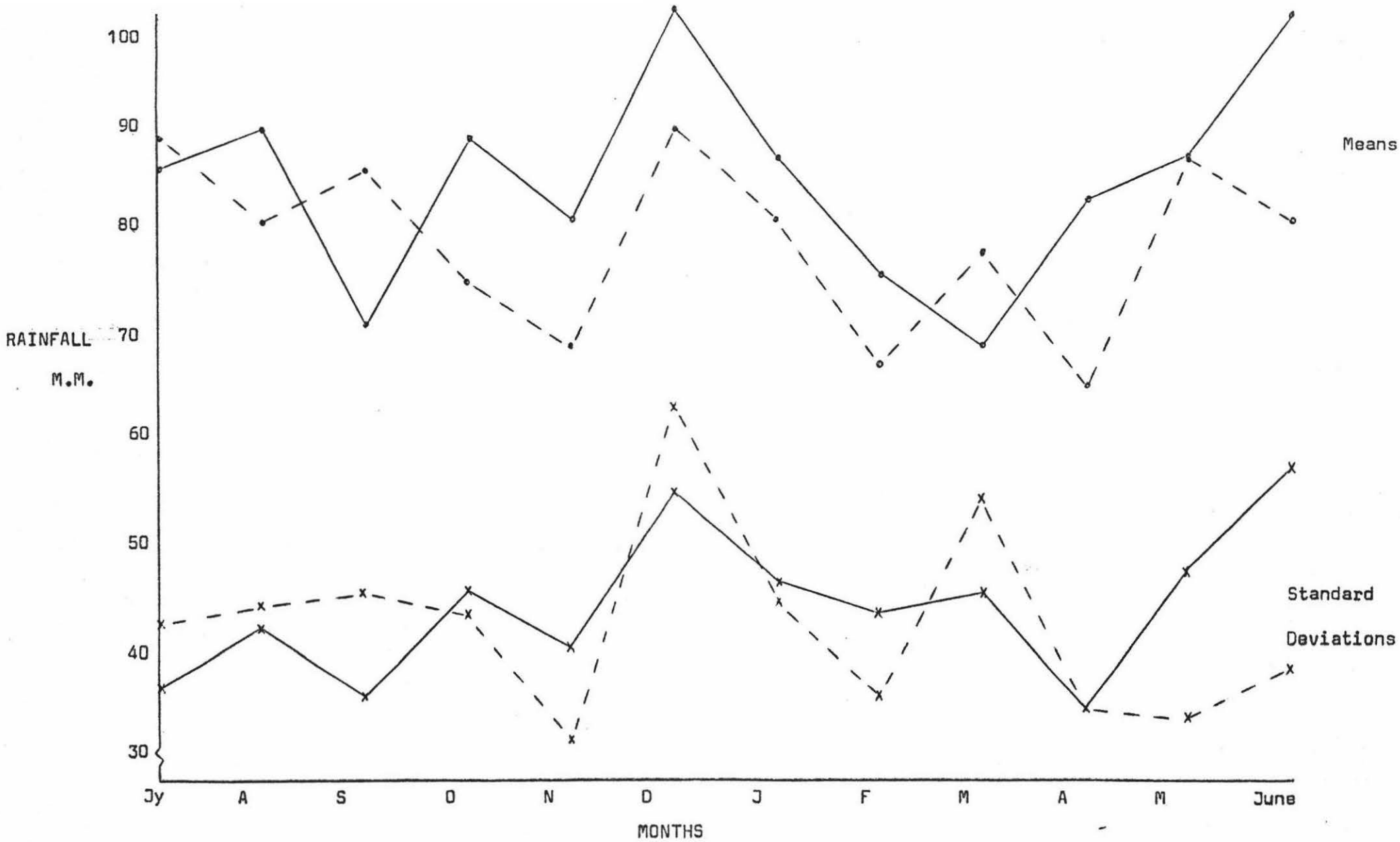

FIGURE 5.6 Monthly Rainfall Means and Standard Deviations

— — 15 years simulation input data

—— 42 years meteorological data

to this study are the comparisons for the months October to April inclusive. The average difference in mean rainfall for these months is 8.0 millimetres lower for the 15 years data compared to the 42 years data. The average monthly standard deviation difference for the same period is 0.5 mm lower for the 15 years data compared to the 42 years data.

Examples of the results obtained are shown in Appendix 2, Table A2.1 for non-irrigated data. This table contains data obtained by averaging the 15 years monthly production data to provide pasture growth relationships for a so-called 'average' year.

A grazing intensity of 1100 kg DM/hectare was assumed as it was considered to be a good average defoliation level (R. Halford pers.comm.).

The irrigation strategy used to generate the irrigated pasture production data involved the application of a net 40 millimetres of water (equivalent to 50 millimetres gross) every 14 days, which is the design strategy of the No.4 Dairy Unit irrigation proposal (R. Clarke, pers. comm.).

The model was programmed so that the 15 years (or any one, or number, of these years) of input data could be used in one run. Each 15 year run took about 16 seconds of computing time. Daily output, and/or monthly output, could be obtained. For each run of the pasture model, the grazing intensity and frequency, and irrigation strategy, were specified. Variation of these management variables therefore required separate runs of the model.

Probability distributions of pasture growth can be derived from the simulation results. In Figure 5.7, non-irrigated and irrigated distributions of annual pasture production, are presented for a grazing frequency and intensity of four weeks and 1100 kg DM/ hectare respectively. These distributions clearly indicate non-irrigated annual pasture production variability over the 15 years and the reduction of this variability for the irrigation

strategy experimented with. Probability distributions like these could have application in a risk analysis of an irrigation proposal, following Bell (1975). These distributions were obtained by smoothing relative frequencies obtained from the simulated data.

5.4.2 Additional applications

(a) Simulation of catchment yield

Catchment yield data are vital in designing a water harvesting irrigation system. Although there is no better substitute than actual catchment yield measurements, very few catchments are gauged because of the time and expense involved.(4) Various methods of estimating catchment yields have been developed, none of which are entirely satisfactory (McConnell, 1968). Generally, the more complex of these (e.g. a simulation water balance method) are applied only on large projects and in other cases, more simple procedures (e.g. applying rules of thumb) are justifiable. Theoretically, a simulation water balance approach (preferably daily) is the most accurate (McConnell, 1968).

The soil moisture component of the simulation model provides a computer programme for the water balance method. One of the outputs of the model is drainage, which is a measure of soil moisture above FC. This parameter can provide the basis of an estimate of water that should theoretically enter the water harvesting dams (via surface runoff and drainage discharge).(5) In Table 5.2, some catchment yield results obtained from the simulation model are presented.

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(4) Catchment yield of the Massey water harvesting project is being gauged. However, apart from the data quoted in Section 5.2, no other data were available at the time of this study.

(5) The model cannot separate these 2 sources of water entering the dams.

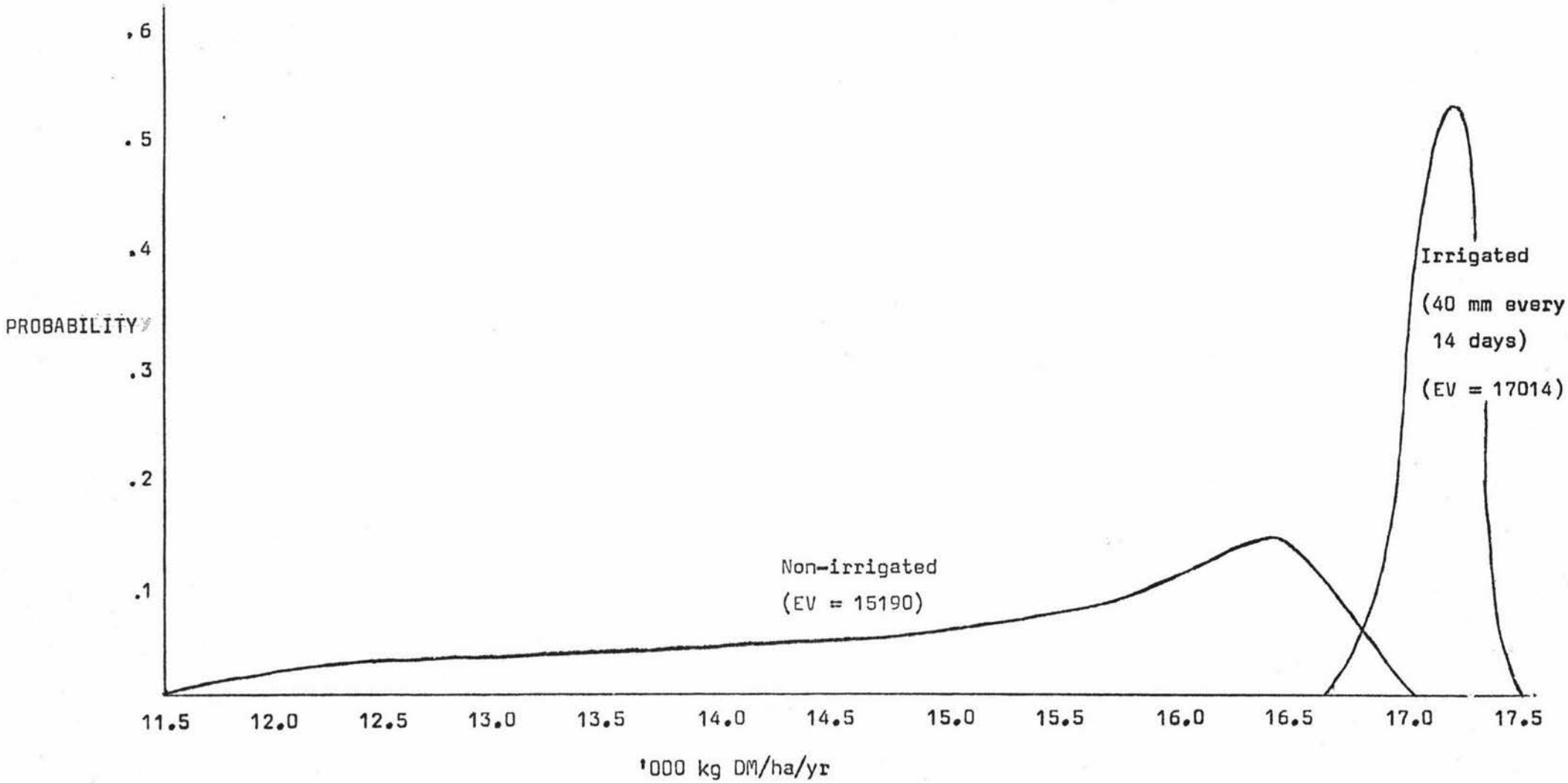

FIGURE 5.7 Probability Distributions of Simulated Annual Pasture Growth (Grazing intensity = 1100 kg DM/ha; Grazing frequency = 4 weeks)

Apart from the use of the DRAINAGE parameter in Section 5.2 for testing the soil moisture component of the model, DRAINAGE results were not used in this study because: (i) only very limited testing and validation of the model results could be carried out, due to a lack of measured data; and (ii) of a lack of knowledge of the soil physics involved in the project area. For example, drainage discharge has been monitored during summer months at soil moisture levels below FC, due probably to soil cracking (D. Bowler pers.comm.).

TABLE 5.2 Monthly Catchment Yield Data (MM), 15 years Simulation, non-irrigated

Month	Mean	Standard Deviation	Range
July	55	37	17 - 131
Aug.	46	40	0 - 151
Sept.	40	41	0 - 115
Oct.	25	29	0 - 95
Nov.	9	12	0 - 27
Dec.	14	23	0 - 73
Jan.	6	16	0 - 55
Feb.	6	15	0 - 54
Mar.	12	33	0 - 126
Apr.	2	5	0 - 20
May	26	29	0 - 97
June	44	35	0 - 128

(b) Simulation of water availability

The simulation model could be used to monitor dam inflow and outflow, and hence dam volume. However, this potential use of the model was not pursued in this study because: (i) a storage behavioural graph was available for the 'No.1 Dam' only; and (ii) of the uncertainty of the soil physics. The model only registers dam inflow after the soil reaches FC and therefore it is unlikely to realistically measure dam inflow during dry periods. A more realistic drainage measure during the summer period could be developed as more knowledge is gained of the system.

Given that dam inflow could be estimated with acceptable accuracy, the model could be easily adapted to monitor dam volume. It could be done on a daily basis. Besides DRAINAGE, the other parameters required are RAINFALL (input) and Eo (estimated by the model as explained in Chapter 4). The only additional refinement of the model would be the incorporation of a dam volume accounting procedure.

The following results, for the 'No.1 Dam' only, were obtained for the defined 'average' and 'dry' years, assuming a catchment area of 12 hectares (Report, Department of Soil Science, Massey, 1975) and an irrigable area of eight hectares.(6) These results are presented to illustrate how the model could be used to monitor dam volume. They also provide a base to test the simplified water constraint included in the LP model in Chapter 6. This simplified constraint incorporated an assumption that, for October to April inclusive, water additions of rainfall on the surfaces of the dams, as well as any surface runoff and tile discharge, would equate water losses due to evaporation from the surfaces.

(i) 'Average' year results:

(1) Evaporation losses from the dam surface exceeded additions by 616 cubic metres;

(2) for the irrigation strategy which applied 50 mm gross (40 mm net) every 14 days, and assuming surface rainfall additions equalled evaporation losses, the results presented in Table 5.3 were obtained: (7)

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(6) This area was estimated as 12/20 x 14 = 8 (rounded to the nearest hectare).

(7) The 'No.1 Dam' was assumed to be full, $\frac{1}{2}$ and $\frac{1}{4}$ full consecutively, for equal time periods. These assumptions are less defendable for the 'dry' year than for the 'average' year.

TABLE 5.3 Dam volume estimates obtained from the simulation model for the 'average' year

Month:	Oct.	N	D	J	F	M	A	M
Water available at start of month (m^3)	15000	14488	12116	10644	7672	4680	3780	3280
Irrigation water applied (m^3)	8000	8000	8000	8000	8000	8000	8000	8000
Drainage with irrigation (m^3)	7488	5628	6528	5028	5008	7100	7500	
Drainage without irrigation (m^3)	2976	1044	1656	684	720	1452	204	
% irrigation water recycled	56	57	61	54	54	71	91	

(ii) 'Dry' year results:

(1) surface evaporation losses exceeded the rainfall additions by 2284 cubic metres, on average. However, no allowance was made for drainage discharge before the soil reached FC (which is likely to be greater in a 'dry' year than in an 'average' year);

(2) for the same irrigation strategy and assumptions concerning dam surface rainfall additions and evaporation losses, as for the 'average' year, the results presented in Table 5.4 were obtained:

TABLE 5.4 Dam volume estimates obtained from the simulation model for the 'dry' year

Month:	Oct.	N	D	J	F	M	A
Water available at start of month (m^3)	15000	8824	5416	-2368			
Irrigation water applied (m^3)	8000	8000	8000	0	0	0	0
Drainage with irrigation (m^3)	1824	4592	216	0	0	0	0
Drainage without irrigation (m^3)	0	0	0	0	0	0	0
% irrigation water recycled	23	57	3				

(c) The determination of irrigation 'needs'

Output from the simulation model can be used in the determination of physical and economic 'needs' for irrigation.

(i) Physical 'needs'

The physical demand for irrigation can be estimated crudely by subtracting rainfall from potential evapotranspiration (Ep), on a monthly basis for example. However, this approach is not sufficiently dynamic and no quantitative account is taken of soil moisture storage. The relationships between rainfall and Ep obtained from the model for the 'average' and 'dry' years are presented in Figure 5.8. The estimated soil moisture deficits (monthly Ep - monthly rainfall) are 28.5 mm (1.1 inches) and 295.4 mm (11.6 inches), for the 'average' and 'dry' years respectively.

The physical 'need' for irrigation is more accurately assessed by a water balance approach, preferably using a daily water balance. The use of daily, and probably even weekly data, would require the use of a computer. It is a more accurate approach than the previous one since it is more dynamic and takes account of soil moisture storage.

Depending on the irrigation strategy(ies) chosen, the demand for irrigation can be determined. If the model is run for a number of years, variability over time in the number of irrigations, amount of water applied and the number of moisture stress days can be determined. For example, the variability of irrigation demand for a single irrigation strategy (irrigation at a 10 mm deficit in the A horizon) simulated for the 15 years are illustrated graphically in the probability distributions presented in Figures 5.9, 5.10 and 5.11. In addition, the irrigation intervals for this strategy are presented in Table 5.5. This information, for various irrigation strategies, could be very useful in planning irrigation systems. The probability distributions were obtained by smoothing relative frequencies obtained from simulated data.

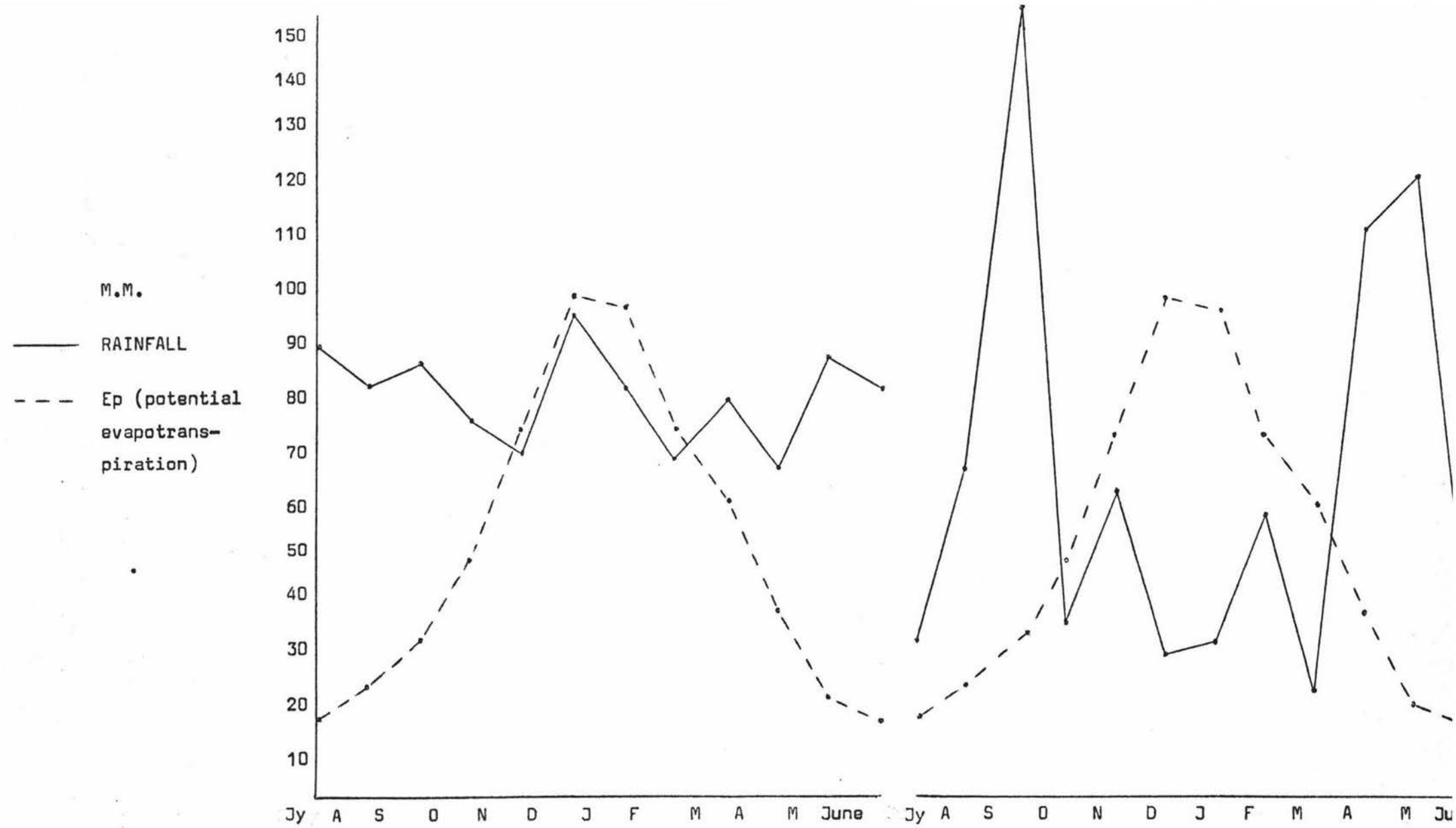

FIGURE 5.8 Monthly Rainfall and Estimated Evapotranspiration (simulation model using Penman's method)

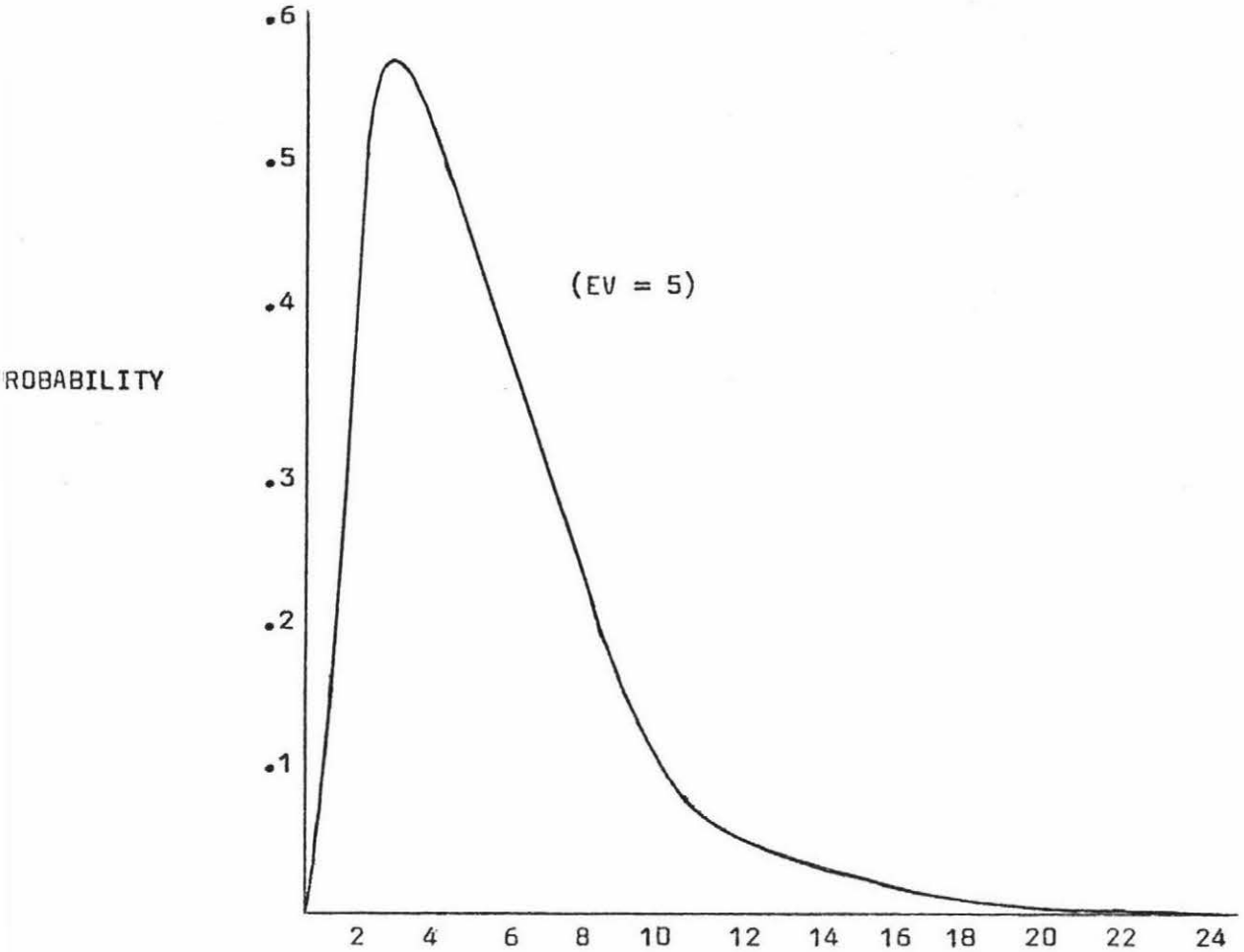

FIGURE 5.9 Probabilities of Moisture Stress (15 yrs data, strategy: dft.10 mm)

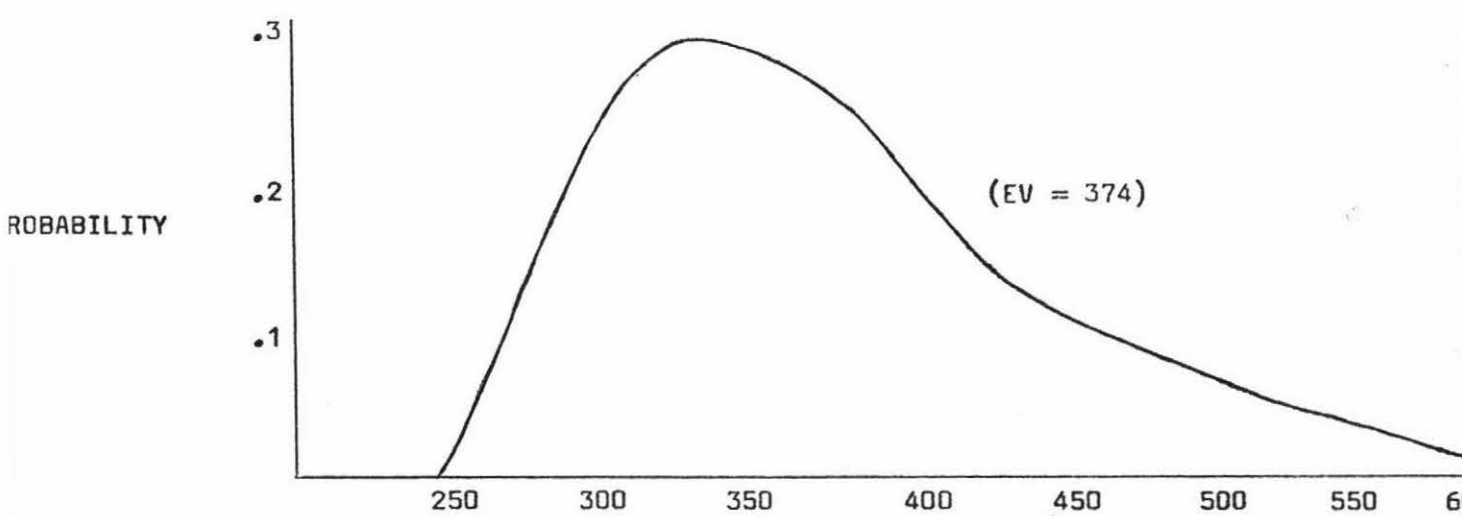

FIGURE 5.10 Probabilities of Water Use (15 yrs data, strategy: dft.10 mm)

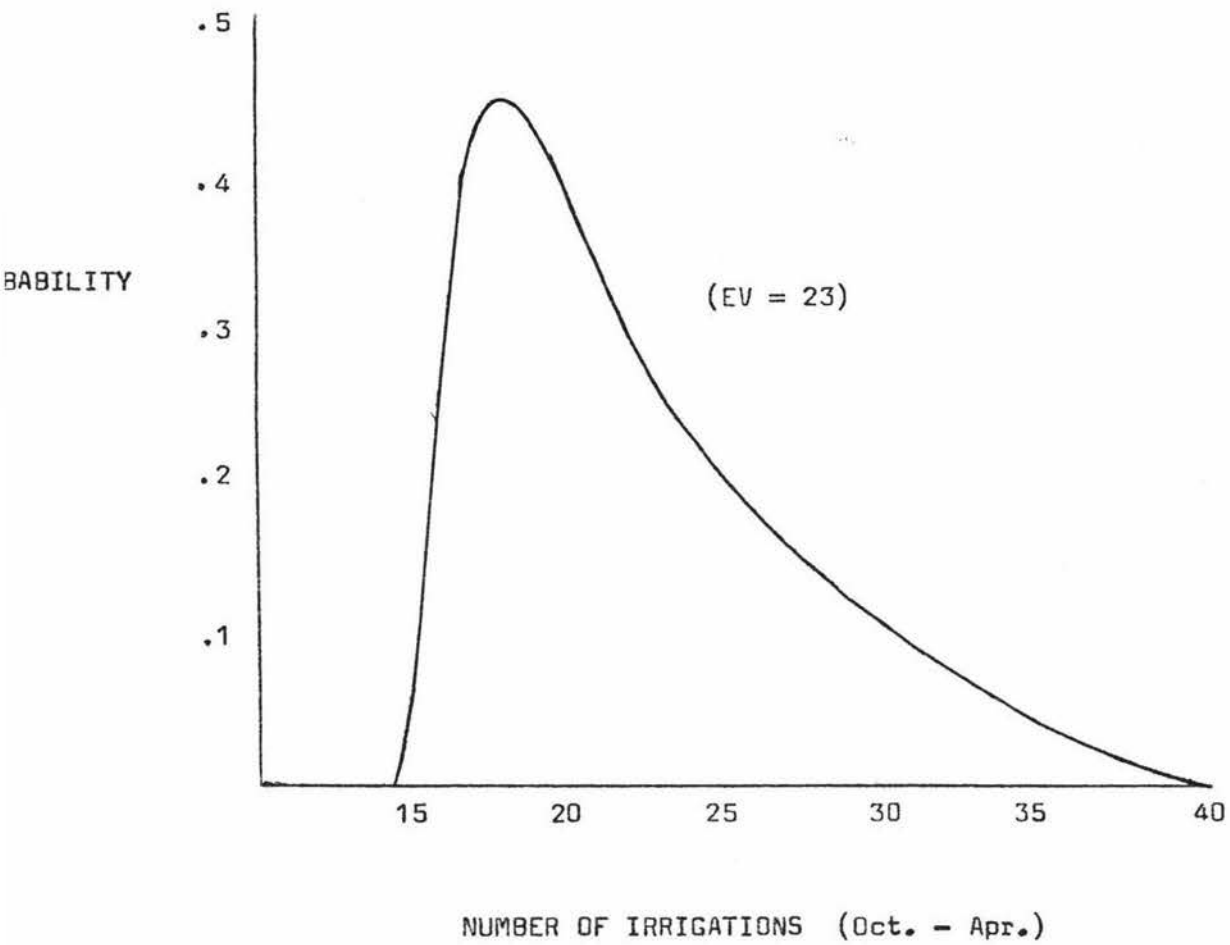

FIGURE 5.11 Probabilities of Irrigations (15 yrs data, strategy: dft.10 m

TABLE 5.5 Irrigation Interval, Days (15 years data, irrigated at a 10 mm deficit)

Month	Mean	Range
October	12	5 - 23
Nov.	10	3 - 29
Dec.	7	3 - 18
Jan.	6	3 - 23
Feb.	6	3 - 16
Mar.	10	3 - 30
Apr.	17	8 - 29

(ii) Economic 'needs'

Output from the simulation model can provide data for application in evaluating economic 'needs' for water. For example, pasture production data from the model were used in this study in normative economic evaluations, which determined (among other things) strategic requirements for water.

(d) Evaluation of irrigation strategies

Four irrigation strategy options were included in the model:

(i) to facilitate irrigation to FC at a specified soil moisture deficit (of the A horizon);
(ii) to facilitate irrigation at a specified A horizon soil moisture deficit, of a specified amount of water less than the deficit;
(iii) to facilitate irrigation to FC on a specified cycle;
(iv) to facilitate irrigation of a specified amount of water, on a specified cycle.

Only strategies (i) and (iv) were experimented with. Summaries of some of the data obtained from these experimentations are presented in Tables 5.6, 5.7 and 5.8.

TABLE 5.6 Strategy (i) - Mean (1959/60 to 1973/74) Monthly Pasture Production (kg DM/ha)[8], varying deficit, net water applied in parentheses (mm)

	10 mm	30 mm	50 mm
Month - Oct.	2281 (30.7)	2278 (9.5)	2270 (0)
Nov.	2297 (53.4)	2283 (31.0)	2233 (14.8)
Dec.	2152 (76.9)	2108 (48.0)	1996 (37.2)
Jan.	1995 (83.1)	1957 (45.6)	1843 (26.0)
Feb.	1465 (62.0)	1441 (38.5)	1364 (29.6)
Mar.	1111 (47.4)	1104 (28.8)	1073 (14.9)
Apr.	839 (19.8)	839 (9.4)	839 (0)
Sub total (non-irrigated = 10191)	12140 (373)	12010 (211)	11618 (123)
Additional production	1949	1819	1427
kg extra DM/10 mm water	52.3	86.3	116.0

TABLE 5.7 Strategy (iv) - Mean (1959/60 to 1973/74) Monthly Pasture Production (kg DM/ha)[8], fixed water application per irrigation, varying cycle length

	40 mm at 7 days	40 mm at 14 days	40 mm at 28 da
Month - Oct.	2281	2280	2273
Nov.	2297	2293	2278
Dec.	2144	2123	2081
Jan.	1996	1968	1899
Feb.	1463	1451	1339
Mar.	1112	1108	1059
Apr.	839	839	838
Sub total	12132	12062	11767
Water applied (mm, net)	1240	640	320
Additional production	1941	1871	1576
kg extra DM/10 mm water	15.7	29.2	49.3

[8] Grazing intensity = 1100 kg DM/ha; Grazing frequency = 3 weeks.

TABLE 5.8 Strategy (iv) - Mean (1959/60 to 1973/74) Monthly Pasture Production (kg DM/ha)[8], fixed irrigation cycle, varying water application per irrigation

	10 mm at 14 days	20 mm at 14 days	40 mm at 14 days	60 mm at 14 days
Month - Oct.	2279	2280	2280	2280
Nov.	2272	2291	2293	2293
Dec.	1985	2101	2123	2125
Jan.	1792	1919	1968	1971
Feb.	1260	1416	1451	1455
Mar.	1012	1091	1108	1108
Apr.	832	834	839	839
Sub total	11432	11932	12062	12071
Water applied (mm, net)	140	280	560	840
Additional production	1241	1741	1871	1880
kg extra DM/ 10 mm water	88.6	62.2	33.4	22.4
- 'dry' year	160.2	139.3	83.8	56.9

The most striking feature of the irrigation strategy experimentation results is that diminishing returns to irrigation water are evident. That is, pasture DM responses to the first few units of water applied are much higher than for consequential units. Thus the model could be used to identify irrigation strategies that economise on water, but reduce DM production only a small amount. This information is particularly useful in situations where limited quantities of irrigation water are available, such as in water harvesting systems. However, information on physical irrigation responses alone is of limited use in evaluating the economics of irrigation systems.

The use of simulation models for scheduling irrigations has also been demonstrated by Jensen (1969), Jensen and Robb (1970) Lembke and Jones (1972) and Baars et al. (1976, in press).

(e) Maize growth simulations

The maize component was simulated for the 15 years, non-irrigated and irrigated (40 mm net every 14 days). The data presented in Table 5.9 were obtained which can be applied in the maize grain and silage models described in Section 5.2.3.

TABLE 5.9 Days of Maize Growth

Month	'Average' year (15 year means)	'Dry' year (1973/74 data)	Increments due to irrigation	
			'Average'	'Dry'
Nov.	29	29	1	1
Dec.	28	21	1	5
Jan.	27	17	2	10
Feb.	18	15	7	7
Mar.	20	5	10	25
Apr.	28	25	2	5

5.5 LIMITATIONS OF THE SIMULATION MODEL

The validity, and hence the limitations, of a model must be judged in relation to the purpose for which it was developed. In this study, the major purpose of the model was to provide non-irrigated and irrigated pasture growth data. The limitations of the pasture growth component are discussed below. Some of the limitations associated with the soil moisture and maize growth components of the model have already been discussed previously in this chapter in sufficient depth.

Realism of the pasture growth data generated from the model was limited for a number of reasons. Firstly, a fixed level of grazing intensity was assumed. This could be varied in the model very easily. However, the incorporation of more than one grazing intensity in the LP model (Chapter 6) would have considerably increased the complexity of the LP model. This therefore, is not a limitation of the pasture production model *per se*.

Secondly, the potential pasture growth curves are largely subjective. Thirdly, use of the pasture growth factor, or soil moisture factor (P), to estimate actual growth by modification of potential growth, has not been experimentally substantiated. Fourthly, constant pasture composition and soil fertility levels, and average temperatures, were assumed for simplicity in the estimation of the potential pasture growth curves. Wright and Baars (1976) have incorporated temperature variation effects in their pasture model. Lastly, the representativeness of the pasture production data generated was restricted. Pasture production of a whole farm system modelled (as for example, in Chapter 6) is represented by a single hectare. More accurate, although much more complex, approaches would involve varying the timings of the management variables (e.g. days on which grazing and irrigation occurred), preferably on a random basis, or alternatively modelling each paddock of a farm system separately. However, in a dairy grazing system, as is modelled in Chapter 6, these two alternatives would be very complex, as break-grazing is usually practised,where only parts of a paddock are grazed at any one time.

Despite the limitations associated with the pasture growth data provided by the simulation model, they were used in this study in Chapters 6 and 7. In fact, these data were considered to be more suitable for this study than data that could be obtained by alternative means (e.g. purely subjectively, or based on field data obtained over a very limited time horizon and subject to a limited number of grazing and irrigation management strategies).

5.6 POSSIBLE APPLICATIONS OF PLANT-SOIL WATER SIMULATION MODELS IN ECONOMIC EVALUATIONS OF IRRIGATION SYSTEMS

It was indicated at the end of Chapter 4 and throughout Chapter 5 that plant-soil water simulation models, provided they have been validated with respect to the problem(s) being analysed, have a number of useful applications in economic evaluations of irrigation systems, especially water harvesting systems. These applications are briefly summarised below under two headings: firstly, project design and project evaluation applications in ex ante economic evaluations carried out prior to a decision being made on proposal implementation; secondly, in irrigation project operation and control, in economic/farm management evaluations following the implementation of a proposal. Before summarising these applications (some of which overlap the two headings), it must be indicated, that, generally the use of a plant-soil water simulation model would only be warranted in the evaluation of a large-scale irrigation proposal involving a number of farms. However, the use of a 'skeleton' model which could be easily adapted for different locations, could be used in the evaluation of small proposals, even single-farm proposals. In fact, the simulation model used in this study can be considered a 'skeleton' model.

5.6.1 Project design and project evaluation (ex ante economic evaluations)

In the design and evaluation of all types of irrigation proposals, a plant-soil water model could be used to generate plant-irrigation response functions for various irrigation strategies. There are numerous examples of this application, including: Flinn (1968); Brockington (1969); Jensen (1969); Jensen and Robb (1970); Lembke and Jones (1972); and Baars et al. (1976, in press). However, the generation and analysis of only physical data (as presented for example, in Tables 5.6, 5.7 and 5.8) are of restricted usefulness in economic evaluations of grazing - irrigation systems. Here data must be used in a grazing system model, as is done in Chapter 6, to derive useful economic (and physical) 'needs' for irrigation.

In the evaluation of water harvesting irrigation proposals, a plant-soil water simulation model may also be used in project design (as well as in project operation and control) to estimate catchment water yields and to monitor water availability.

5.6.2 Project operation and control (following proposal implementation)

Plant-soil water models may be used in the operation and control of an irrigation project. They may be used in aiding to extrapolate limited field experimental results to a variety of management systems used on farms (Wright and Baars, 1976). They may also be used to simulate irrigated plant growth rates for sites for which only non-irrigated field trials have been carried out. Also, a further use could be to simulate non-irrigated and irrigated plant growth rates for areas not covered by field trials. These three uses could also be applied in project design and project evaluation. They can be used in conjunction with optimising techniques (for example, LP) to determine most profitable inter- and intra-seasonal allocations of water. This use is explored in Chapter 6. Baars et al. (1976, in press), have also suggested that plant-soil water simulation models, applied to farm systems, may assist in bridging the "communication gap" thought to exist in N.Z. between scientists, farm advisory officers and farmers.

CHAPTER 6

THE GRAZING SYSTEM MODEL

6.1 INTRODUCTION

In Chapter 6, a normative study of an irrigation-grazing system, represented by the Massey No.4 Dairy Unit, is documented. Attention was centred on the efficient utilisation of a limited quantity of irrigation water and since the allocation of water within a grazing system was of concern, it was considered to be desirable to construct a model that incorporated all of the important components of a grazing system.

Initially, the approaches that have been used to model grazing systems are briefly outlined. The dairy production grazing system model that was formulated to normatively evaluate the No.4 Dairy Unit irrigation proposal is described and then the data and assumptions that were used to formulate the model are outlined in detail. The results obtained by experimenting with the model are presented and finally the limitations of the model are discussed.

6.2 GRAZING SYSTEM MODELLING APPROACHES

Studies that have employed analytical methods to investigate grazing management have been reviewed by Dillion and Burley (1961). Problems that were encountered in these studies, through using analytical methods, were outlined.

Published simulation studies of grazing management problems have been reviewed by Wright (1970). However, despite the potential of simulation for incorporating elements of uncertainty associated with the real world, usually only one stochastic parameter (normally associated with climate) has been included in these simulation studies. Wright suggested that for most farming regions, there is usually only one climatic factor that has a major effect on a grazing system.

Pollard (1972) developed a deterministic LP model of a dairy production grazing system. Pollard discussed at some length the use of simulation and LP as grazing system modelling techniques and the problems associated with each. He concluded that because of the stochastic nature of the inter-relationships involved in a grazing system, simulation models are likely to be the most appropriate for grazing system modelling studies, but that any "first approach" systems modelling exercise will be largely deterministic in nature based on 'average' conditions. In this situation, LP offers a comprehensive modelling framework.

A deterministic LP approach similar to Pollard's was taken by McRae (1975) in modelling a beef production grazing system.

In this study, simulation and LP were used in tandem to model a grazing system.

6.3 A DESCRIPTION OF THE GRAZING SYSTEM MODEL

A dairy production grazing system was modelled in this study. It was considered to be composed of four components: viz. pasture production; pasture availability; animal intake; and animal production.

The pasture production component was modelled using simulation. Details of the simulation model were presented in Chapters 4 and 5.

The other components were modelled using LP. The LP model was formulated by the author for operation on a Burroughs 6700 computer using the Tempo LP package.

A grazing area of 162 hectares, equal to the productive area of the No.4 Dairy Unit, was modelled. The ryegrass/clover pasture [1] was assumed to be grazed by Jersey Friesian cross dairy stock. Lactating and dry cows were assumed to be fed on the farm at all times, but calves were assumed to be grazed out from the beginning of April and returned 12 months later (as yearlings).

As well as non-irrigated pasture grazed *in situ*, the following feed management policies were incorporated in the model: (i) irrigated pasture (the area of which was constrained) for grazing and/or hay and silage production; (ii) the production and feeding of non-irrigated pasture hay and silage; and (iii) the purchase of hay and meal.[2] Unfortunately time available did not permit the incorporation of maize (greenfeed, silage and grain) activities in the model.

Three stocking rates were considered: 2.471 lactating cows per hectare (or 1.0 cow per acre) plus replacement stock; 3.707 lactating cows per hectare (or 1.5 cows per acre) plus replacement stock; and 4.942 lactating cows per hectare (or 2.0 cows per acre) plus replacement stock. These stocking rates are referred to as 1.0, 1.5 and 2.0 respectively. Only stable situations based on the three stocking rates were considered and no attempt was made to consider the organisation of resources required, or the profitability, of a farm development programme.

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(1) As noted in Chap.2, at the time of writing this thesis the No.4 Dairy Unit was undergoing a development programme. Approximately 45% of the farm was productive ryegrass/clover pasture with the balance being browntop dominant. It was assumed that the farm was fully developed, in an attempt to determine the long term economic impact of irrigation.

(2) The model allowed meal to be fed (when profitable) to lactating cows and/or calves only.

For the LP submodel, each month of the year was divided into two equal time periods.(3) This level of breakdown was considered necessary for satisfactory experimentation with grazing frequency and irrigation. The incorporation of shorter time intervals, particularly during the irrigation season, may have been desirable. However, time available did not permit this.

For each year modelled (e.g. an 'average' year) the LP submodel consisted of a matrix of 397 columns and 110 rows. However, a considerable number of the matrix coefficients remained the same irrespective of the year modelled.

The animal production component was basically very simple. This was necessitated also by a time constraint. Pollard (1972) incorporated a much more complex (but more realistic) animal production component in his grazing system model. Although Pollard's animal component could have been used in this study, this possibility was not explored.

6.4 DATA AND ASSUMPTIONS USED IN FORMULATING THE GRAZING SYSTEM MODEL

6.4.1 Pasture growth component

Factors known to affect pasture growth include pasture composition, soil type, climatic parameters, soil nutrient availability, frequency and intensity of grazing, and treading. All of these factors, apart from two climatic parameters (viz. rainfall and E_o) and grazing frequency and intensity, were assumed *ceteris parabus*. Details of the pasture growth model were presented in Chapters 4 and 5.

Output from the pasture growth component of the simulation model provided the basic pasture growth data for the grazing system model. Substantial modification of these data for use in the grazing

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(3) Period lengths were rounded to the nearest whole day.

model was required. This modification is described below.

(a) Specification of pasture growth relationships used in the grazing model

Relationships between monthly pasture 'available for grazing'[4] in kg DM/hectare, and grazing frequency in weeks, provided the basic data. These data were generated by simulating pasture growth with 15 years of historical rainfall and pan evaporation data. Monthly figures were averaged and these were used for the 'average' year. Monthly figures for the 1973/74 year were used for the 'dry' year. Non-irrigated pasture production data were generated by suppressing the irrigation options of the simulation model. Irrigated pasture data were generated for the one irrigation strategy, viz. to irrigate a net 40 mm of water every 14 days during the months October to April inclusive. These data for the 'average' year only are presented in Appendix 2, in which the non-irrigated and irrigated data are presented in Tables A2.1 and A2.2 respectively.

These data obtained from the simulation model were then rearranged. Monthly pasture productions were proportioned into weekly periods, assuming each month had four weeks, to derive relationships between DM production and length of spell following grazing. These relationships are presented in Appendix 2 in Tables A2.3 (non-irrigated) and A2.4 (irrigated) for the 'average' year, and in Tables A2.5 (non-irrigated) and A2.6 (irrigated) for the 'dry' year. Growth curves, from the time of grazing at weekly intervals, were derived from the data contained in these tables. These curves were then used to estimate pasture 'available for grazing' (in kg DM/hectare) for the 24 periods[5] of a year following specified grazing spells. The curves were not altered for experimentation with different stocking rates, since Campbell (1969) has observed that, under similar systems of grazing management, increased stocking rates had little effect on total annual DM production.

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(4) Pasture 'available for grazing' is equal to the total pasture grown over a period of time adjusted for the pasture left following grazings (which was set at 1100 kg DM/ha).

(5) A period was defined as one half of a month, rounded to the nearest whole day.

Grazing frequency and intensity, as well as frequency and intensity of irrigation, have been observed to have a delayed effect on pasture productivity by changing pasture composition (e.g. Brougham, 1960). It could be argued that since the purpose of constructing a grazing system model in this study was to determine the long term impact of irrigation, pasture production changes due to pasture composition changes should have been incorporated. However, incorporation of these effects would have involved considerable expense in terms of model complexity and again time available prevented this. Also, it is doubtful if in fact suitable experimental time series data on pasture production/composition are available. Variability in pasture production due to variations in rainfall and Eo, and variations in grazing and irrigation frequences only, were incorporated into the pasture production model. To the extent that these parameters do not account for variations in pasture production, the model will not represent the real world situation.

6.4.2 Pasture availability component

Estimating pasture 'available for grazing' in a dairy production grazing system is complicated, as different areas of a farm are grazed at different points in time and may be subject to different frequencies and intensities of grazing.

Since a large number of potential grazing management systems exist, LP with its built-in optimising procedure, provides an efficient modelling technique for evaluating the impact of irrigation in grazing systems. Also, the LP approach provides information on grazing and irrigation management that should accompany changes in stocking rate and irrigation water availability, if pasture growth is to be efficiently used and economic results estimated by the use of output from the grazing system model are to be approached in practice. This information on grazing and irrigation management could be useful in farm management analysis and farm advisory work in an area where the economic results of a positive ex ante evaluation of an irrigation proposal are significantly lower than the economic results of a normative ex ante evaluation based on optimal, or near optimal (sub-optimal), resource use.

(a) The pasture production model

As detailed in Section 6.4.1(a), the basic monthly pasture growth/grazing frequency relationships were generated by the simulation model and these relationships were modified to derive estimates of pasture available for grazing in each period following specified spells from grazing.

In Appendix 3, Figure A3.1, a summary version of the LP matrix is presented. The pasture production sub-matrix consists of 78 PASTURE activities (P001,...., P078) and 50 constraints (F01, ...,F24, Z00, L01, ..., L24, T00).

The PASTURE activities (P001, ..., P078) each represent one hectare of pasture spelled for a specific period of time following grazing to the assumed intensity of 1100 kg DM/ha. Grazing was assumed to occur at the midpoint of a period. The pasture spelling lengths following grazing in each period were restricted within the ranges presented in Table 6.1. The amounts of pasture produced and available for grazing (kg DM/ha) attributed to each PASTURE activity were obtained from Tables A2.3 and A2.5 for the 'average' and 'dry' years respectively, with the use of a chart, part of which is illustrated in Figure A2.1. The constraints of the pasture production model are detailed in Appendix 3.

The IRRIGATED pasture activities (I001, ..., I148), are alternative land use activities, which represent one hectare of pasture irrigated at least once with a net application of 40 mm. Irrigation was assumed to occur at the midpoint of a period and irrigation was not allowed less than two weeks prior to a grazing.

The constraints (A01,..., A20) limit the irrigable area as in practice, the area irrigated from the water harvesting dams on the No.4 Dairy Unit will be limited to an area surrounding the dams (as illustrated in Figure 2.2). The amounts of pasture produced, in kg DM/hectare, attributed to each IRRIGATED pasture activity, were obtained from Tables A2.4 and A2.6 for the 'average' and 'dry' years respectively, with the use of a chart, part of which is illustrated in Figure A2.2.

TABLE 6.1 Restrictions imposed on the spelling lengths following grazing of pasture in each period

Period	Minimum length of spell (weeks)	Maximum length of spell (weeks)
Jy 1	4.4	10.9
2	4.4	11.0
A 1	2.1	8.7
2	2.3	8.7
S 1	2.0	6.4
2	2.4	6.9
O 1	2.1	6.4
2	2.3	6.6
N 1	2.0	6.4
2	2.3	6.7
D 1	2.1	6.6
2	2.3	6.6
J 1	2.1	6.3
2	2.1	6.6
F 1	2.0	6.3
2	2.1	6.6
M 1	2.1	6.4
2	2.3	6.6
A 1	2.0	6.4
2	2.3	6.7
M 1	2.1	6.4
2	2.3	6.6
June 1	4.3	10.9
2	4.4	11.1

To account for the assumed differences between the feed quality of irrigated pasture and non-irrigated pasture, the units of pasture production for the IRRIGATED pasture activities were converted into kg DM/hectare, non-irrigated pasture equivalents, using the relevant feed quality factors given in Table 6.3. All feedstuffs in

the LP matrix were expressed in these units (i.e. kg DM/hectare, non-irrigated pasture equivalents) for convenience, as all feed demands (ANIMAL activities) were expressed in the same units.

The pasture conservation activities (SILAGE and HAY production activities) included in the grazing system model are presented in Table A2.7. The closing and harvesting of pasture conservation areas were assumed to occur at the midpoint of a period. The same assumptions regarding the timing of irrigation, as for the IRRIGATED pasture activities, were made for the irrigated SILAGE and HAY production activities. The irrigated conservation activities differ with respect to the number and timing of irrigations.

The method used to incorporate the SILAGE and HAY production activities into the LP matrix was similar to that used for the non-irrigated and irrigated pasture activities. The only differences were that the DM harvested, corrected for DM losses and expressed in terms of kg DM/hectare of non-irrigated pasture equivalents, (to account for the feed quality of conserved pasture according to the relevant conversion factors detailed in Section 6.4.4), enter the silage and hay reconciliation rows (constraints S00 and H00 respectively), and the activities (A001, ..., A024) and (B001, ..., B024) allow silage and hay respectively to be fed in any period. Losses in DM were assumed to occur during the silage and hay making operations and during storage. These losses were assumed to be 10% of the DM harvested for silage and 15% for hay. They follow those used by Pollard (1972) and assume a high technical efficiency in the production processes. The yields of silage and hay at each harvest were obtained from Tables A2.3, A2.4, A2.5 and A2.6. It was assumed that 1100 kg DM/hectare of pasture was left following harvesting.

A HAY BUY activity (G000), which allowed hay to be purchased, and a HAY SELL activity (K000), were also included in the LP matrix. Respectively, they add and subtract from the hay reconciliation row (H00).

A MEAL BUY activity (J00) was also included in the LP model. Purchased meal is added to the meal reconciliation row (M00) and the activities (M001, ..., M024) allow meal to be fed in any period where meal feeding is profitable.

Constraints (U01, ..., U24) were imposed on supplementary feeding. Meal was the only supplement that could be fed to calves. Similarly, pasture hay and silage were the only supplements fed to yearlings and dry cows. No constraints were imposed on the amounts of these supplements that could be fed to calves, yearlings and dry cows. Constraints were placed on the amount of supplementary hay and silage that could be fed to lactating cows. Details relating to the feeding of hay and silage to lactating cows are given in Section 6.4.4. Meal fed to lactating cows was not constrained. The MEAL BUY activity, besides offering an alternative source of DM for lactating cows and calves, was included in addition to the HAY BUY activity to ensure feed demands were met in all periods, especially during any extreme feed shortage period at high stocking rates.

6.4.3 Animal intake component

The approach used in this study with respect to the utilisation of pasture, is essentially the same as that used by Pollard (1972). It was a highly simplified attempt to include the more important factors affecting pasture utilisation.

A fixed grazing pressure, indicated by a constant amount of pasture left following grazings (viz. 1100 kg DM/ha), was assumed when the pasture growth data was simulated.

The combined effects of trampling and faecal contamination were assumed to be constant at all three stocking rates and to reduce pasture availability (the pasture DM production figures in Appendix 2) by 10% at each grazing.

The assumptions made concerning the amount of 'available feed' [6] utilised by replacement stock, dry cows and lactating cows, for the 'average' and 'dry' years, are presented in Table 6.2.

TABLE 6.2 Assumed percentage of 'available feed' utilised by stock at three stocking rates

Stocking rate (lactating cows/ acre)	Replacement stock and dry cows	Lactating cows			
		Jy,A,S,O	N,D	J,F,M	A,May
1.0	90	75	80	85	80
1.5	90	85	88	90	88
2.0	90	90	90	90	90

This represented an attempt to approximate utilisation losses that are likely to occur at the three stocking rates throughout the year because of variation in per cow feed availability levels.

In the animal production model, DM feed demands required in each period to produce a specified level of annual butterfat production, were increased accordingly to take account of the utilisation losses specified in Table 6.2. The same utilisation losses were assumed for hay and silage. Meal was assumed to be completely utilised.

6.4.4 Animal production component

Sections 6.4.1, 6.4.2 and 6.4.3 dealt with the production and intake of pasture DM under grazing conditions. Section 6.4.4 deals with DM intake in each period, assessed in terms of nutrient content, and a simplified animal production model which described the relationship between nutrient intake and animal production used in this study.

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[6] 'Available feed' henceforth in this chapter refers to the amount of pasture available at a grazing (i.e. pasture grown per hectare from the previous grazing) less 10% to account for faecal contamination and trampling losses.

Feed quality was measured in this study in terms of available energy. Available energy accounts for gaseous, faecal and urinal losses of energy, and is termed the metabolic energy content. The units of available energy used were megajoules of metabolisable energy (MJ ME) per kg of DM.

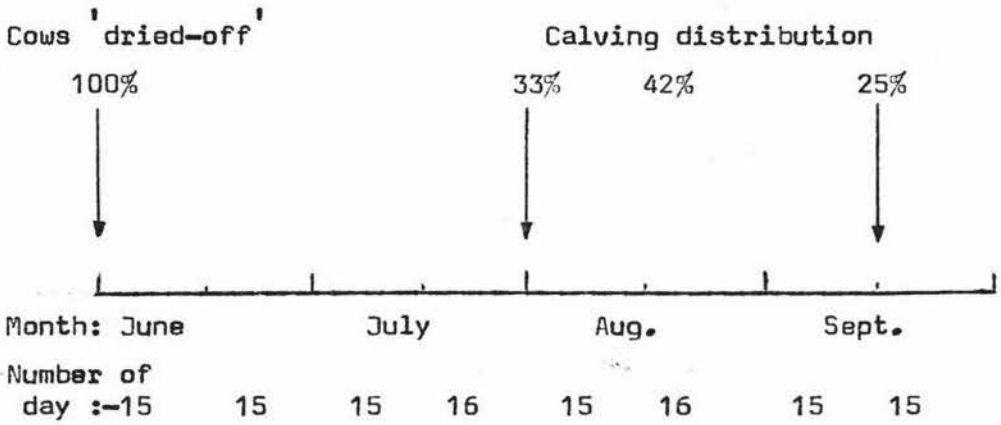
The major factors that influence pasture quality are: length of spell, grazing management and season. However, data limitations under N.Z. conditions exist as to the effects these factors actually have on pasture quality. The approach that was used in this study to incorporate pasture quality differences involved the use of the pasture quality estimates used by Pollard (1972, Table 5.1, P.45). These estimates, converted into metric units, are presented in Table 6.3.

TABLE 6.3 Pasture quality estimates assumed

Period	Pasture quality (MJ ME/kg DM)
July, A, S, O	11.81
N, D	11.08
J, F	10.15
M, A	10.61
M, June	11.08

For irrigated pasture, it was assumed that the quality was 11.81 MJ ME/kg DM for November to April inclusive (K. Bartlett, pers. comm.).

An average lactation length of 290 days was assumed, with calving extending from 31 July to 15 September and the whole herd being dried-off on 31 May. The calving distribution and length of the dry period for different proportions of the herd are given in Figure 6.1.



	% of dry cows	Length of dry period (days)
	33	61
Dry cow	42	76
distribution	25	92

(Weighted average dry period = 75 days)

FIGURE 6.1 Calving and dry period distributions

As noted previously, a simplified animal production model was used in this study. A fixed level of butterfat production per cow was assumed (viz. 145 kg butterfat/annum) and the feed demands in each period of the year required to achieve this level of butterfat production and assumed liveweight changes, were specified. Feed demands in terms of kg DM/cow/day were obtained from Hutton (1975). These data were then converted to MJ ME/cow/day using conversion factors given by Coop (1965). The dry cow energy requirements obtained primarily from Hutton (1975), and converted into MJ ME, are presented in Table 6.4.

TABLE 6.4 Dry cow energy requirements

Weeks pre-calving	Total daily requirement (MJ ME/cow/day)
8 - 16	42.9
4 - 8	48.0
2 - 4	58.2*
0 - 2	63.0*

Dry cow feed demands for an 'average' cow in the herd for each period were derived from Figure 6.1 and Table 6.4 in terms of MJ ME/cow/day. DM requirements, expressed in non-irrigated pasture equivalents, were obtained by dividing by the corresponding figures in Table 6.3. The DM demands for the dry cows for the relevant periods of the year, adjusted for utilisation losses (assumed to be 10%, Table 6.2), are presented in Table 6.5.

TABLE 6.5 Dry cow feed demands (kg DM, non-irrigated pasture equivalents/cow/day)

Period	Feed demand
June 1	67.1
2	70.3
July 1	70.7
2	86.1
Aug. 1	54.2
2	21.9
Sept.1	22.2

Lactating cow feed demands for an 'average' cow in the herd in each period were derived from Figure 6.2 and Table 6.6 (which was based on Hutton, 1975) in units of MJ ME/cow/day.

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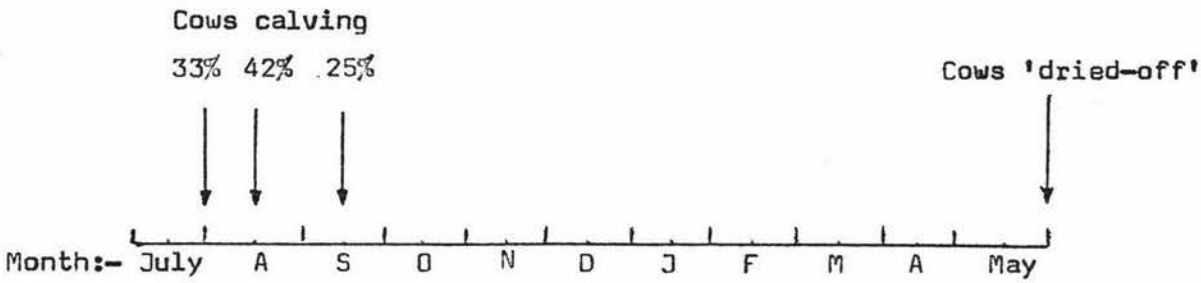
* Figures based on Hutton (1975) for 1 month pre-calving and partitioned into 0 - 2 and 2 - 4 weeks based on Pollard (1972, Table 5.2, P.47).



	% of lactating cows	Length of lactation (days)
	33	304
Assumed lactation	42	289
period distribution	25	273

(Weighted average lactation = 290 days)

FIGURE 6.2 Calving distribution and lactation period

TABLE 6.6 Lactating cow energy requirements

Weeks post calving	Total daily requirement (MJ ME/cow/day)
0 - 4	135.0
4 - 8	154.0
8 - 12	150.0
12 - 16	137.5
16 - 20	121.2
20 - 24	106.0
24 - 28	94.7
28 - 32	83.3
32 - 36	79.5
36 - 40	75.7

DM requirements for the lactating cows, expressed in non-irrigated pasture equivalents, were then derived by dividing by the corresponding figures in Table 6.3. The DM demands per lactating cow at the three stocking rates, for the relevant periods of the year, are presented in Table 6.7.

TABLE 6.7 Lactating cow feed demands (kg DM, non-irrigated pasture equivalents/cow/day)

Period	Feed demand			
	Unadjusted for utilisation losses	Adjusted for utilisation losses (based on Table 6.2)		
		1.0	1.5	2.0
Aug. 1	56.6	75.5	66.6	63.9
2	137.2	182.9	161.4	152.4
Sept.1	179.4	239.2	211.1	199.3
2	189.6	252.8	223.1	210.7
Oct. 1	193.9	258.5	228.1	215.4
2	204.6	272.8	240.7	227.3
Nov. 1	197.5	246.9	224.4	219.4
2	190.4	238.0	216.4	211.6
Dec. 1	178.9	223.6	203.3	198.8
2	180.9	226.1	205.6	201.0
Jan. 1	171.7	202.0	190.8	190.8
2	173.1	203.7	192.3	192.3
Feb. 1	141.1	166.0	156.8	156.8
2	134.5	158.2	149.4	149.4
Mar. 1	128.6	151.3	142.9	142.9
2	129.9	152.8	144.3	144.3
Apr. 1	116.0	145.0	131.8	128.9
2	113.7	142.1	129.2	126.3
May 1	105.9	132.4	120.3	117.7
2	110.7	138.4	125.8	123.0

Only one replacement stock management alternative was included in the model. This alternative involved feeding calves on the No.4 Dairy Unit until the end of April and then grazing them out until the end of the following April. From Figure 6.1, Figure 6.3 was prepared.

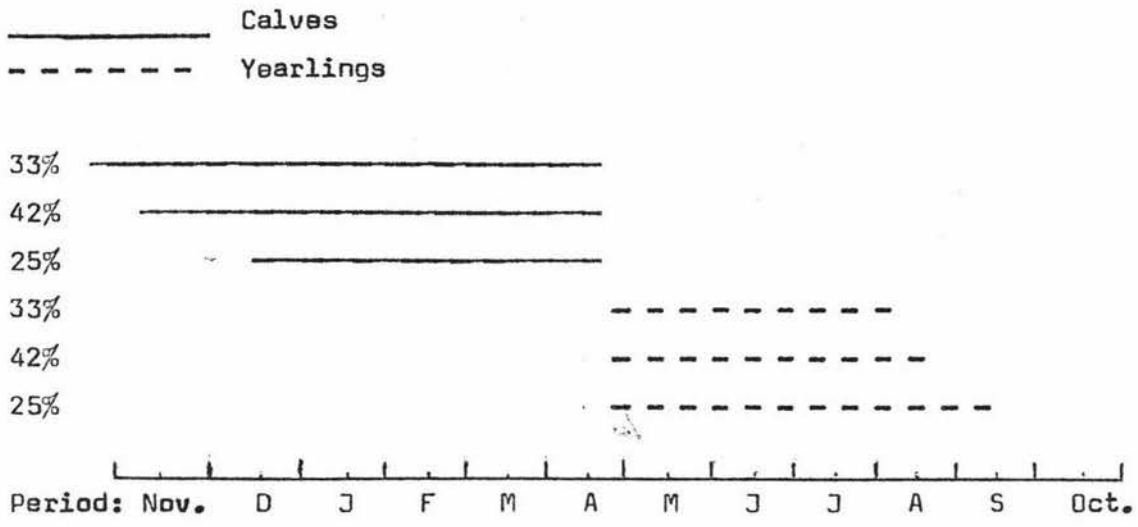


FIGURE 6.3 Feed distribution of replacement stock

Based primarily on Lowe et al. (1975, P.6), Table 6.8 was prepared. From Figure 6.3, Table 6.8, Table 6.2 (to account for utilisation losses) and Table 6.3 (to account for feed quality), Table 6.9 was prepared.

The per hectare total feed demands for each animal activity (as labelled), at the three stocking rates, are presented in Table 6.10. This table was derived from Tables 6.5, 6.7 and 6.9.

As noted previously, the constraints (U01, ..., U24) were imposed on the feeding of supplements. Meal was the only supplement that could be fed to calves, and pasture hay and silage were the only supplements that could be fed to dry cows up to 100% of rations. Ruakura research has shown that with palatable supplementary crops (digestibility 67% or more) approximately 90 to 100% of milk produced on a sole diet of good quality pasture can be obtained with a 25% crop to 75% pasture diet (Research Adviser, No.15, 1975). Following the results of this research, supplementary feeding of pasture hay and silage was limited to between 0 and 25% of the diet of lactating cows in the animal production component. Further, pasture silage was assumed to contain 9.0 MJ ME/kg DM and pasture hay 8.0 MJ ME/kg DM (Research Adviser, No.15, 1975). Feed intake

TABLE 6.8 Replacement stock energy requirements

Age (months)	Daily requirement (MJ ME/animal/day)	Daily requirement x .25 (7)
4	21.2	5.3
5	24.7	6.2
6	25.4	6.4
7	26.5	6.6
8	31.2	7.8
9	33.6	8.4
10	37.9	9.5
11	39.4	9.9
12	41.4	10.4
13	43.4	10.9
14	63.0	15.8
15	65.0	16.3
16	68.1	17.0
17	45.1	11.3
18	43.5	10.9
19	40.9	10.2
20	44.3	11.1
21	61.8	15.5
22	69.1	17.3
23	64.9	16.2
23.5	58.2	14.6
24	63.0	15.8

levels for all stock were assumed to be unaffected by supplementary feeding and the percentage utilisation of pasture silage and hay at the three stocking rates (Table 6.2) were assumed to be the same as for pasture.

(7) 25% replacements were assumed (K. Lowe, pers.comm.).

TABLE 6.9 Replacement stock feed demands (kg DM, non-irrigated pasture equivalents /lactating cow/day).

Period	Calves	Yearlings
July 1		22.5
2		23.2
Aug. 1		15.1
2		5.5
Sept.1		5.6
Nov. 1	2.6	
2	6.0	
Dec. 1	6.4	
2	9.6	
Jan. 1	9.9	
2	11.1	
Feb. 1	9.8	
2	10.0	
Mar. 1	10.9	
2	12.6	
Apr. 1	12.1	
2	13.8	
May 1		22.6
2		25.4
June 1		24.8
2		24.8

TABLE 6.10 Animal activities - per hectare feed demands

(kg DM, non-irrigated pasture equivalents, per hectare)

Stocking rate:		1.0				1.5				2.0			
Activity name:		L001	D001	C001	Y001	L002	D002	C002	Y002	L003	D003	C003	Y003
		Lact. cows	Dry cows	Clvs	Ylgs	Lact. cows	Dry cows	Clvs	Ylgs	Lact. cows	Dry cows	Clvs	Ylgs
July	1		174.7		55.6		262.1		83.4		349.4		111.2
	2		212.8		57.3		319.2		86.0		425.5		114.7
A	1	186.6	133.9		37.3	246.9	200.9		56.0	315.8	267.9		74.6
	2	451.9	54.1		13.6	598.3	81.2		20.4	753.2	108.2		27.2
S	1	591.1	54.9		13.8	782.5	82.3		20.8	984.9	109.7		27.7
	2	624.7				827.0				1041.3			
O	1	638.8				845.6				1064.5			
	2	674.1				892.3				1123.3			
N	1	610.1		6.4		831.9		9.6		1084.3		12.8	
	2	588.1		14.8		802.2		22.2		1045.7		29.7	
D	1	552.5		15.8		753.6		23.7		982.5		31.6	
	2	558.7		23.7		762.2		35.6		993.3		47.4	
J	1	499.1		24.5		707.3		36.7		942.9		48.9	
	2	503.3		27.4		712.9		41.1		950.3		54.9	
F	1	410.2		24.2		581.3		36.3		774.9		48.4	
	2	390.9		24.7		553.8		37.1		738.3		49.4	
M	1	373.9		26.9		529.7		40.4		706.2		53.9	
	2	377.6		31.1		534.9		46.7		713.1		62.3	
A	1	358.3		29.9		488.6		44.9		637.0		59.8	
	2	351.1		34.1		478.9		51.2		624.2		68.2	
M	1	327.2			55.8	446.0			83.8	581.7			111.7
	2	342.0			62.8	466.3			94.2	607.9			125.5
June	1		165.8		61.3		248.7		91.9		331.6		122.6
	2		173.7		61.3		260.6		91.9		347.4		122.6

6.4.5 The gross margins used

A summary of the gross margins used in this study is presented in Table 6.11. Details relating to the derivation of these gross margins are given in Appendix 4.

TABLE 6.11 Summary of the gross margins

Activities	Gross margin (COO) - $
PASTURE activities (non-irrigated)	0.00
IRRIGATED pasture activities	14.76/ha/irrigation
SILAGE production activities (non-irrigated)	45.50/ha
SILAGE production activities (irrigated)	45.50/ha plus irrigation costs at $14.76/ha/irrigation
HAY production activities (non-irrigated)	19.25/ha plus 0.0166/kg DM
HAY production activities (irrigated)	19.25/ha plus 0.0166/kg DM plus irrigation costs at $14.76/ha/irrigation
HAY BUY activity - mean price	50.00/tonne total weight or 1.20/bale
- high price	1000.00/tonne total weight
HAY SELL activity	37.68/tonne total weight or 1.00/bale less additional fertiliser cost
MEAL BUY activity - mean price	130.00/tonne total weight
- high price	2600.00/tonne total weight
ANIMAL activities 1.0	391.01/ha
1.5	586.61/ha
2.0	782.03/ha

6.5 EXPERIMENTATION AND RESULTS

The grazing system model was designed primarily to determine maximised annual TGM's (total gross margins) at each stocking rate, with and without irrigation. However, the model can also be used to determine the irrigation and grazing management strategies inherent in optimal solutions.

The model was used in a normative sense, i.e. it was used to provide estimates of what economic results could be achieved if scarce resources were used optimally (subject to the constraints and assumptions included in the model).

Experimentation with the LP model was, unfortunately, limited by available time. However, sufficient experimentation was performed to illustrate the type of results that can be obtained from the model.

6.5.1 Experimentation

At each stocking rate, the model was run using the pasture production data for the 'average' and 'dry' years. For each set of pasture production data, animal production and price and cost parameters were set at their mean (or 'most likely') levels for three water constraint situations: (i) no irrigation (WOO = 0); (ii) a constrained maximum level of water (WOO $\leq$ 40,000 m^3); and (iii) water unconstrained (WOO $\geq$ 0). The same runs were also repeated, but with the prices of purchased hay and meal set at artificially 'high' levels (see Table 6.11), in attempts to test the impact of irrigation for 'self sufficient' feeding plans (but to also ensure feasible solutions could be attained). This experimentation involved 36 runs of the LP model. These included 18 for each set of pasture data and 12 runs at each stocking rate.

6.5.2 Results

A summary of the results obtained from experimentation with the LP model are presented in Table 6.12. The results that were obtained at the 'high' prices of purchased feed are not presented because: (i) the purchase of feed at a stocking rate of 1.0 was not profitable in the 'average' and 'dry' years, even at mean prices; and (ii) at the 1.5 and 2.0 stocking rates, the purchase of feed was necessary even at 'high' feed prices (although the feed management plans were different than at mean prices) in both years,

with and without irrigation. The purchase of feed was necessary for the management plans to remain feasible. The economics of irrigation in 'self sufficient' plans at stocking rates of 1.5 and 2.0 could not therefore be tested. As expected, TGM losses at 'high' feed prices were large, due to the 'high' purchased feed prices, (e.g. at the stocking rate of 2.0 and 40,000 m^3 of water used, losses were estimated to be $1,012,483 and $2,202,160 for the 'average' and 'dry' years respectively).

(a) Economic results

'Most likely' estimates of annual TGM for the 'average' and 'dry' years are given in Table 6.12. These figures take account of variable costs only.

In Figure 6.4, the estimated relationships between TGM, stocking rate and water, for both years are illustrated. The highest TGM's were estimated, for both the non-irrigated and irrigated situations, at stocking rates of 1.5 and 1.0 for the 'average' and 'dry' years respectively. As expected, the economic impacts of irrigation (measured by difference in TGM of comparable irrigated and non-irrigated situations) were higher for the 'dry' than for the 'average' year. Also, when the amount of water was not constrained, more water was used in the 'dry' year than in the 'average' year. The economic response to irrigation was estimated to be negative for the 'average' year at the stocking rate of 1.0 (i.e. the shadow price for water was negative in the 'average' year at the 1.0 stocking rate, refer to Table 6.12), but positive at the 1.5 and 2.0 stocking rates. For the 'dry' year, the economic response to irrigation was positive at all three stocking rates.

The relationships between the economic responses to irrigation (measured as TGM differences between irrigated and non-irrigated situations) and stocking rate, are illustrated in Figure 6.5. Only grazed pasture was irrigated in the optimal plans. Irrigated pasture hay and silage activities did not enter the optimal plans. In Figure 6.5 rapid diminishing returns to irrigation water are

TABLE 6.12 Summary of LP results

Stocking rate	Data*	WOO (m^3)	TGM ($)	TGM difference due to irrigation ($)	Shadow price of water ($/$m^3$ water)	Water used (m^3)	GOOO (tonnes)	JOOO (tonnes)
1.0	A	0	73,873		Negative	0	0	0
1.0	A	≤40,000	73,873	0	Negative	0	0	0
1.0	A	FR	73,873	0	Negative	0	0	0
1.0	D	0	56,977		.19090	0	0	25.97
1.0	D	≤40,000	60,558	3581	.03610	40,000	0	0
1.0	D	FR	60,963	3986	0	70,000	0	0
1.5	A	0	88,892		.03691	0	66.38	0
1.5	A	≤40,000	89,535	643	0	28,000	27.96	0
1.5	A	FR	89,535	643	0	28,000	27.96	0
1.5	D	0	40,544		.23622	0	662.57	160.07
1.5	D	≤40,000	46,778	6234	.11339	40,000	635.45	118.91
1.5	D	FR	48,632	8088	0	74,431	591.21	112.96
2.0	A	0	66,604		.09559	0	1094.12	41.38
2.0	A	≤40,000	68,616	2012	.01794	40,000	1087.85	19.33
2.0	A	FR	68,836	2232	0	63,000	1059.37	23.27
2.0	D	0	2,087		.27094	0	1280.31	466.05
2.0	D	≤40,000	9,246	7159	.12193	40,000	1279.76	407.56
2.0	D	FR	11,408	9321	0	77,000	1277.44	387.50

* A denotes the 'average' year and D the 'dry' year

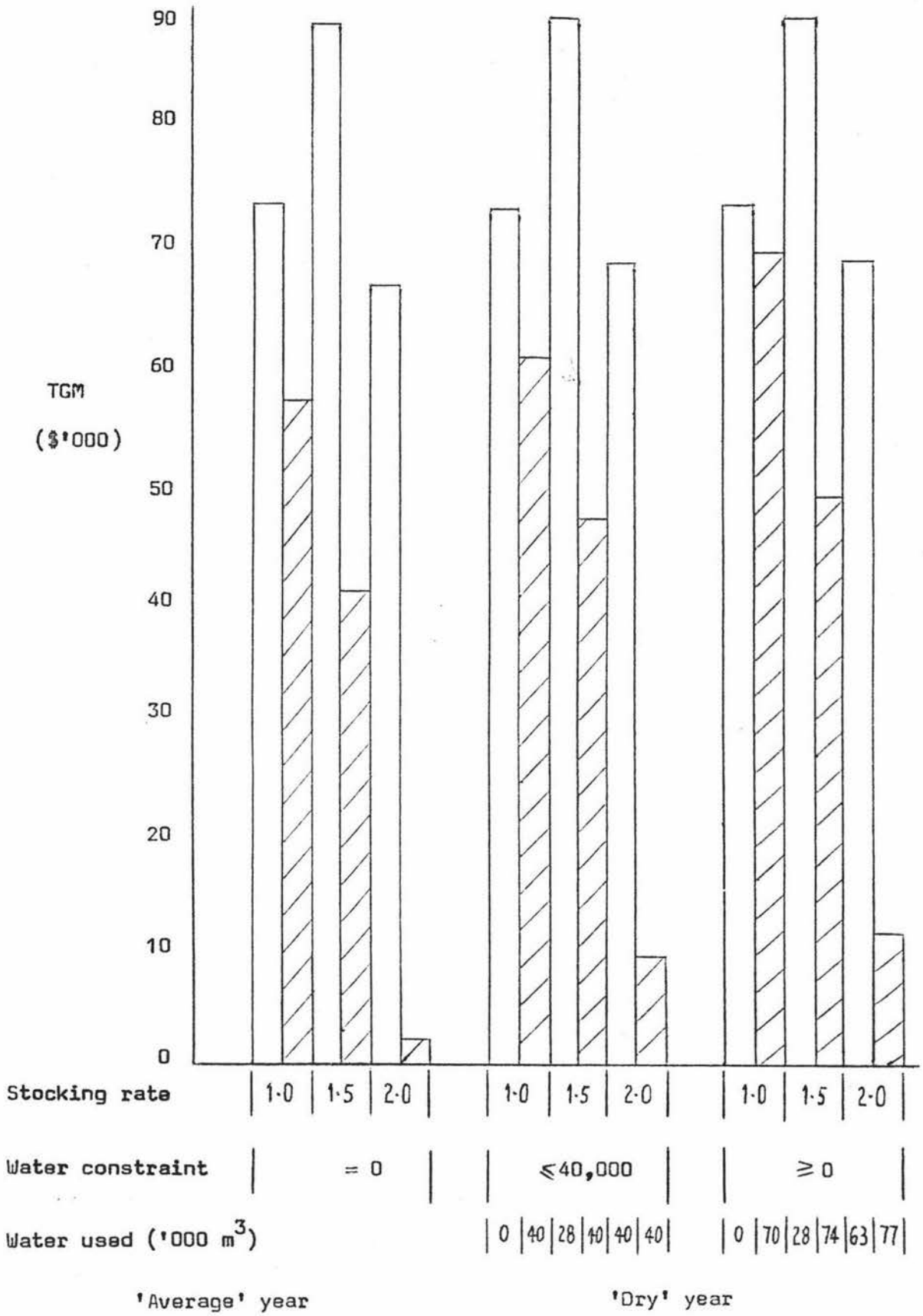
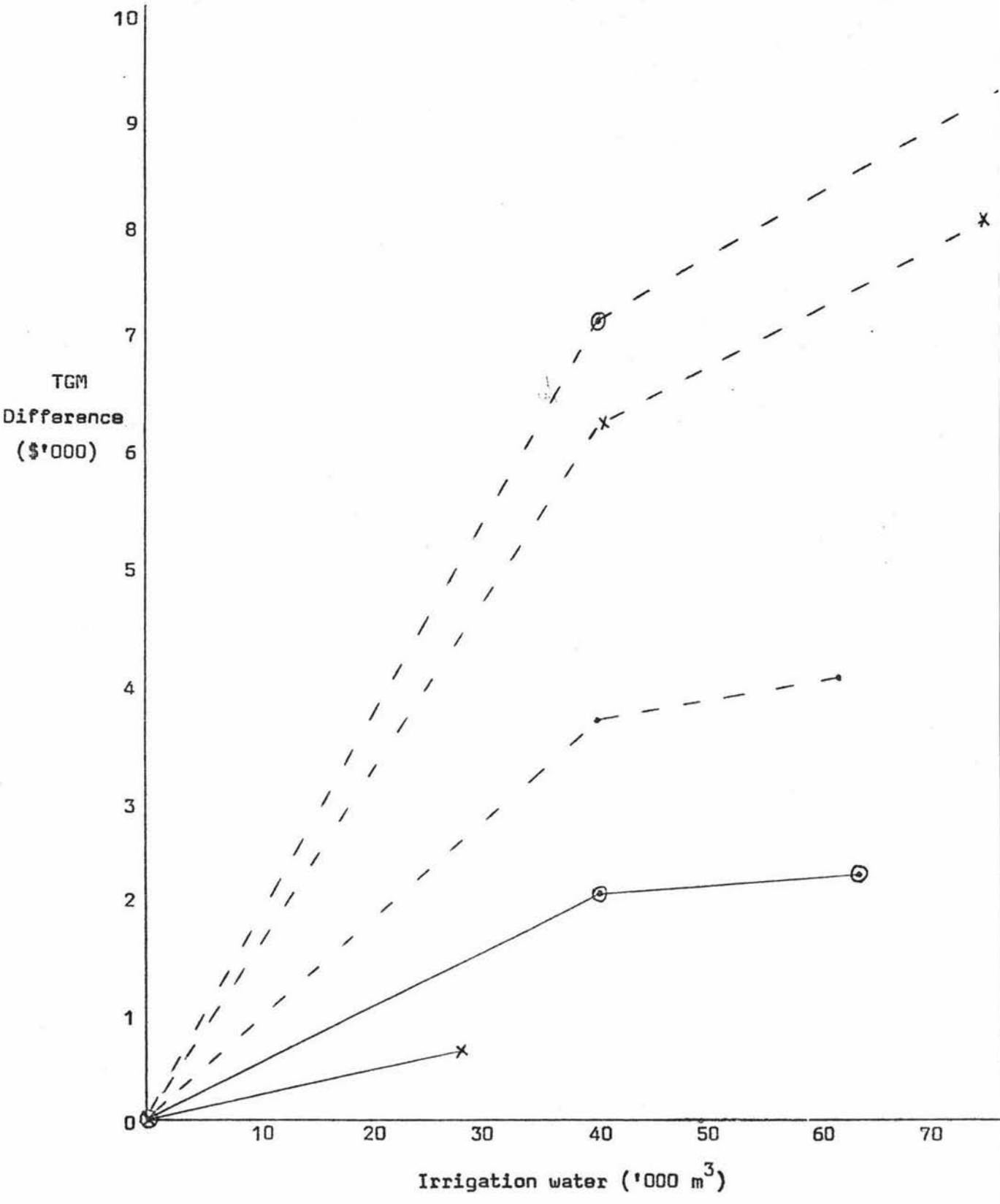


FIGURE 6.4 Relationships between TGM, stocking rate and irrigation water



Assumption : linear segments between observations

• • Stocking rate 1.0
× × Stocking rate 1.5
⊙ ⊙ Stocking rate 2.0

——— 'Average' year
– – – – – 'Dry' year

FIGURE 6.5 Relationships between economic response to irrigation and stocking rate

apparent, especially in the 'average' year, when more than 40,000 cubic metres of water are assumed to be available.

(b) Irrigation management results - the allocation of water

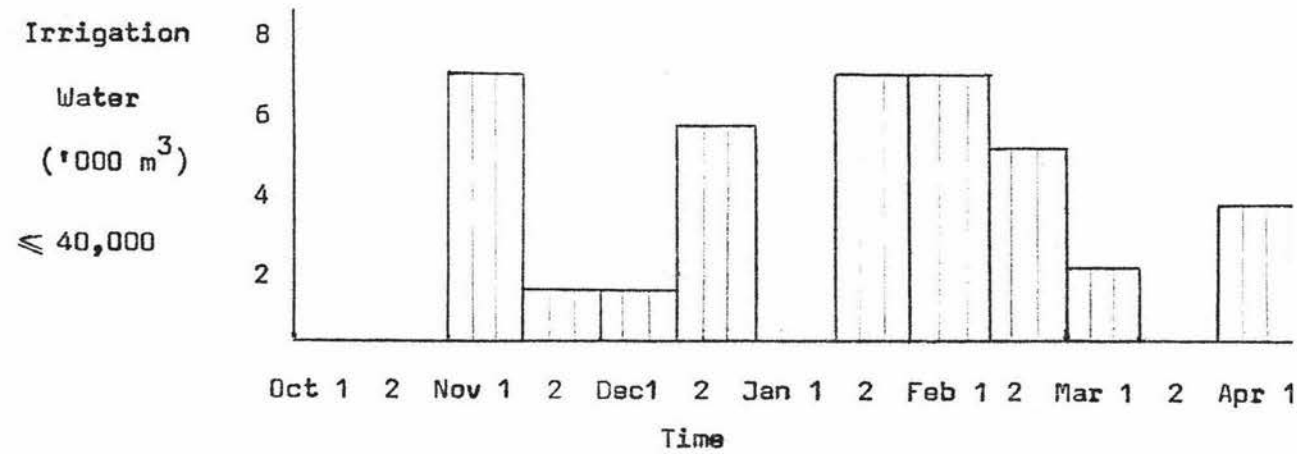
One of the objectives of this study was to investigate the problems of optimally allocating a limited quantity of water between crops, both inter- and intra-seasonally. For this reason, the water allocation results obtained by experimenting with the model are detailed.

A number of attempts have been made to solve inter- and intra-seasonal irrigation water allocation problems. DP was used by Flinn (1968) in a deterministic model and Dudley et al. (1971) in a stochastic model, to optimally allocate water to a single crop during an irrigation season. Salcedo (1972) used a combination of LP, DP and simulation to construct a model to optimally allocate water to a number of crops. De Lucia (1969) used a LP framework, that involved the sequential solution of a series of related LP problems, to determine an optimal irrigation strategy to allocate water to a number of crops. De Lucia incorporated stochastic supply and demand for water in his model.

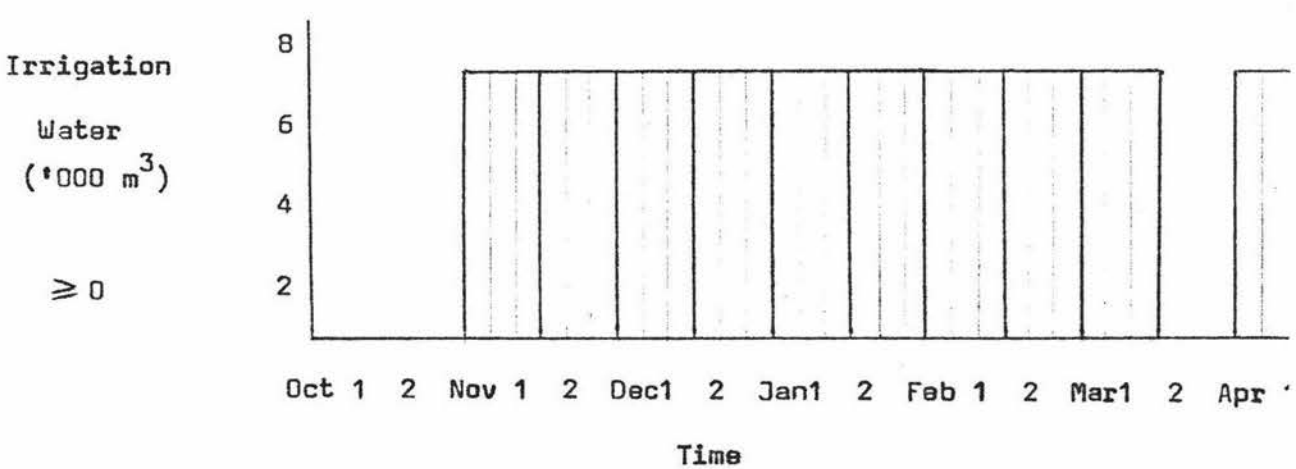
The LP model developed by the author, solves intra- and inter-seasonal management problems of optimally allocating irrigation water to any number of crops, for any year (or number of years) for which plant production data are inputed into the model. However, the model has a number of limitations, due primarily to simplification, and these are discussed in Section 6.6.

The allocation of water, in each period, to each irrigated crop can be derived from the model. As previously noted, although three types of irrigated crop activities were included in the model, only one was selected in the optimal plans. The optimal allocations of water (in each period and month) for the 'average' and 'dry' years, at the three stocking rates, are illustrated in Figures 6.6, 6.7 and 6.8. Optimal allocations over the irrigable

'Dry' Year



Monthly totals –							
'average'	0	0	0	0	0	0	0
'dry'	0	8350	7000	7000	12100	1900	3650

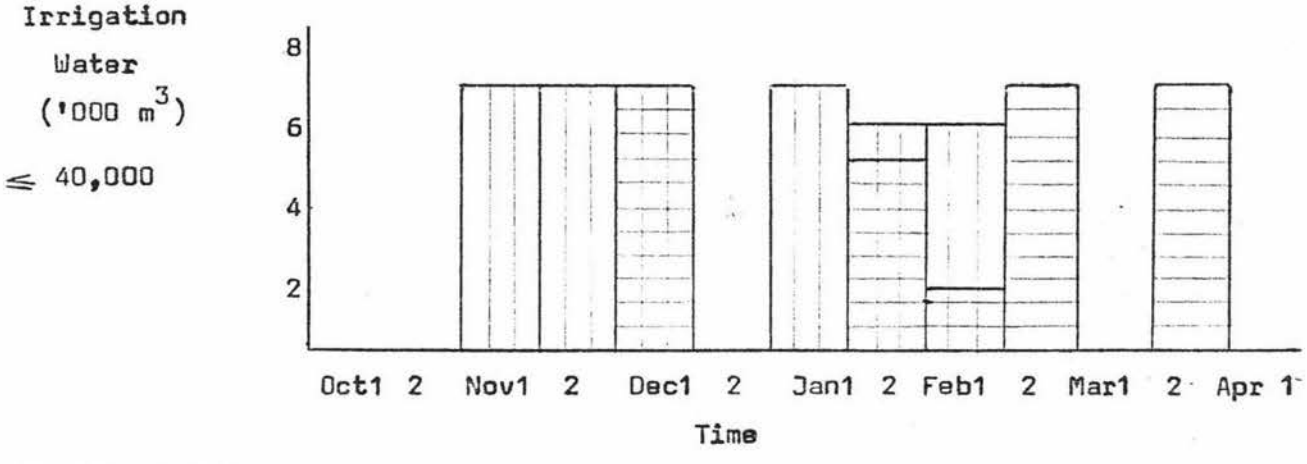


Monthly totals –							
'average'	0	0	0	0	0	0	0
'dry'	0	14000	14000	14000	14000	7000	7000

FIGURE 6.6 Relationships between irrigation water and time of application Stocking Rate = 1.0

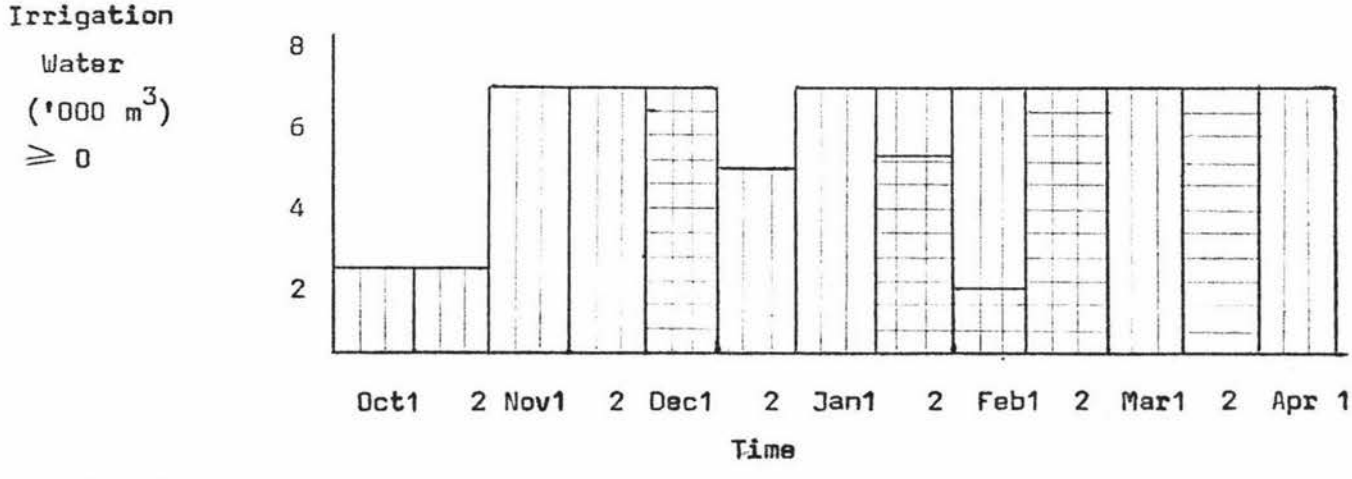
'Average' year 

'dry' year 



Monthly totals –

'average'	0	0	7000	5150	8850	7000	0
'dry'	0	14000	7000	13000	6000	0	0



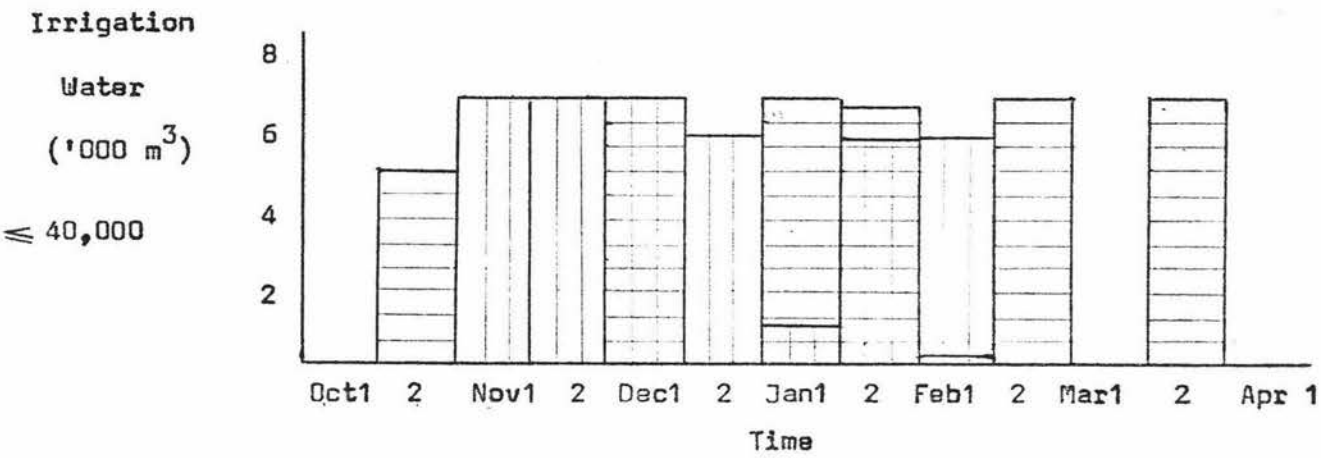
Monthly totals –

'average'	0	0	7000	5150	8850	7000	0
'dry'	4400	14000	11800	14000	14000	7000	7000

FIGURE 6.7 Relationships between irrigation water and time of application
Stocking rate = 1.5

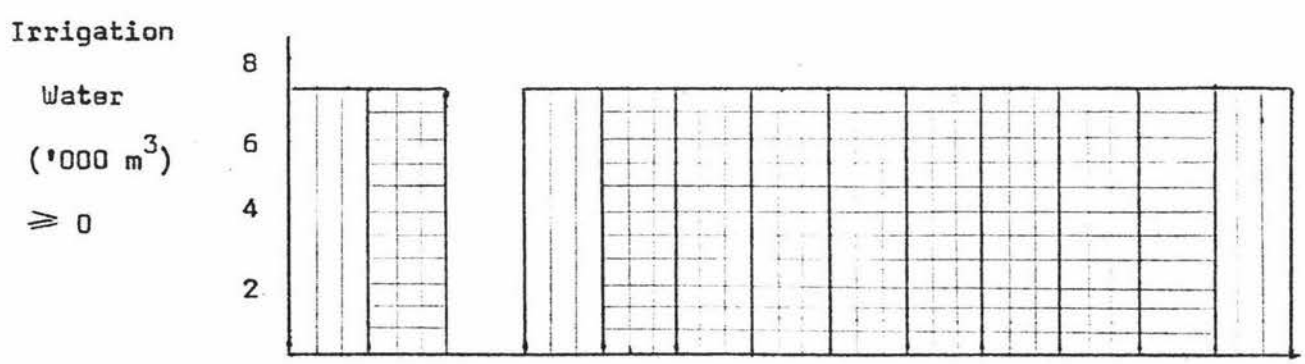
'Average' year

'Dry' year



Monthly totals –

'average'	5000	0	7000	13900	7100	7000	0
'dry'	0	14000	13000	7000	6900	0	0



Monthly totals –

'average'	7000	0	14000	14000	14000	14000	0
'dry'	14000	7000	14000	14000	14000	7000	7000

FIGURE 6.8 Relationships between irrigation water and time of application
Stocking rate = 2.0

area (14 hectares) are given for two assumed water constraints (viz. $W00 \leqslant 40{,}000\ m^3$ and $W00 \geqslant 0\ m^3$). The actual areas of pasture irrigated per period can be obtained from Figures 6.6, 6.7 and 6.8 by dividing the amount of water applied (in cubic metres) by 500, the assumed gross water application per irrigation per hectare. Significant differences in optimal water allocations appear between the stocking rates (in response to changing feed demands) for any one year and especially at the same stocking rate between the two years evaluated.

(c) Grazing and feeding management

Farm management implications of the optimal solutions of a normative grazing model are of vital importance in the control of the grazing system if optimal economic results are to be approached or attained. This is especially so if normative ex ante evaluation economic results are significantly greater than positive ex ante evaluation results, i.e. if there is a significant difference between the predicted actual economic performance of a system and its predicted potential performance. The grazing management results obtained by experimenting with the LP model were not analysed in this study for the following reasons: (i) the major subject of this study is economic evaluation; (ii) Pollard (1972) and McRae (1975) have concentrated on the analysis of grazing and feeding management, of dairy and beef grazing systems respectively, using LP grazing system models similar in terms of output to the model developed in this study; (iii) farm management per se, while of integral importance in the implementation and control of an irrigation proposal, is not necessarily of explicit importance in ex ante economic evaluation. All that is required in terms of farm management, at a normative evaluation stage, is that the optimal plans are feasible and hence the grazing model should ensure that this requirement is met. Only the economic results are of importance for the normative evaluation itself; and (iv) Pollard (1972) found that only small reductions in net profit occurred at any one butterfat/nitrogen fertiliser price combination with sub-optimal grazing plans, despite widely different feed resource organisations.

6.6 DISCUSSION OF THE GRAZING MODEL INCLUDING ITS MAJOR LIMITATIONS

Experimentation with the model at a defined stocking rate determined the annual TGM, grazing and irrigation management that accompanied optimal use of the scarce resources for any set of pasture production data used, subject to the imposed constraints and assumptions. Unfortunately, available time limited the preparation and use of only two years of pasture data and these data were subdivided into time periods of approximately two weeks. Also, only three stocking rates were evaluated, although the range was fairly wide. However, a direct comparison of profitability between the stocking rates cannot be made because changes in stocking rate also involve changes in fixed costs. Assumptions would be required concerning the herd size at which 'lumpy' inputs such as cow shed, and possibly water supply extensions, and extra labour, were required. The LP model cannot therefore be used to determine the optimum stocking rate.

The experimentation results can be used, though, to draw some tentative conclusions regarding stocking rate. A stocking rate of 2.0 would most likely not be as profitable as 1.5, as the fixed cost structure at 2.0 (equivalent to 800 lactating cows) would be higher than at 1.5 (equivalent to 600 lactating cows), although the estimated TGM is lower at 2.0 than 1.5 for the 'average' and 'dry' years with (for all water constraints) and without irrigation. Although the TGM for each stocking rate was not estimated for a 'wet' year, it is unlikely that even if the TGM was higher at 2.0 than 1.5, this would more than compensate the additional loss sustained in the 'average' and 'dry' years at 2.0 compared to 1.5.

The validity of the results obtained from experimentation with a mathematical model of a system is dependent on the degree of realism of the real system that is incorporated in the model. This is dependent on the accuracy of the mathematical relationships and the inclusion of all the important relationships with respect to the problem being investigated. In this study, to some extent

the relationships have been based on research results, but some are largely subjective and have not been experimentally verified. Testing and validation of the pasture component (the simulation model) was discussed in Chapter 5. Testing and validation of the other components of the LP model consisted only of a subjective examination of their basic assumptions and relationships.

The net profit, or TGM, indicated by a solution for any single non-irrigated or irrigated situation, based on pasture growth coefficients averaged through time will be higher than the average annual TGM which could be achieved over a 20 year time period, which is the time period analysed in Chapter 7 in evaluating the No.4 irrigation proposal.(8) This is because, generally, the losses sustained as a result of unfavourable climatic conditions (such as represented by the 'dry' year) are not fully offset by an equivalent gain in seasons of above average pasture growth. The converse applies to the TGM differences between comparable irrigated and non-irrigated situations, i.e. responses to irrigation are underestimated when pasture growth coefficients averaged through time are used to determine economic impacts of irrigation. A corollary is that the normative economic impacts of the No.4 irrigation proposal are most likely underestimated. Unfortunately, this aspect was not explored. The 'average' year's data, and the economic results obtained from these, were assumed to represent the 'most likely' normative estimates of the impact of irrigation.(9)

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(8) In the context of this study, this argument assumes that climatic parameters (rainfall and Eo) will follow similar patterns over the next 20 years as they did during the last 15 years.

(9) The fact that 15 years of climatic data were used to generate mean pasture growth coefficients, somewhat reduces the disadvantage of the simplified approach used in this study to obtain 'most likely' estimates of the effects of irrigation.

Ideally all 15 years of simulated pasture growth data should have been prepared for input into the LP model. The results could have then been averaged to derive expected results. Alternatively, a probability analysis based on three or more years of simulated pasture data could have been used to derive expected results.

Only two years of pasture growth data were prepared for input into the LP model. A considerable amount of time was involved in preparing for input even this amount of data. It is likely that the application of the Burrough's Gamma computer programme package in the arrangement and inputing of data into the LP model (as well as in the analysis of output from the model) would have considerably reduced the data preparation (and output analysis) chores. These chores were carried out with the aid of a desk calculator as the author did not have sufficient time to become familiar with the GAMMA procedure. The fact that only two years of pasture data were evaluated is not a limitation of the grazing model. The model could, in fact, handle any number of years of data.

Simulation of the optimal 'bench mark' management policies derived from the LP model with random pasture production data, to determine the effects of adopting any one management policy, would have been a useful exercise. However, again time was the inhibiting factor.

A possible limitation of the LP model relates to the irrigated pasture activities. The only irrigation strategies incorporated in the model involved irrigating, or not irrigating, any hectare of pasture (within the defined irrigable area) every 14 days with a 50 mm gross (40 mm net) application. That is, the irrigation decision variables incorporated in the model are limited. However, this in a sense is realistic, as generally in a practical farming situation similar to that modelled, a farmer rotates his spray irrigation plant around a defined irrigable area

according to the design characteristics of the plant.[10]

Experimentation with the LP model was limited to only three crops, viz. grazed pasture and pasture conserved for hay or silage. Other crops (irrigated and/or non-irrigated) could have been included. Of special interest to the No.4 Dairy Unit system would have been maize. Simulation models of maize greenfeed, silage and grain were developed, as described in Chapter 5. Again, the time available prevented the incorporation of maize activities in the LP model.

The irrigable area was constrained to 14 hectares. This constraint, similar to the irrigation water constraint, could have been easily varied. The model was constructed to facilitate this type of variation. Changing the irrigable area would be useful in the design of an irrigation proposal, i.e. in project design. This potential usefulness of the model was not explored.

The animal component of the grazing model was a very simplified representation of animal production. The significance of this with respect to the problem being studied (i.e. the evaluation of an irrigation project) was not explored. An interesting exercise would have been to compare the economic results obtained using the animal production component of this study to economic results obtained using the more complex, but more realistic, animal production component developed by Pollard (1972). However, the time available also prevented this. Further limitations of the animal component relate to the fixed calving and lactation patterns assumed.

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(10) The design characteristics of a spray irrigation system are based on physical factors mainly, with generally very little account taken of economic factors. This planning procedure can be described as 'conventional' project design (which was discussed in Chapter 3).

The LP model is deterministic. However, climatic uncertainty, and its effect on pasture production, is accommodated by running the LP model for a number of years of pasture production data, or by using pasture data averaged over time (the limitations of which have been discussed). The model assumed perfect knowledge on the part of the decision maker. The model knows what pasture production for any year considered is going to be. Output from the model, though, could be used in a stochastic sense as described previously in this section, where optimal plans are simulated with randomly selected pasture data.

Price and productivity variables (apart from purchased feed prices) were not varied. Emphasis was placed on obtaining 'most likely' or 'most probable' results and hence mean, or 'most likely', price and productivity estimates were used.

The water constraint was a simplified representation of the availability of irrigation water. However, as was discussed in Chapter 5, the simulation model could not be used confidently to monitor the volume of water in the dams over time. The errors likely to be caused by this simplified constraint were illustrated, to some extent, in Chapter 5.

Limitations generated by the pasture production component were also discussed in Chapter 5.

Due to the limitations of the grazing model, it can be concluded that the intra-seasonal and inter-seasonal optimal water allocation problems were only partially solved. The optimal solutions obtained can only strictly be described as 'sub-optimal' solutions as decision variables of the system were restricted (e.g. the restricted irrigation strategies, the restricted grazing spells and the inclusion of decision periods of approximately two weeks) and only two years of pasture growth data were used. However, the model can accommodate the allocation of water to any number of crops, which can be a distinct advantage over DP irrigation models which can model only single, or double crop irrigation systems.

CHAPTER 7

ECONOMIC EVALUATIONS OF THE CASE STUDY IRRIGATION SYSTEM

7.1 INTRODUCTION

In this chapter, project evaluations that were carried out on the Massey No.4 Dairy Unit water harvesting system are presented. The analyses are broadly classified as normative and positive. The normative analyses are based on economic results derived from the LP model described in Chapter 6. The physical basis of the positive analyses was provided by data from the simulation model described in Chapter 5 and two 'rule of thumb guesstimates'. The analyses were carried out from the point of view of the nation or farmers. Differences between the two points of view are due to fertiliser price and fertiliser transport subsidies. These subsidies were added to fertiliser costs in the national viewpoint analyses, and deducted from fertiliser costs in the farmer viewpoint analyses. Only marginal analyses, based on partial budgeting and gross margins, were carried out using 'most probable outcome' discounting techniques (Gittinger, 1972), although sensitivity analyses on various parameters are included.

Following a presentation of the assumptions used and the results of the evaluations, including the sensitivity analyses, the methodology used and the results are discussed in detail.

7.2 ASSUMPTIONS

The following assumptions were made for the economic evaluations:

(i) the life of the irrigation project was assumed to be 20 years;

(ii) the irrigation equipment at the end of the project life was assumed to have a zero salvage value;

(iii) repairs and maintenance expenditures were assumed to be sufficient to maintain the irrigation equipment over the project life;

(iv) irrigation capital costs were assumed to be incurred at the beginning of year one and associated costs were timed to the end of the year in which they accrue;

(v) maintenance costs were assumed to cover maintenance for the year following incurrence;

(vi) the costs and prices that were assumed are detailed in Appendices 4 and 5;

(vii) in the farmer viewpoint evaluations, only pre-tax cash surplus analyses were carried out. Also, it was assumed in these evaluations (similar to the national viewpoint evaluations) that all irrigation equipment was purchased at the beginning of the first year and not by borrowing money. Therefore,in the discounted flow analyses, the opportunity cost of this capital was assumed to be equal to the discount rate used;

(viii) in half of the normative analyses and half of the positive analyses, it was assumed that:

(a) the fenced area of the dams was two hectares and an opportunity cost of this land was based on the stocking rate assumed and the dairy cow gross margins (Appendix 4)[1]; and

(b) additional nitrogen fertiliser (in addition to non-irrigated pasture fertiliser requirements) would be required on the irrigable area, the cost of which is detailed in Appendix 5.

In the other normative and positive analyses, the above two assumptions (i.e. a and b) were relaxed on the premise that the dams did not encroach on productive land

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(1) The dams were constructed in a gully. Therefore a part of the flooded area was unproductive before the dams were constructed. This initially unproductive area was considered to be negligible in comparison to the total area flooded in these analyses.

and that no additional fertiliser would be required on the irrigable area. Limited research on the recycling of nutrients on the Massey water harvesting area (of which the irrigable area is a part, as outlined in Chapter 2) suggested that phosphorus is likely to be significantly recycled, but that recycling of nitrogen is likely to be very limited (Report, Department of Soil Science, Massey, 1975).

7.3 NORMATIVE EVALUATIONS

Twelve normative evaluations were carried out. These involved consideration of the three stocking rate levels (viz. 1.0, 1.5 and 2.0) defined in Chapter 6. At each stocking rate, national and farmer viewpoints were analysed, initially taking into account loss in production of the area of the dams and additional fertiliser on the irrigable area, and then ignoring these two latter effects. A listing of the normative analyses is presented in Table 7.1:

TABLE 7.1 A listing of the normative analyses

Analysis key	Stocking Rate	Viewpoint	
N1A	1.0	National	Allowance was made for lost production from the area of the dams and additional fertiliser on the irrigable area
N2A	1.5	"	
N3A	2.0	"	
N4A	1.0	Farmer	
N5A	1.5	"	
N6A	2.0	"	
N1B	1.0	National	No allowance was made for the above
N2B	1.5	"	
N3B	2.0	"	
N4B	1.0	Farmer	
N5B	1.5	"	
N6B	2.0	"	

The benefit and cost flows of the normative analyses are presented in Appendix 6, Table A6.1. These cash flows were discounted at various discount rates to obtain present values (PV) of the benefit and cost streams and present worth (PW) estimates.[2] The PW results of the normative analyses are presented in Table 7.2. Only two analyses (N3B and N6B) had positive PW's at the discount rates used. The PW's of these two analyses, which were the same at various discount rates, are graphed in Figure 7.1. The internal rate of return (IRR) estimated is 16 percent.

TABLE 7.2 Normative evaluation results

Model	PW, $, at discount rate (%)				
	5	7	9	10	11
N1A	-27046	-24799	-23032	-22287	-21621
N2A	-23705	-22129	-20730	-20142	-19613
N3A	-11717	-11769	-11803	-11815	-11827
N4A	-26696	-24500	-22772	-22044	-21394
N5A	-23555	-21830	-20471	-19899	-19406
N6A	-11387	-11468	-11543	-11573	-11600
N1B, N4B	-11995	-11977	-11964	-11958	-11952
N2B, N5B	-3982	-5165	-6094	-6479	-6831
N3B, N6B	13079	9338	6403	5171	4070

7.4 POSITIVE EVALUATIONS

Eight positive evaluations were carried out. The economic basis of these was similar to that of the normative evaluations, details of which are set out in Appendices 4 and 5.

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(2) The discount rates used were arbitrarily chosen around the 10% rate, (the rate used in cost-benefit analyses of N.Z. agricultural projects) to test the sensitivity of the results to variation in discount rate.

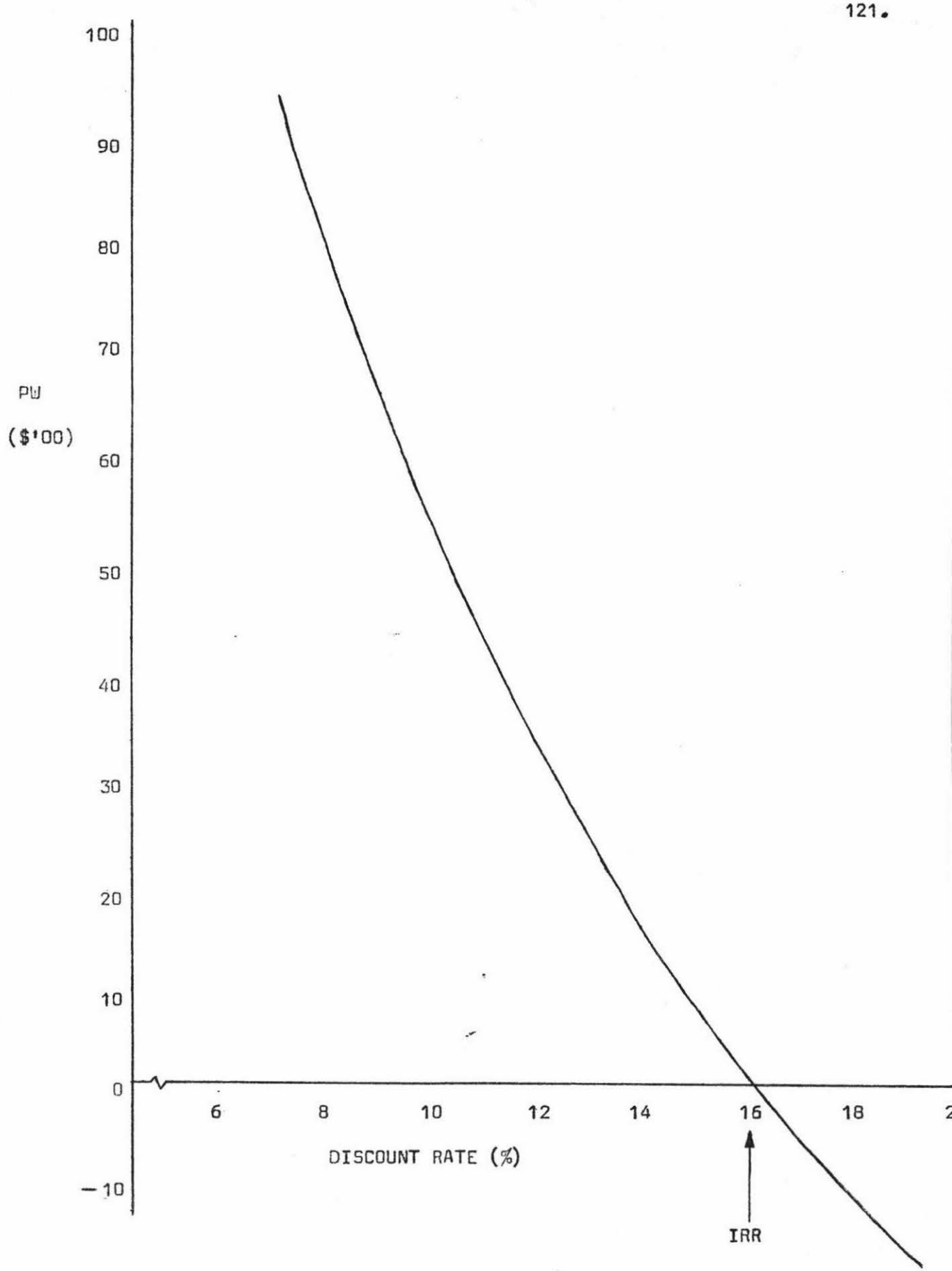

FIGURE 7.1 Present worth versus discount rate - Analyses N3B and N6B

The pasture irrigation response used was based on data obtained from the simulation model presented in Appendix 2, Tables A2.1 and A2.2. 40,000 cubic metres of water were assumed to be available and the amount of water applied per irrigation, per hectare, was assumed to be 500 cubic metres. Six irrigations were assumed to be applied over the 14 hectare irrigable area during December, January, February and March at 14 day intervals. The response to this level of irrigation, on average, was estimated at 1400 kg DM per hectare. Only one stocking rate (viz. 1.5) was used in the positive analyses. Ninety per cent pasture utilisation during the irrigation period was assumed. Therefore the amount of additional pasture dry matter grown as a result of irrigation, and utilised, was 1260 kg DM per hectare, or 17,640 kg DM for the total irrigable area.

The two 'rule of thumb guesstimates' used for estimating the milkfat response to this additional pasture are outlined in Sections 7.4.1 and 7.4.2.

7.4.1 Method 1

Based on research at Ruakura, Halford and Lowe (1975) used a conversion ratio of 20 lb DM of irrigated pasture to 1 lb of additional milkfat. This conversion ratio was used and resulted in an additional 882 kg milkfat, which, at $1.17 per kg (Appendix 4), results in an additional annual revenue of $1032.

7.4.2 Method 2

A 'rule of thumb' commonly used (Bowler, 1975 and Phillips, 1975) is that for each additional kg of pasture DM grown as a result of irrigation, one extra litre of milk is produced. A test of 4 per cent was assumed. Therefore an additional 706 kg of milkfat are produced per annum, which at $1.17 per kg, results in an additional annual revenue of $826.

A listing of the positive analyses is presented in Table 7.3:

TABLE 7.3 A listing of the positive analyses

Analysis Key	Stocking Rate	Viewpoint	
P1A	1.5	National	Allowance was made for lost production from the area of the dams and additional fertiliser on the irrigable area
P2A	1.5	"	
P3A	1.5	Farmer	
P4A	1.5	"	
P1B	1.5	National	No allowance was made for the above
P2B	1.5	"	
P3B	1.5	Farmer	
P4B	1.5	"	

The benefit and cost flows of the positive analyses are presented in Appendix 6, Table A6.2 and the PW results obtained by discounting the cash flows are presented in Table 7.4:

TABLE 7.4 Positive evaluation results

Model	PW, $, at discount rate (%)				
	5	7	9	10	11
P1A	-37077	-33329	-30379	-29141	-28032
P2A	-34510	-31146	-28499	-27388	-26391
P3A	-36727	-33028	-30120	-28899	-27804
P4A	-34160	-30845	-28239	-27146	-26163
P1B, P3B	-17155	-16364	-15743	-15482	-15250
P2B, P6B	-14587	-14181	-13862	-13728	-13609

7.5 SENSITIVITY ANALYSES

In addition to the discount rate sensitivity analyses and the inclusion and non inclusion of lost production on the area of the dams and additional fertiliser on the irrigable area, other sensitivity analyses were carried out. These sensitivity analyses, from the national point of view only, involved the following:

(i) for analyses N2A and N2B, the annual TGM difference due to irrigation required for the project to show a return of 10 per cent to the nation, was calculated; (ii) for analyses P2A and P2B, the additional annual revenue required (and therefore the additional annual milkfat produced and pasture irrigation response required) using method 1 (Section 7.4.1) for the project to return 10 per cent to the nation; and (iii), for the positive analyses P2A and P2B, the sensitivity of these analyses to a reduction in the variable costs of irrigation was explored.

The results of these sensitivity analyses are presented in Tables7.5 and 7.6.

TABLE 7.5 Sensitivity results - Normative evaluations

Analysis	Irrigation cost ($ per irrigation per hectare)	Annual TGM differences due to irrigation to return 10% ($)
N2A	14.76	2936
N2B	14.76	1405

TABLE 7.6 Sensitivity results - Positive evaluations

Analysis	Irrigation cost ($ per irrigation per hectare)	Annual Estimated Requirements to return 10%		
		Milk Fat (kg) at $1.17 per kg using Method 1	Irrigation Response (kg DM/ha) available for grazing using Method 1 & 90% utilisation	Additional Revenue ($)
P2A	14.76	3632	5765	4250
	11.07	3368	5346	3940
	7.38	3103	4925	3630
P2B	14.76	2261	3589	2645
	11.07	1996	3168	2335
	7.38	1731	2748	2025

7.6 DISCUSSION

The most significant feature of the evaluation results is the apparent economic unattractiveness of the No.4 Dairy Unit irrigation project. However, in interpreting these results, careful consideration must be made of the methodology and assumptions used. Of major importance is the fact that the estimated pasture responses to irrigation used are based on a pasture simulation model which, as discussed in Chapter 5, was only validated to a limited extent. Also, historical meteorological data were used to simulate the pasture irrigation responses and the extent to which the future 20 years of weather patterns will be represented by the last 15 years will determine the appropriateness of using these data. The method used of averaging pasture response data through time and then using these as being representative of an 'average' year, and in turn using the 'average' year data to determine the expected economic impact of irrigation, has disadvantages which were outlined in Chapter 6 (Section 6.6). In addition, results from the LP model were used in the normative evaluations and therefore are limited by the assumptions incorporated in the model. Also, the two methods used in the positive evaluations for estimating the conversion of additional pasture to milkfat must be regarded as 'guesstimates'. The differences between the results obtained from the two methods highlights the approximate nature of these 'rules of thumb'.

In addition to the limitations caused by the methodology and assumptions used, there is a further reason why the economic results presented in this chapter should <u>not</u> be used to indicate the impact of water harvesting (or irrigation generally) on seasonal supply dairy farms in the Manawatu region (or other regions) of N.Z. This reason relates to the fact that only a small part of the No.4 Dairy Unit will be irrigated, because of the limited amount of water available. A project design exercise, involving changes in the size of the irrigable area, rate of water application per irrigation and irrigation cycle length, was not carried out due to a limitation of the time available for this research project. As was noted in Chapter 6, the LP model was developed for application in project design.

However, only very limited experimentation with the model in project design was carried out in the time available. This involved experimentation with varying amounts of available water, the economic impacts of which were illustrated in Table 6.12.

The effects of the above mentioned limitations on the results of the economic evaluations were not explored.

7.6.1 Normative results

The results of the normative evaluations (Table 7.2) indicate that, at the margin, the irrigation project could have a greater economic impact at a stocking rate of 2.0, than at the 1.0 or 1.5 stocking rates. However, as noted in Chapter 6, the TGM (for an 'average' year, both with and without irrigation) is significantly higher at 1.5 than at either 1.0 or 2.0.

Analyses N1B/N4B have the same benefit and cost flows since no additional fertiliser was assumed to be applied to the irrigable area. This comment also applies to analyses N2B/N5B and N3B/N6B.

As expected, there is only a minimal difference between the national and farmer viewpoint results (e.g. a comparison of the results of analyses N1A and N4A).

Exclusion of the costs associated with the area of the dams and additional fertiliser on the irrigable area, had a very significant effect on the PW's. At each stocking rate level, and at each discount rate, these cost exclusions more than approximately doubled the respective PW's (e.g. a comparison of the PW's of analyses N1A/N4A and N1B/N4B). To further highlight this, the income forgone caused by the loss in production from the area of the dams is greater than the TGM difference due to irrigation at the 1.5 stocking rate.

In most of the normative analyses, the PW results are not sensitive to a variation in discount rate. This is due to the low level of the benefit flows (in relation to the cost flows). Also, a significant proportion of the total PV of the cost flows is incurred at the beginning of year 1. The only real exceptions are analyses N3B and N6B. For some of the normative analyses, it is not surprising that their PW's increase (become less negative) as the discount rate is increased. This is because the estimated benefit flows of these analyses are zero, or insignificantly positive (in relation to their cost flows).

The only analyses with an IRR greater than five per cent (and indeed, greater than one per cent, as even N2B and N5B have a PW of -$443 at a discount rate of one per cent) are N3B and N6B. Their IRR was estimated to be 16 per cent (Figure 7.1). However, the significance of this is limited as the estimated TGM levels, with and without irrigation, at the stocking rates of 2.0 and 1.5 (Table 6.12) are significantly in favour of the 1.5 level (although the TGM difference between irrigated and non-irrigated situations is greater at 2.0 than 1.5). Also, the exclusion of the costs associated with the loss of productive area flooded by the dams in the No.4 Dairy Unit situation is unrealistic, as also (although less defendable) is the exclusion of the costs associated with additional nitrogen fertiliser requirements.

7.6.2 Positive results

The results presented in Table 7.4 indicate that the positive evaluation results are significantly lower than those of the normative evaluations. This indicates that the allocation of resources inherent in the positive analyses is not as economically efficient as those incorporated in the normative analyses. Specifically, the additional revenue flows less the corresponding variable irrigation cost flows of the positive analyses, are less than the TGM differences (with minus without irrigation) flows of the normative analyses at the 1.5 stocking rate. In fact, the

additional revenue flows less the variable irrigation cost flows of the positive analyses (using both methods 1 and 2, Sections 7.4.1 and 7.4.2 respectively) result in negative cash flows (i.e. the variable costs of irrigation alone exceed the estimated benefits of irrigation in all of the positive analyses).

Exclusion of the costs associated with the loss of productive area of the dams and additional fertiliser on the irrigable area, had a very significant effect on the PW estimates, similar to that on the normative PW estimates.

The same comments on the sensitivity of the results to discount rates apply to the positive analyses as applied to the normative analyses. However, the IRR's of the positive analyses are all less than five per cent and are in fact negative.

7.6.3 Sensitivity analyses

The sensitivity of the PW results of the evaluations to discount rates, as well as the inclusion and exclusion of the costs associated with lost production from the area of the dams and additional fertiliser on the irrigable area, were discussed in Section 7.6.1 and 7.6.2.

The results presented in Table 7.5 indicate that from the nation's point of view, the annual TGM differences due to irrigation at a stocking rate of 1.5 would need to be $2986 and $1405 respectively, when dam area and additional fertiliser costs are included and excluded, for the project to return ten per cent. It would be unlikely (and probably impossible) to obtain these differences (at the levels of production, costs and prices assumed) as even at a difference of $643, a near optimal (sub-optimal) allocation of resources and very high technical efficiencies were assumed. These estimates indicate the TGM differences, attributable to irrigation, necessary for the hypothetical case of the Massey

irrigation project to meet Treasury guidelines for subsidy approval.

The results presented in Table 7.6 indicate the annual levels of milkfat, pasture irrigation response and additional revenue required, at three levels of irrigation variable costs (the 'most likely' cost level, as well as three quarters and half of this level), for the project to return ten per cent (when method 1, Section 7.4.1, is used). The sensitivity of the PW estimates to variations in the variable costs of irrigation was not very significant, indicating that the variable cost of irrigation is not critical to the profitability of the No.4 Dairy Unit project. The irrigation pasture responses required for the project to return ten per cent on invested capital, at the most likely estimates of costs and prices, can be compared to the 1400 kg DM per hectare estimate obtained from the simulation model. Even when the dam area and additional fertiliser costs are ignored, and the low variable irrigation cost is used, the pasture response to irrigation required would still be approximately twice the simulation model estimate (2748 cf 1400 kg DM per hectare).

7.7 SUMMARY

Only ex ante project evaluations were presented in this chapter. However, both normative and positive analyses were presented from the nation and farmer points of view. Evaluations carried out from the nation's viewpoint employed cost-benefit analysis, whereas those from the farmer viewpoint employed investment analysis. Unfortunately, normative project design models were not formulated and evaluated due to insufficient experimentation with the LP model.

Pre-tax cash surplus analyses only were incorporated in the farmer viewpoint evaluations. Post-tax analyses, in addition to allowing for the borrowing of capital for irrigation investment, would increase the profitability of the case study irrigation system from a farmer point of view.

Although limitations of the results of the evaluations have been outlined in detail in this chapter, one significant feature has emerged. For the system evaluated, when it was assumed that initially productive land was flooded by the dams, the income forgone by this action had a very significant impact on the economics of the system. The level of significance was so high that it can be concluded that,generally,very careful consideration should be given in the planning of water harvesting irrigation proposals not to flood large areas of productive land. It appears to be essential, from an economic point of view, to confine dams to largely unproductive areas.

The large differences in the results of the normative and positive analyses, even when the assumptions and limitations of the evaluations are considered, indicate that the farm management implications of them should be carefully studied. This exercise was outside the scope of this study. However, the author believes that the models developed in this thesis could be usefully employed in such an exercise.

CHAPTER 8

SUMMARY AND CONCLUSIONS

A physical requirement for irrigation undoubtedly exists in most farming regions in N.Z. There is likewise no doubt that water harvesting could provide a technically feasible source of water to a significant part of these regions. However, an economic requirement for irrigation and for water harvesting to provide the source of water, is not so clear. In this study, the importance of evaluating the economics of irrigation is emphasised. It is argued that the methodology adopted could be usefully employed in the economic evaluation of irrigation, especially of water harvesting irrigation systems.

The major contribution economists can make in ex ante economic evaluations of irrigation proposals is at the initial design or planning stage working in collaboration with engineers. This exercise is referred to in this thesis as project design, during which a number of project design alternatives are formulated and evaluated. This can be contrasted to project evaluation, which is the term used when only a single design alternative is evaluated.

Unfortunately, M.A.F. economists in N.Z. have been almost exclusively involved in project evaluation. A yes/no (or accept/reject) answer on a single design alternative is provided to decision makers. No guarantee can therefore be given that the design selected for evaluation (by the engineer on largely technical grounds) is the most economic form of the project.

It is concluded in this study that the project evaluation role played by M.A.F. economists may in part be due to the fact that only 'conventional' comparative techniques of analysis have been used. This view is substantiated by a review

of overseas work, which indicates that involvement of economists in project design of irrigation and other water resource projects in recent years has been largely dependent on the application of new techniques of analysis (numerical and DP) in applications of systems research.

Plant-irrigation response functions must be formulated when irrigation investments are evaluated ex ante. In N.Z., a single-valued function (in which a fixed plant response to a fixed water demand is assumed) has been almost exclusively used. This is the most simplistic approach to take. In contrast, a simulation approach to determine plant-irrigation response functions, although considerably more time consuming, is the most realistic. This approach has not yet been used by the M.A.F.

The majority of N.Z. field research on plant-irrigation responses has been carried out by the Research Division of the M.A.F. Although the results have been reasonably well documented, they are of limited use in the economic evaluation of irrigation proposals and in attempting to optimise inter- and intra-seasonal water allocations. These limitations can be summarised as:

(a) the research, by necessity, has been confined to a very limited number of locations, crops, years, and irrigation and grazing management strategies (which are limitations of most field research programmes). Hence the response data are directly applicable only to the soils and crops experimented with, the irrigation and grazing strategies used, and the climatic conditions of the research areas for the years the research was carried out;

(b) limited attention has been given to the strategic use of water between pasture and other crops. Therefore, there has been a lack of attention given to irrigation systems experimentation to better understand the inter-relationships between irrigation/pasture and livestock and/or cropping;

(c) little effort has been made to derive plant growth rate functions.

A relatively simple plant-soil water simulation model was adapted and used in this study to simulate a water harvesting irrigation/grazing/cropping system. The Massey No.4 Dairy Unit was the case study farm modelled. The simulation model provided a method of generating plant-irrigation response data for a wide range of irrigation, grazing and crop management strategies over a 15 year period. Input required for the model involved daily rainfall and open-pan evaporation data collected by the Climatological Service of the Ministry of Transport. These data are readily available for at least 40 years from some 140 weather stations around N.Z.

Testing of the soil moisture, pasture and maize growth components of the simulation model was limited due to a paucity of real world data to compare model output to. However, the author felt that the model was sufficiently realistic to justify its use in this study, despite its limitations. Simulated non-irrigated and irrigated pasture growth data were used as there were no suitable alternative data.

The LP model developed and used in this study was designed to optimise the allocation of available water, and other resources, on the case study farm. The model has a major advantage over DP models of irrigation systems, as it can accommodate simultaneously the allocation of water to any number of crops over periods of time for which crop growth data are inputed into the model. On the other hand, DP models of crop irrigation systems have accommodated normally only a single crop, or at the most two crops, due to dimensionality problems.

Despite this advantage of LP, the model has a number of limitations, due primarily to simplified relationships incorporated. These simplifications are mainly the result of the limited time that was available to construct the model. Only limited use could

be made of available data and limited consultation with personnel from various disciplines in the time that was available. The model also had to be kept to a size which was manageable in terms of construction within the time available. Some of its limitations, though, are due to a paucity of relevant real-world data on some of the plant-soil water-animal relationships of the system modelled. This necessitated subjective assumptions being made on these relationships. In summary, the major limitations of the model are:

(a) decisions to irrigate, or not irrigate, any single hectare of potentially irrigable land were restricted to two weekly intervals;

(b) the amount of water applied at any irrigation was constant;

(c) simulated pasture growth data used were obtained from the simulation model which was only partially tested;

(d) only two years (a defined 'average' and a 'dry' year) of plant production data were used, although more years could have been accommodated had there been sufficient time to prepare the data;

(e) a very simplified dairy cow production component was incorporated in the model.

Normative and positive ex ante economic evaluations of an irrigation proposal for the case study farm were carried out during the course of this study, from the point of view of the nation and of a farmer. The positive evaluations were based partly on pasture irrigation response data obtained from the simulation model and the normative evaluations were based on economic results obtained from the LP model. Although the results of the evaluations are subject to the limitations of the simulation and LP models, as well as a

number of additional assumptions incorporated in the evaluations, it is the author's opinion that two tentative conclusions can be drawn:

(a) the farm management implications which can be obtained from output of the LP model should be carefully studied, since there is a very significant difference between the economic results of comparable normative and positive evaluations (significantly in favour of the normative evaluations). The exercise of studying the farm management implications of the normative evaluations was outside the scope of this study. However, the author believes that the model could be usefully employed in such an exercise;

(b) for the case study system evaluated, when it is assumed that productive land is flooded by the water harvesting dams, the income forgone by this action has a very significant impact on the economics of irrigation. The level of significance was so high that it can be tentatively concluded that very careful consideration should be given in the planning of water harvesting irrigation proposals not to flood productive land and to confine dams to largely unproductive areas.

In relation to the major objective of this study, the author considers that there is a definite role in N.Z. for relatively simple plant-soil water simulation models, and optimising models, similar to those used in this study. They could be profitably applied in ex ante economic evaluations of irrigation projects, in solving optimal water allocation problems and in determining the potential (from an economic point of view) of irrigation. Specifically, the methodology provided by the application of numerical techniques of analysis would make it feasible, the author believes, for M.A.F. economists within the Economics and Advisory Services Divisions to become more involved in

project design and thus ensure that the most economic designs (from the point of view of the nation and/or farmers) of irrigation projects will be submitted to national decision making bodies responsible for the allocation of public funds to irrigation projects. In addition, the roles of numerical techniques in optimising water allocations and in determining the potential of irrigation, would be particularly useful for predicting potential regional water demands and in discerning 'best bet' irrigation systems for field experimentation by the Research Division, or for direct adoption (via extension personnel) on farms.

The author believes that to be used to solve irrigation problems, mathematical models of irrigation systems must be kept as simple as possible to minimise the amount of time required in their construction or adaption. Their simplicity, though, must be judged in relation to their being sufficiently accurate representations, with respect to the problem(s) studied, of the real-world systems modelled. The models used in this study could be described as being relatively simple (in relation to those developed, for example, in the U.S.A.). In addition, it would be desirable to develop models which could be easily adapted for application in different locations. Such models are referred to in this study as 'skeleton' models. The simulation and LP models used in this study are 'skeleton' models.

It would be essential that mathematical models used by the M.A.F. could be quickly constructed, or adapted, for application in any irrigation project or in any water allocation problem, and preferably be sufficiently simple so that staff could be easily trained to adapt and use them. The development and use of them could be carried out by one, or a number, of officers trained in computer modelling.

In practice, a trade-off must be made between the time available to construct, or adapt, a mathematical model using numerical techniques vis a vis the utility of its results compared

to those that can be obtained using simpler 'conventional' comparative techniques of analysis. Generally, this question must be answered in project evaluation exercises, but in project design and in optimising water allocations, only numerical techniques will suffice and the question is whether or not to carry out the project design or optimal water allocation exercise (using numerical techniques). The advantages of carrying out these latter two exercises have been highlighted throughout this thesis. Briefly, they provide an aid so as to ensure the most efficient use of scarce resources.

Also, in practice, the availability of suitable models to generate irrigation/plant/animal response data (such as the simulation and LP models used in this study), or alternatively the availability of suitable response data obtained from field experiments, will in part determine the development and use of the more complex (numerical) models in economic evaluations of irrigation. In general, the use of more complex models gives improved answers to decision problems than the use of simpler models, but in turn they require better and more involved basic information to construct them.

Due to the simplified relationships incorporated in the grazing system model, it can be concluded that the second objective of this study, to solve inter- and intra-seasonal optimal water allocation problems, was only partially achieved. The optimal solutions obtained can only strictly be described as 'sub-optimal' as the decision variables incorporated in the model were restricted and only two years of pasture growth data were used.

Obviously there is considerable scope for refining the simulation and LP models used in this study. It would be desirable for refinements to be carried out by an interdisciplinary team of researchers so as to fully utilise extensive knowledge of research workers in different specialised areas. In the course of this study, the author consulted a number of specialised researchers individually. Undoubtedly a team effort would improve communication

between disciplines and increase researcher participation. It has been noted by systems researchers, that the 'systems approach' requires a crossing of interdisciplinary boundaries and more extensive communication between researchers than occurs at present. In general, the extent to which this occurs is likely to determine how significantly systems research will contribute to agricultural research.

The following extensions could be made to the present study:

(a) pasture growth simulation models for various regions in N.Z. are being developed by the Research Division of the M.A.F. (J.A. Baars, pers.comm.). These models will be similar to the pasture growth model used in this study, although more refined, especially with respect to explicitly allowing for daily temperature variation. These models could be used to derive pasture-irrigation responses for various irrigation and grazing management strategies to aid in determining pasture irrigation benefits for ex ante economic evaluations. An obvious application by the Economics Division would be to use the pasture simulation model derived by the Research Division for Winchmore, to determine pasture responses to irrigation at fixed intervals, as occurs on large-scale projects in Canterbury where water is rostered. Pasture responses to irrigation at pre-determined soil moisture deficits only, have been determined at Winchmore. In these situations, intervals between irrigations, at any one soil moisture deficit, varies considerably;

(b) in conjunction with soil scientists, the soil moisture component of the simulation model could be refined to accurately predict water harvested from a catchment and to reliably monitor available dam water. This

would be useful in project design exercises of water harvesting irrigation proposals;

(c) the LP model could be further developed to research the potential of irrigation in regions throughout N.Z. This could be done now for pasture systems. For systems involving crops other than pasture, it would be most desirable to have available for them growth simulation models to provide non-irrigated and irrigated crop growth input data for the LP model. Initially, the potential for irrigation in dairy pasture systems could be evaluated. As a first step in this, it would be useful to compare the economic and farm management results obtained from the present model to those obtained using the more complex dairy cow component developed by Pollard (1968) in place of the more simple dairy cow component developed in this study. This would establish the significance of the dairy cow component on the physical and economic output of a dairy grazing system. If it was found to be significant, there is probably sufficient experimental data available at Ruakura to improve Pollard's model. If a reliable dairy cow production model could be developed, this would undoubtedly have application by the Economics Division at least at Ruakura, in evaluating dairy research. Evaluating the potential for irrigation in beef production systems could be easily developed, as a beef production component is more simple to model. Also, a considerable amount of work on modelling beef systems has been carried out in N.Z.;

(d) before simulation and LP models similar to those applied in this study could be used routinely by the M.A.F.

the following two developments will be necessary: (i) reliable simulation model growth components for lucerne, and at least the major cash crops, will have to be developed to derive plant-irrigation response functions; and (ii) reliable dairy, beef and sheep production models will have to be developed.

The possible extensions to this study noted above are considerable. Most of them are very challenging and should they be carried out, will test the skills of those involved. The first two extensions are fairly narrow and specific. The latter two are very broad with ramifications in many other areas of evaluating aspects of agriculture using systems modelling than in just the economic evaluation of irrigation, e.g. in evaluating research proposals to aid in efficient allocation of research resources. The development of crop growth and animal production models should be carried out by a specialised systems modeller, preferably co-ordinating an inter-disciplinary team of researchers. Such an effort would probably take a number of years. However, the foundation for this work, the author believes, has already been carried out in N.Z. Economic evaluations in the fields of irrigation project design, optimising water allocations and determining the economic potential of irrigation,alone, would make building on to this foundation worthwhile.

APPENDIX I

A CATEGORISED LIST OF M.A.F. IRRIGATION ECONOMIC REPORTS (1)

Category	Project Name	Year of Report	Author
(i) Feasibility Studies	Maniototo	1952	Stuart et al.
	Cromwell-Ripponvale	1954	Schofield
	Dumbarton-Ettrick	1957	Stonyer et al.
	Upper Waitaki	1957	Twomey et al.
	Upper Waitaki	1958	Woods
	Fraser River	1958	Stonyer et al.
	Waimea	1960	Barwell et al.
	Hawea	1960	Stonyer et al.
	Wairau	1960	Stuart et al.
	Upper Aparima	1963	Farm Economics Section
	Lower Waitaki	1964	Donovan et al.
	Waianakarua	1969	Butler
	Glenmark	1972	Le Couteur
	Barrhill	1972	Johnson
	Hautere	1974	Dean
	Balmoral	1974	Neill et al.
	Awatere	1974	Greer
	Ashburton-Hinds	1974	Johnson
	Ngatarawa	1975	King et al.
	Kerikeri	1975	Hadfield
	Moroa	1975	King et al.
(ii) Project Evaluations	Maniototo	1961	Woods et al.
	Maniototo	1962	Woods et al.
	Hawea	1963	Woods

(1) This listing was compiled from Technical Paper No.3/75 (1975). These reports are unpublished and remain confidential documents until the proposal evaluated is accepted for funding by Government, at which stage a copy of the relevant report can be obtained from the M.A.F. by anyone requesting it.

Category	Project Name	Year of Report	Author
(ii) continued	Maniototo	1965	Plunkett
	Maniototo	1966	Plunkett
	Waiareka	1967	Plunkett
	Upper Waitaki	1967	Plunkett
	Lower Waitaki	1967	Butler et al.
	Maniototo	1967 (Sept.)	Butler
	Maniototo	1967 (Oct.)	Butler
	Lower Waitaki	1967	Butler
	Lower Waitaki	1968	Butler
	Maniototo	1968	Butler
	Lower Waitaki	1968	Butler
	Morven Glenavy	1968	Watkins
	Lower Waitaki	1969	Butler
	Rakaia	1970	van Asch
	Rakaia	1970	van Asch
	Waianakarua	1970	van Asch
	Maniototo	1970	van Asch
	Maniototo	1971	van Asch
	Loburn	1971	Bell
	Waiau	1973	Bell
	Maryburn-Simons Pass	1974	Johnson
	Hautere	1974	Dean
	Waiau Plains	1974	Ross et al.
	Glenmark	1974	Le Couteur
	Maniototo	1974	Johnson
	Inaha	1974	Dean
	Waimea	1975	Greer
	North Bank - Rakaia River	1975	Johnson
	Moutere	1975	Greer
	Greenstreet	1975	Ross
(iii) Project Designs	Maniototo	1967 (Dec.)	Butler
	Teviot	1973	Sorrenson et al.
(iv) Other	Valetta - Analysis of Accounts	1968	Economics Section
	Hawera - Ex post study	1968	Economics Section
	Maniototo - Survey of Private Irrigation	1969	Butler

Category	Project Name	Year of Report	Author
(iv) continued			
	Upper Waitaki – Ex post Study	1969	Economics Section
	Upper Waitaki – Ex post Study	1972	Bell
	Canterbury – Productivity Study	1973	Le Couteur et al.
	Otago – Review of Irrigation	1974	Cairns et al.

APPENDIX 2

PASTURE GROWTH RELATIONSHIPS AND PASTURE CONSERVATION ACTIVITIES

Relationships between monthly available pasture produced (kg DM/ha/month) and grazing frequency (weeks) for grazing intensity of 1100 kg DM/ha

TABLE A2.1 'Average' year, non-irrigated

Grazing frequency	2*	3**	4*	5**	6*	7**	8*	9**	10*	11**	12*
Month:-											
July	634	641	647	646	645	636	627	613	598	578	558
A	808	828	848	865	881	885	889	891	893	885	877
S	1399	1459	1518	1556	1593	1603	1612	1604	1595	1582	1569
O	2115	2244	2372	2392	2412	2374	2336	2279	2222	2162	2102
N	1988	2140	2291	2297	2302	2242	2181	2064	1946	1826	1705
D	1564	1695	1826	1851	1875	1822	1768	1689	1610	1474	1338
J	1428	1502	1575	1609	1643	1584	1524	1435	1345	1226	1106
F	934	962	990	998	1005	955	905	870	834	742	650
M	827	849	870	880	890	877	863	803	743	711	678
A	786	799	811	819	826	806	786	766	745	703	661
M	728	735	742	740	738	719	699	669	638	596	554
June	684	692	699	696	693	683	672	648	624	609	593
Total	13895	14546	15190	15349	15503	15186	14859	14331	13792	13094	12391

* Derived by experimentation with the simulation model

** Mid-points of the figures derived from the simulation model

TABLE A2.2 'Average' year, irrigated

Grazing Frequency	2*	3**	4*	5**	6*	7**	8*	9**	10*	11**	12*
Month:-											
July	634	641	647	646	645	636	627	613	598	578	558
A	808	828	848	865	881	885	889	891	893	885	877
S	1399	1459	1518	1556	1593	1603	1612	1604	1595	1582	1569
O	2124	2253	2382	2402	2422	2384	2346	2289	2231	2177	2123
N	2112	2271	2430	2432	2433	2365	2296	2175	2053	1974	1895
D	1944	2106	2268	2285	2302	2205	2108	2002	1895	1731	1566
J	1838	1943	2047	2049	2051	1934	1816	1654	1492	1365	1238
F	1370	1417	1463	1455	1447	1358	1268	1179	1089	968	846
M	1064	1096	1127	1128	1129	1077	1025	947	869	790	710
A	816	830	844	850	855	825	794	752	710	648	585
M	729	736	742	749	736	715	693	664	634	681	541
June	684	692	699	696	693	685	672	648	623	601	578
Total	15521	16272	17014	17113	17187	16672	16144	15418	14683	13980	13083

* Derived by experimentation with the simulation model

** Mid-points of the figures derived from the simulation model

Relationships between available pasture produced (kg DM/ha) and length of spell following grazing (weeks) for grazing intensity of 1100 kg DM/ha.

TABLE A2.3 'Average' year, non-irrigated

Spell	2	3	4	5	6	7	8	9	10	11	12
Month:-											
July	317	428	748	972	1204	1604	2009	2401	2787	3297	3776
A	404	779	1183	1600	2034	2640	3225	3759	4264	4644	4963
S	700	1291	1945	2572	3209	3737	4233	4629			
O	1058	1657	2332	2919	3508	3885	4193	4471			
N	994	1496	2059	2537	3026	3339	3621	3797			
D	782	1224	1701	2133	2581	2734	2821	2933			
J	714	992	1283	1554	1827	1956	2099	2190			
F	467	693	930	1159	1393	1557	1709	1813			
M	414	625	841	1054	1271	1425	1568	1670			
A	393	584	777	965	1151	1293	1428	1538			
M	364	541	721	892	1062	1202	1336	1443			
June	342	506	674	833	992	1199	1408	1605	1803	2164	2517

TABLE A2.4 'Average' year, irrigated

Spell	2	3	4	5	6	7	8	9	10	11	12
Month:-											
July	317	528	748	972	1204	1604	2009	2401	2788	3300	3787
A	404	779	1183	1600	2034	2642	3230	3767	4273	4696	5079
S	700	1293	1950	2580	3219	3777	4299	4722			
O	1062	1695	2406	3025	3644	4108	4521	4822			
N	1061	1663	2349	2930	3519	3872	4163	4331			
D	972	1539	2158	2680	3202	3377	3504	3539			
J	919	1326	1756	2116	2473	2594	2689	2716			
F	685	983	1296	1574	1853	1962	2056	2101			
M	532	756	986	1202	1420	1543	1654	1724			
A	403	599	793	987	1164	1299	1426	1526			
M	365	541	721	897	1061	1202	1333	1440			
June	342	506	674	833	992	1200	1408	1605	1803	2160	2509

TABLE A2.5 'Dry' year, non-irrigated

Spell	2	3	4	5	6	7	8	9	10	11	12
Month:-											
July	316	529	753	974	1202	1604	2018	2425	2794	3293	3723
A	403	783	1199	1629	2083	2673	3252	3771	4288	4579	4969
S	697	1287	1946	2553	3153	3675	4189	4451			
O	1036	1625	2283	2805	3308	3487	3611	3562			
N	966	1213	1472	1708	1991	2044	2142	2315			
D	338	496	659	854	1049	1267	1481	1753			
J	287	462	643	834	1036	1131	1226	1299			
F	336	392	451	521	594	762	929	1100			
M	97	265	435	610	790	975	1161	1319			
A	330	517	709	896	1079	1252	1429	1515			
M	366	545	727	893	1053	1223	1398	1474			
June	342	506	675	827	975	1207	1430	1640	1870	2171	2471

TABLE A2.6 'Dry' year, irrigated

Spell	2	3	4	5	6	7	8	9	10	11	12
Month:-											
July	316	529	753	974	1201	1604	2018	2425	2794	3327	3843
A	403	783	1199	1629	2083	2686	3277	3801	4318	4775	5367
S	697	1299	1972	2591	3204	3762	4291	4591			
O	1060	1704	2427	2989	3517	4015	4459	4804			
N	1067	1649	2293	2880	3520	3827	4034	3773			
D	941	1498	2015	2568	3137	3206	3340	2910			
J	868	1241	1641	1981	2305	2424	2667	2436			
F	639	941	1260	1535	1814	1904	2082	2184			
M	533	760	996	1215	1431	1556	1669	1735			
A	409	605	806	986	1158	1306	1458	1540			
M	366	545	727	890	1048	1206	1368	1459			
June	342	506	675	827	974	1207	1430	1640	1870	2154	2437

TABLE A2.7 Pasture conservation activities

Activity name	Period in which conserved area is closed	Period in which conserved area is harvested	Number of irrigations
(A) SILAGE PRODUCTION			
S001	Sep. 2	Nov 1	
S002	Sep. 2	Nov 2	
S003	Oct. 1	Nov 2	
S004,S005	Sep. 2	Nov 1	1
S006	"	"	2
S007,...,S009	"	"	1
S010,...,S012	Sep. 2	Nov 2	2
S013	"	"	3
S014,...,S016	Oct. 1	Nov 2	1
S017,...,S019	"	"	2
S020	"	"	3
(B) HAY PRODUCTION			
H001	Oct. 1	Dec. 1	
H002	Oct. 2	Dec. 2	
H003	Nov. 1	Jan. 1	
H004	Nov. 2	Jan. 2	
H005,...,H008	Oct. 1	Dec. 1	1
H009,...,H014	"	"	2
H015,...,H018	"	"	3
H019	"	"	4
H020,...,H023	Oct. 2	Dec. 2	1
H024,...,H029	"	"	2
H030,...,H033	"	"	3
H034	"	"	4
H035,...,H038	Nov. 1	Jan. 1	1
H039,...,H044	"	"	2
H045,...,H048	"	"	3
H049	"	"	4
H050,...,H053	Nov. 2	Jan. 2	1
H054,...,H059	"	"	2
H060,...,H063	"	"	3
H064	"	"	4

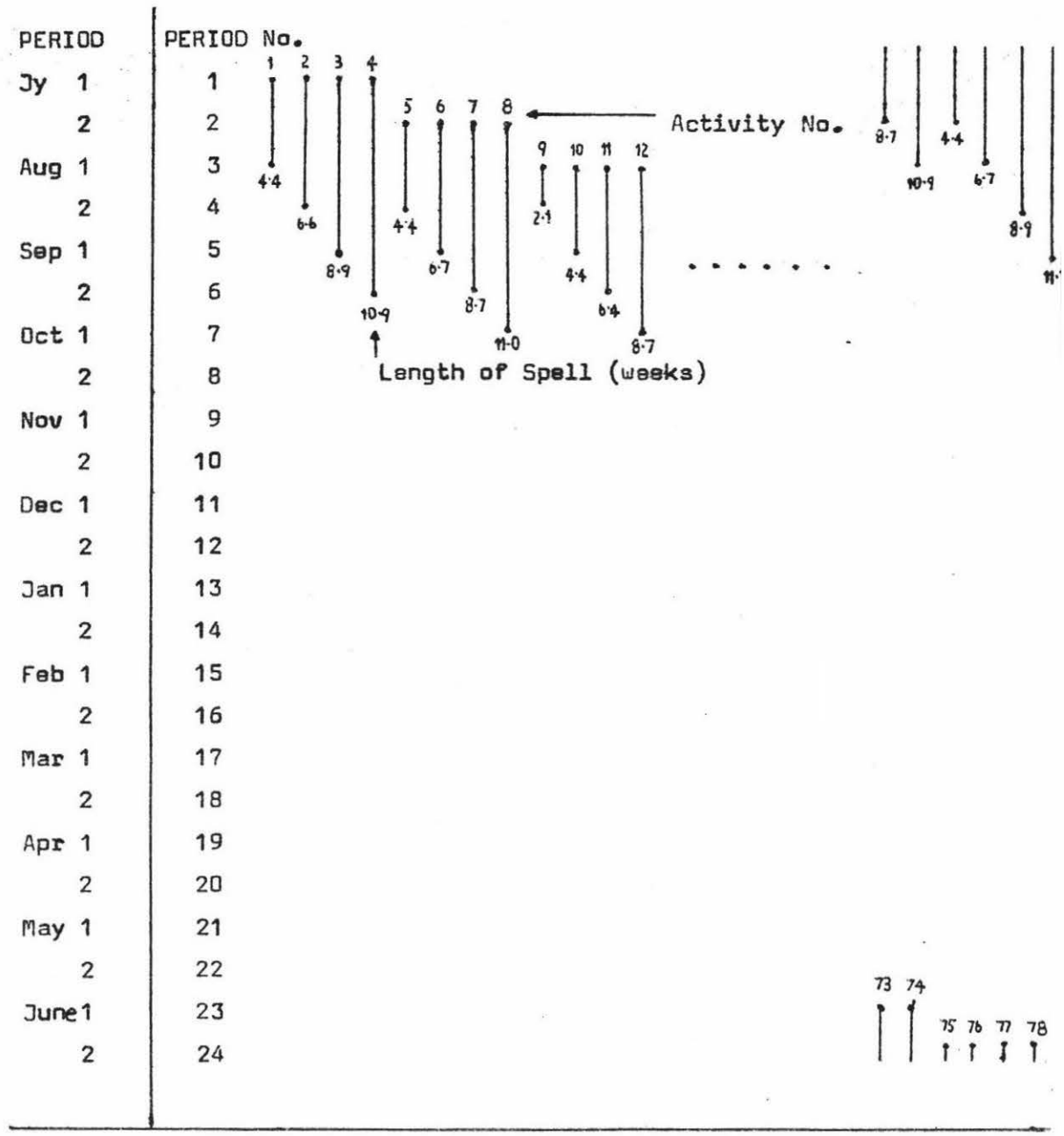

FIGURE A2.1 An illustration of the pasture activities, non-irrigated (P001,...,P078).

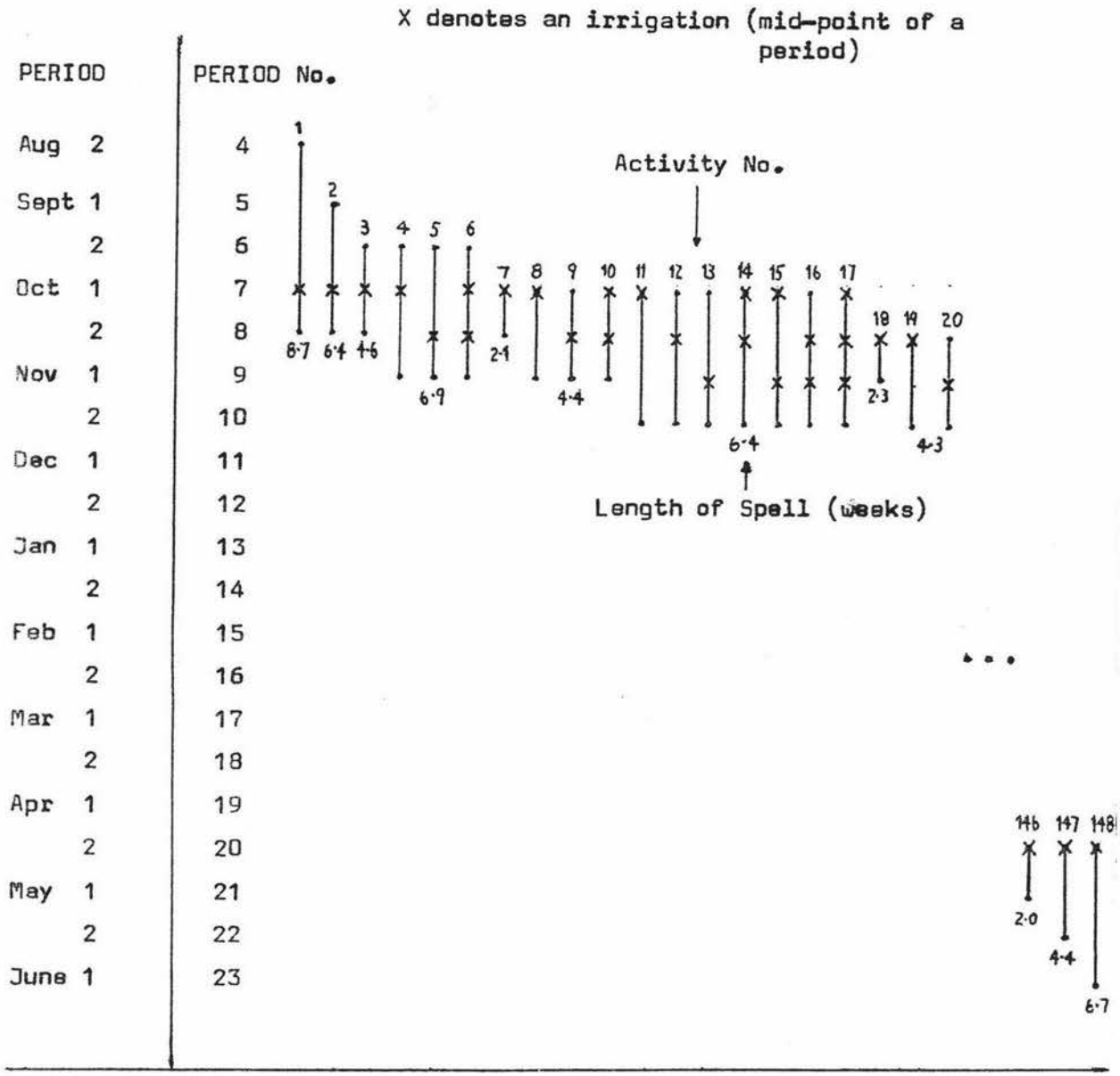

FIGURE A2.2 An illustration of the irrigated pasture activities (I001,...,I148)

APPENDIX 3

DETAILS OF THE LP MATRIX

A summary of the LP matrix is presented in Figure A3.1. A key to the rows and columns of the matrix is given below:-

COLUMNS (ACTIVITIES) (1)

P001,...,P078	PASTURE activities which refer to 1 hectare of non-irrigated pasture grazed to a specified height of 1100 kg DM/ha and spelled for a specified period of time following the previous grazing.
I001,...,I148	IRRIGATED pasture activities. They are the same as the above activities except that they refer to irrigated pasture.
S001,...,S020	per hectare SILAGE production activities (S001,...,S003 non-irrigated; S004,...,S020 irrigated).
H001,...,H064	per hectare HAY production activities (H001,..., H004 non-irrigated; H005,...,H064 irrigated).
G000	HAY BUY activity (per tonne total weight).
J000	MEAL BUY activity (per tonne total weight).
K000	HAY SELL activity (per tonne total weight).
L001,...,Y003	ANIMAL activities expressed per hectare.
A001,...,A024	SILAGE FEEDING activities.
B001,...,B024	HAY FEEDING activities.
M001,...,M024	MEAL FEEDING activities.

ROWS (CONSTRAINTS)

F01,...,F24	feed reconciliation rows.
Z00	a free row that calculates the total amount of DM produced (in kg DM/162 ha. non-irrigated pasture equivalents) as a result of the pasture production activities chosen.

(1) All activities are expressed in kg DM/ha, non-irrigated pasture equivalents.

L01,...,L24	land constraints.
T00	total land constraint.
A01,...,A20	total irrigable area constraints.
S00	silage reconciliation row)
H00	hay reconciliation row) in kg DM non-irrigated
M00	meal reconciliation row) pasture equivalents.
E11,...,E14	animal constraints that calculate total farm animal demands at 1.0 lactating cow/acre.
E21,...,E24	animal constraints that calculate total farm animal demands at 1.5 lactating cows/acre.
E31,...,E34	animal constraints that calculate total farm animal demands at 2.0 lactating cows/acre.
U01,...,U24	supplementary feed constraints that ensure no more than 25% of lactating cow demands are supplied by hay or silage, but meal can be fed at any level. They also ensure that no hay or silage is fed to calves, although meal can, and that dry cows and yearlings can be fed up to 100% on hay or silage, but no meal.
W00	irrigation water constraint.

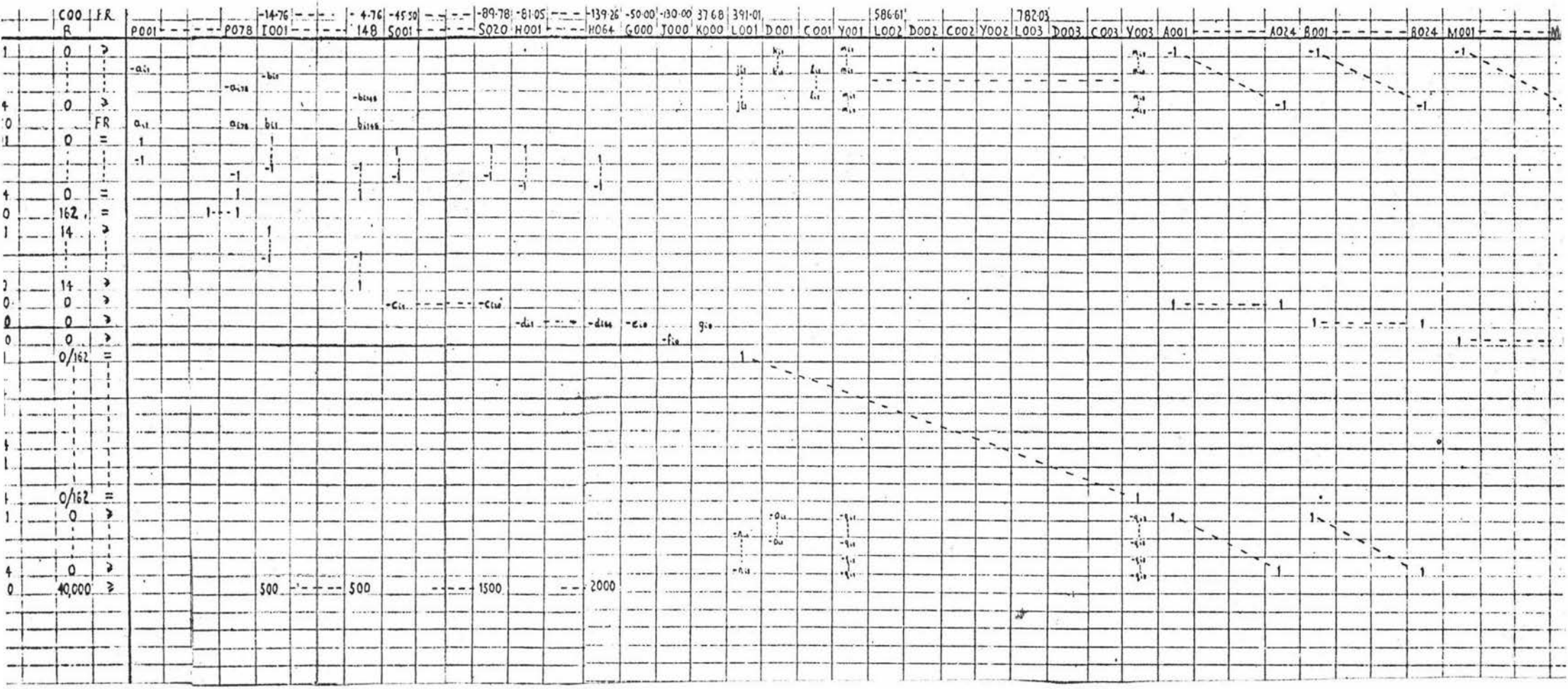

FIGURE A3.1 Summary of the LP matrix

APPENDIX 4

GROSS MARGIN DETAILS

PER HECTARE IRRIGATION COSTS

Basic assumptions

Plant operated 6 hours per irrigation.

Area irrigated per shift 1.25 acre = .50 hectare.

2 shifts per day.

0.5 man hour of labour involved per shift of pipes.

Every cycle, engine and pump (including pipes) shifted 3 times (each dam). 1.5 hours involved per engine and pump shift. Opportunity cost of casual labour, $1.60 per hour.(1)

Repairs and maintenance (R&M) are assumed to maintain the engine, pump and other irrigation equipment for 20 years. Cost of R. & M. of irrigation equipment is assumed to be $0.02 per kW hour (2).

Costs

Labour per rotation of 14 days = [0.5 x (14x2)-3] + [1.5x3] = 17 hours

17 hours at $1.60 = $27.20

Hours of plant operation per rotation =

6 x 2 x 14 = 168

∴ labour cost per hour of operation = $0.16

Fuel - power of engine = 55 HP
Engine running at 20 HP
1 gallon of diesel provides 16 HP work for 1 hour (3)

∴ 20 HP requires 1.25 gals per hour

Cost of diesel (Sept.1975), bulk delivery =

$0.095 per litre = $0.432 per gallon

∴ cost of fuel per hour of operation = $0.54

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(1) Assumptions concerning labour were obtained from K.Lowe (pers.comm.)

(2) This cost was obtained from J. Bealing, FAO, MAF, Palmerston North (pers.comm.).

(3) Detail provided by R. Clarke (pers.comm.).

R. & M. = $0.02 per kW hour

∴ @ 20 HP = 20 x .75 = 15 kW

∴ cost per hour = $0.30

Running costs : lubricants, oils, filters etc. =
$0.015 per kW hour (J. Bealing pers.comm.).

∴ @ 15 kW = $0.23 per hour

∴ total irrigation cost per hour of operation = $1.23

∴ per hectare cost of an irrigation = 12 x $1.23 = $14.76[4]

PER HECTARE SILAGE PRODUCTION COSTS

Non-irrigated= $45.50 including stacking (Price Book, 1975).
Irrigated = $45.50 plus $14.76 per irrigation

PER HECTARE HAY PRODUCTION COSTS

Basic assumptions

1 bale of hay = 53 lb = 24 kg (Jagusch, 1973)
% DM of hay = 85 (Research Adviser, No.15, 1975).
Costs: baling = $0.16 per bale
mowing = $9.25 per hectare
side raking = $5.00 per hectare
hay conditioning = $5.00 per hectare
transport = $0.18 per bale
(Price book, 1975)

Yields of hay produced (kg DM/hectare) from pasture growth simulation model.

Costs

Common per hectare costs:	mowing	$9.25
	side raking	5.00
	conditioning	5.00
		$19.25

(4) The simplifying assumption is made that $14.76 is the per hectare cost of an irrigation for every period. Because of the varying number of days in each period this cost should in fact vary. However, the pasture growth simulation model only represents the portions of the irrigable area that are irrigated only once every 14 days. This in itself is a simplifying assumption. For e.g. in Dec.2, which has 16 days, only 87.5% = (14/16 x100) is represented. The remaining 12.5% should receive 2 irrigations, but in fact doesn't.

Other costs: baling $0.16 per bale
transport $0.18 per bale
$0.34

Each bale = 24 x 0.85 = 20.40 kg DM
∴ other costs = $0.34 ÷ 20.40 = $0.0166 per kg DM

Irrigated hay = $19.25 per hectare, plus other costs at $0.0166 per kg DM produced per hectare, plus $14.76 per irrigation.

PER TONNE TOTAL WEIGHT HAY SELL GROSS MARGIN

Basic assumptions

Hay sold at $1.00 per bale (K.I. Lowe, pers.comm.).
Additional fertiliser required is 3 cwt of potassic super per acre (R. Halford, pers.comm.).

Gross margin - per tonne total weight

Hay sold is subtracted from the hay reconciliation row (HOO). ∴ costs of producing it are included in the HAY BUY activity.

Return, per tonne = $\frac{1000}{24}$ = 41.66 bales @ $1.00 = $41.66

Unaccounted cost = additional fertiliser costs =
.6405 ¢/kg DM, non-irrigated pasture equivalents, farmer view point;
.9409 ¢/kg DM, non-irrigated pasture equivalents, national view point.

∴ gross margin = 41.66 - (621 x .6405 = 3.98) = 37.68 farmer viewpoint ;
= 41.66 - (621 x .9409 = 5.84) = 35.82 national viewpoint.

PER TONNE TOTAL WEIGHT HAY BUY COSTS

Basic assumptions

1 bale of hay = 24 kg

% DM = 85

Per bale cost = $1.20 including transport and stacking (K.I. Lowe, pers.comm.).

Costs

Bales per tonne = 1000 ÷ 24 = 41.66

Cost @ $1.20 per bale = 41.66 x 1.20 = $50.00

kg DM, non-irrigated pasture equivalents per tonne =

41.66 x 14.90 = 621

(where 14.90 = (8 ÷ 10.95) x 24 x .85).

PER TONNE TOTAL WEIGHT MEAL BUY COSTS

Basic assumptions

Meal cost $130.00 per tonne total weight (Price Book, 1975)

% DM of meal = 87% and energy content = 3.1 MCal ME/kg DM

(Jagusch, 1973)

Costs

$130.00 per tonne total weight = 870 kg DM =

(13.1 - 10.95) x 870 = 1041 kg DM, non-irrigated pasture equivalents.

PER HECTARE ANIMAL ACTIVITIES GROSS MARGINS (FARMER AND NATIONAL VIEWPOINTS)

Basic assumptions

145 kg milk fat produced per cow; breeding own replacements; 25% replacements; 90% calving; cows first calve at 2 years of age.

Gross margins

Stocking rate	2.471 (1.0)	3.707 (1.5)	4.942 (2.0)
	Mean ($)	Mean ($)	Mean ($)
Gross revenue (farm gate)			
Butterfat 145 kg @ $1.17[5]	419.21	628.89	838.41
Bobby calves .65 @ $8.00[5]	12.85	19.28	25.70
Cull cows .15 @ $48.00[5]	17.79	26.69	35.58
Total gross revenue	449.85	674.86	899.69
Direct costs[6]			
Bull or AB ($3.04 per cow)	7.51	11.27	15.02
Shed costs ($2.05 per cow)	5.07	7.60	10.13
Power ($3.57 per cow)	8.82	13.23	17.64
Vet. & An.Health ($4.60 per cow)	11.37	17.05	22.73
Freight ($2.75 per cow)	6.80	10.19	13.59
Replac. grazing ($7.80 per cow[7])	19.27	28.91	38.55
Total direct costs	58.84	88.25	117.66
Gross margin	391.01	586.61	782.03

(5) Product prices (1975)

(6) Gross margins (1975/76)

(7) Costs based on those supplied by K. Lowe (pers.comm.).

APPENDIX 5

IRRIGATION AND FERTILISER COSTS

DAMS (D. Bowler, pers.comm.)

'No.1 Dam'	$650
'No.2 Dam'	$600
'No.3 Dam'	$2000
	$3250

Maintenance cost of the dams (associated cost) $10/annum

SPRAY IRRIGATION PLANT (R.M. Clarke, pers.comm.)

Item	Capital cost ($)
Diesel engine and trailer	4362.00
Diesel tank plus fittings	145.00
Additional stop for low fuel	60.00
Intake, outlet, spray lines and sprinklers	2968.50
Cartage and contingencies	250.50
	7786.00

ADDITIONAL FENCING

Around the dams

3 wire electric fence

Cost per 20 m - materials = $9.40 (Price Book, 1975)

- labour = $4.00 (Price Book, 1975)

$13.40

$\therefore$ estimated additional fencing cost = $\frac{1250}{20} \times 13.40 = \$837.50$

ADDITIONAL FERTILISER

Additional maintenance fertiliser on the irrigable area (over and above that applied to non-irrigated areas) was accounted for. This consisted of urea applied at a rate of 1 cwt per acre or .1255 tonnes/hectare (R. Halford, pers.comm).

Costs ($ per tonne) :	National viewpoint	Farmer viewpoint
Ex Works (N.Z. Farmers' Fert. Co., August 1975)	244.95 (Subsidy 18.25, Price Book, 1975)	226.70
Transport (Price Book, 1975)	8.17 (Subsidy 3.17)	5.00
Spreading (Price Book, 1975)	10.63	10.63
	263.75	242.33

Irrigable area = 14 hectares

∴ additional associated fertiliser cost per annum

= $463.41 national viewpoint

= $425.77 farmer viewpoint

SAVED FERTILISER

Costs ($ per tonne - Price Book, 1975) :	National viewpoint	Farmer viewpoint
Cost ex Works	45.70 (18.25 subsidy)	27.45
Transport	8.17	5.00
Spreading	7.21	7.21
	61.08	39.66
∴ Saved fertiliser cost (dam area)	24.43	15.86

(Assumed fertiliser rate = 200 kg/hectare)

APPENDIX 6

CASH FLOWS

TABLE A6.1 Normative evaluation cash flows (Farmer viewpoint differences in parentheses)

	Year: 0	1	19	20
ANALYSES N1A and N4A				
BENEFITS ($)				
TGM		0		0
Saved fertiliser costs		24	24	
		(16)	(16)	
COSTS ($)				
Capital				
Dams	3250			
Irrigation equipment	7786			
Fencing	838			
Associated				
Dams		10	10	
Additional fertiliser		463	463	
		(426)	(426)	
Income forgone		782		782
ANALYSES N2A and N5A				
BENEFITS ($)				
TGM		643		643
Saved fertiliser costs – same as Analyses N1A and N4A				
COSTS ($)				
Capital				
Same as Analyses N1A and N4A				
Associated				
Dams	same as Analyses N1A and N4A			
Additional fertiliser	" " " " " "			
Income forgone		1173		1173
ANALYSES N3A and N6A				
BENEFITS ($)				
TGM		2012		2012
Saved fertiliser costs – same as Analyses N1A and N4A				
COSTS ($)				
Capital				
Same as Analyses N1A and N4A				
Associated				
Dams	same as Analyses N1A and N4A			
Additional fertiliser	" " " " " "			
Income forgone		1564		1564

TABLE A6.2 Positive evaluation cash flows (Farmer viewpoint differences in parentheses)

	Year: 0	1	19	20
ANALYSES P1A and P3A				
BENEFITS ($)				
Additional revenue		826	826	826
Saved fertiliser costs		24	24	
		(16)	(16)	
COSTS ($)				
Capital (same as normative analyses)				
Dams	3250			
Irrigation equipment	7786			
Fencing	838			
Associated				
Dams (same as normative analyses)		10	10	
Irrigation		1240		1240
Additional fertiliser (same as normative analyses)		463	463	
		(426)	(426)	
Income forgone		1173		1173
ANALYSES P2A and P4A				
BENEFITS ($)				
Additional revenue		1032		1032
Saved fertiliser costs – same as Analyses P1A and P3A				
COSTS ($)				
Capital				
Same as Analyses P1A and P3A				
Associated				
Same as Analyses P1A and P3A				

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