ABARE CONFERENCE PAPER 93.2

The West Berriquin Irrigation District
A case study in bioeconomic modelling

David Poulter, Nigel Hall and Leanne Greer
Australian Bureau of Agricultural and Resource Economics
GPO Box 1563, Canberra 2601

37th Annual Conference of the
Australian Agricultural Economics Society
University of Sydney, 9–11 February 1993

A recursive linear programming model of agriculture in the West Berriquin Irrigation District is described in this paper. Yields are made endogenous by including the effects of farm production decisions on the groundwater table and therefore salinity and waterlogging which affect yields.

Using the model, three simulations are run to examine farm enterprise mix decisions, farm profit and groundwater rises. First, the model is used to examine the effects of rising groundwater under current input and output prices. Second, the effect of raising water delivery prices is simulated. Third, the effect of installing district drainage is simulated.

ABARE project 9142.102

Introduction

Many irrigation districts are facing the problem of high groundwater tables. When groundwater tables rise to or near the surface, plant yields can be reduced through waterlogging of plant root zones and salinity. The way farmers adjust their farm production decisions in response to the effects of rising groundwater can have important implications for the viability of future irrigation and for the development of policies to mitigate the effects of rising groundwater. Farmers can be expected to change their farm management in response to falling yields. These changes could include reducing farming intensity or changing farming methods, or altering enterprise mix, for example, by choosing more salt tolerant plants.

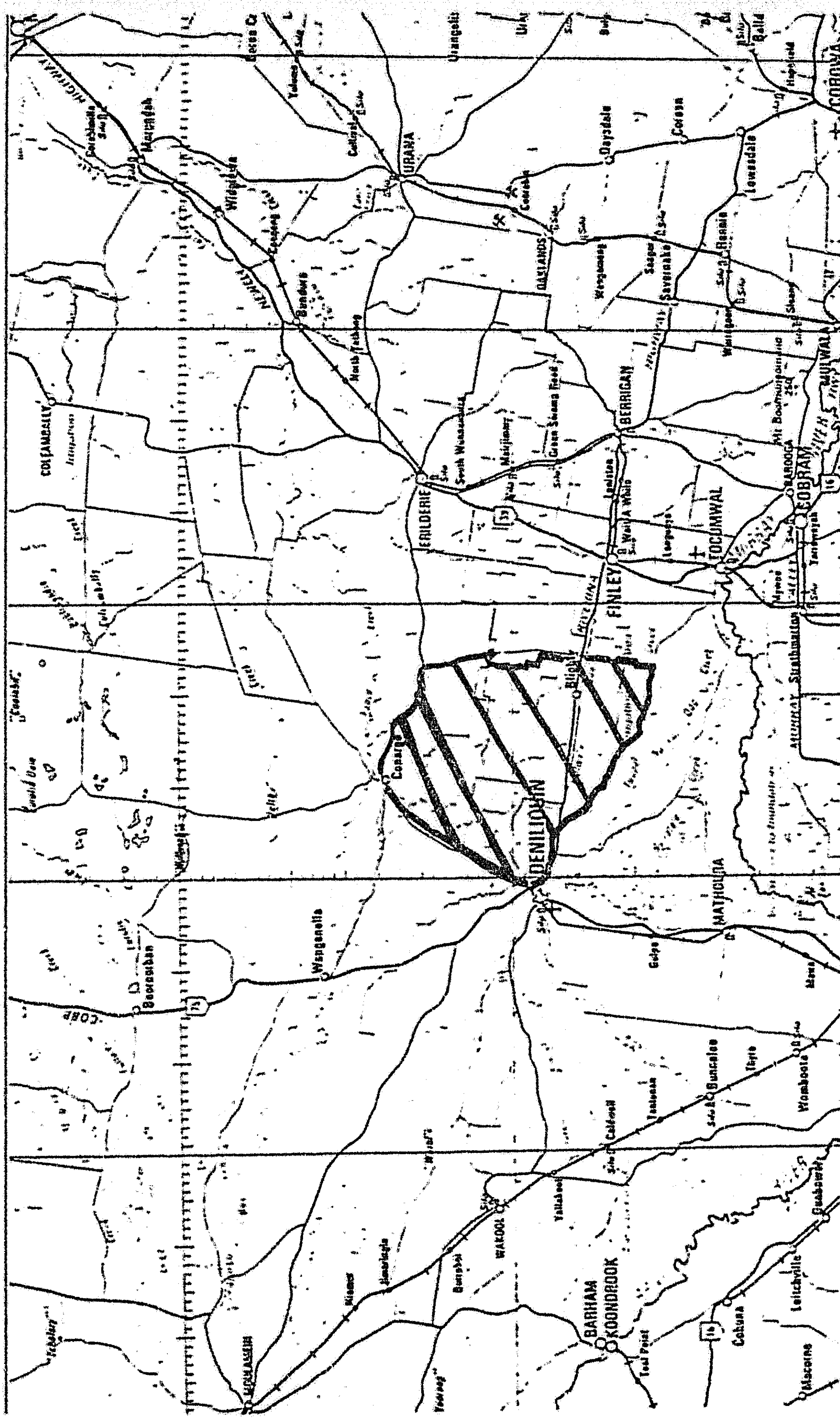
Often assessments of resource management policy alternatives have been based on the assumption that livestock and cropping patterns will not change, despite yield losses resulting from salinity and waterlogging (see, for example, Young 1992). This assumption is relaxed in this paper.

A mathematical programming model based on the West Berriquin area is described in this paper. Traditionally, linear programming models have been used to model farm production decisions where the model chooses between different production and investment options to satisfy an objective function, usually profit maximisation. Agronomic relationships such as yields have often been assumed to be constant in these models. In this study, a model of farm production and investment decisions is developed — based on a model developed by Hall, Mallawaarachchi and Batterham (1991) — which incorporates the effects of farm production decisions on groundwater accessions. The effect of rises in the groundwater table and the consequent problems with waterlogging and irrigation salinity are included in the model as a reduction in plant yields. Specifying the model in this way allows the possible responses of farmers to rising groundwater tables over time to be analysed. The model is then used to analyse the effects of policy options such as increasing water delivery prices and introducing regional drainage schemes.

Background

In November 1990 the Murray–Darling Basin Commission started a pilot study of three areas in the Murray–Darling Basin. The purpose in the study was to develop the methods needed to evaluate the present state and condition of natural resources in these study areas and assess their likely condition in twenty years time. The aim in the pilot study was to

Map 1: West Berriquin Irrigation District of New South Wales



provide the basis for developing and testing methods that could be applied to the basin as a whole.

The West Berriquin Irrigation District in New South Wales was one of the areas chosen for the pilot study. In the first stage of the study, data were collected on soils, land use, water table depths and salinity. These data were largely supplied by officers of state agencies. However, some additional data were collected from a survey of sites in the Berriquin area (Landsberg, Hirst and Nanninga 1991).

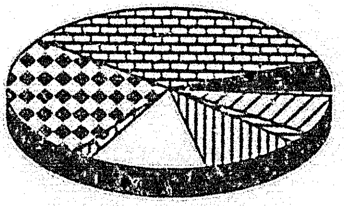
The Berriquin Irrigation District is located in the Riverina area of southern New South Wales. Major towns bordering the District are Deniliquin and Berrigan. The area chosen for the pilot study was the western part of the Berriquin Irrigation District, roughly bordered by Deniliquin, Conargo and Finely (map 1). There are around 280 properties in this district.

The West Berriquin Irrigation District is part of an alluvial flood plain dissected by light soil prior streams. These prior streams have left a distinct pattern of soils. Soils in the West Berriquin District can be grouped into five main categories: sand, loams, clay loams, light clays and medium to heavy clays. These areas have had a high rate of rise in groundwater from water accessions (New South Wales Department of Water Resources 1991b).

Initially, land in the district was used for wool and sheep production. The district was gazetted in 1934 as a Domestic and Stock Water Supply and Irrigation District (Landsberg et al. 1991). Water distribution started in 1939 and by 1944 much of the area was supplied with irrigation water. Originally, the scheme was designed to provide drought relief for stock and for the irrigation of pasture and fodder crops. Use of water for irrigating rice was not permitted. However, this has changed and currently there is extensive growing of rice and other irrigated crops in the district. Landsberg et al. (1991) reported from their field survey that around two thirds of the area was under pasture. The remainder of the land in the district was used for irrigated rice, irrigated wheat, dryland wheat and other crops (figure 1).

Gradual increases in water allocations and the introduction of intensive agriculture have increased the area of high water table and waterlogging (Landsburg et al. 1991). The problem currently facing the district is related to excess irrigation and rainfall runoff. Irrigation water or rainfall that is not used by plants and does not leave the paddock as

Figure 1. Land use of the West Berriquin Irrigation District, 1990



Irrigated permantent pasture 6%
Irrigated annual pasture 34%
Dryland annual pasture 25%
dryland permanent pasture 2%
Rice 12%
Irrigated wheat 10%
Dryland wheat 2%
Other irrigated crops 8%
Other dryland crops 1%

Source: Landsberg, Hirst and Nanninga (1991)

drainage or evaporation soaks through the soil until it reaches a layer that will not let water through. The aquifer then begins to fill from the bottom up and the water table begins to rise (Evans, R., Australian Geological Survey Organisation, personal communication, July 1992). When the water table becomes high enough, capillary rise draws water to the surface. This causes the soil in the plant root zone to become waterlogged and brings salt to the surface. Waterlogging reduces the oxygen available to the plant roots and encourages the spread of disease organisms, particularly when there is standing water on the soil surface. The salts in the root zone reduce water inflow to the plant by reducing the osmotic pressure within the roots. It has been estimated that annual yield losses from a shallow saline groundwater table are 12.5 per cent for annual pasture, 20 per cent for winter cereals and 25 per cent for perennial pasture. The total loss from the district was estimated at 16 per cent of (potential) production in 1984 (Landsberg et al. 1991).

Extrapolating the trend in groundwater table rise over recent years led Landsburg et al. to predict that the area of the region with high groundwater tables would increase from 45 per cent to 65 per cent within ten years. However, a major shortcoming of this prediction is the assumption that current irrigation practices are fixed, and therefore farmers will not respond to resulting yield losses. By assuming agricultural production patterns will not or should not change, groundwater management strategies being developed may suffer from focusing on only a narrow set of management options.

The model

A schematic representation of the model is shown in figure 2. A more technical description of the model is provided in appendix A. The model is designed so that input purchases and the use of farm resources, such as land, are combined to produce farm output. Capital costs are included through a depreciation cost. The model is designed to simulate the production decisions of farmers by finding the combination of input use and outputs which maximises the capital value of farm activities. This is defined as the net present value of after-tax consumption income. The model is designed so that a proportion of net after-tax farm income is allocated to consumption income for the farm family. This approach is similar to that used in Hall, Mallawaarachchi and Batterham (1991).

The effects that production decisions have on groundwater tables are included in the model. Groundwater accessions add to the water table each year, increasing groundwater tables for the following years. Resulting changes in soil salinity and waterlogging are then used to recalculate plant yields.

The main source of yield and farm input data was the farm budget handbooks for the area, published by the New South Wales Department of Agriculture and Fisheries (Crean 1991, 1992a,b). Physical data for the West Berriquin Irrigation District were mainly obtained from the Geographical Information System (GIS) model developed by the Murray–Darling Basin Commission (Nanninga, P.M., Murray–Darling Basin Commission, personal communication 1992). The Commission's GIS model simulates the effect of current irrigation practices on groundwater tables and plant productivity in the district. In the GIS model, the district is divided into 23 areas of varying size. Each area is assumed to have homogeneous soil, water table depth, water table salinity and soil salinity characteristics. Soil is grouped into three types: sands and gravel, clay loam and heavy clay. Each soil type has different groundwater accession rates for each crop (table 1). For the lighter textured soils such as sands and gravel, groundwater accession rates are higher for various crop types than for heavier texture soils such as heavy clay.

The process by which groundwater tables rise and affect plant yields is complicated, and varies depending on the local hydrology, soil type and agricultural systems being used. Therefore the relationship between groundwater and yields is difficult to quantify beyond a rough approximation. In this study, the relationship for soil salinity used by the Murray–Darling Basin Commission in their GIS model of the area is used. This is a function of the groundwater depth, groundwater salinity, plant root depth and starting soil salt (see

Figure 2: Model structure

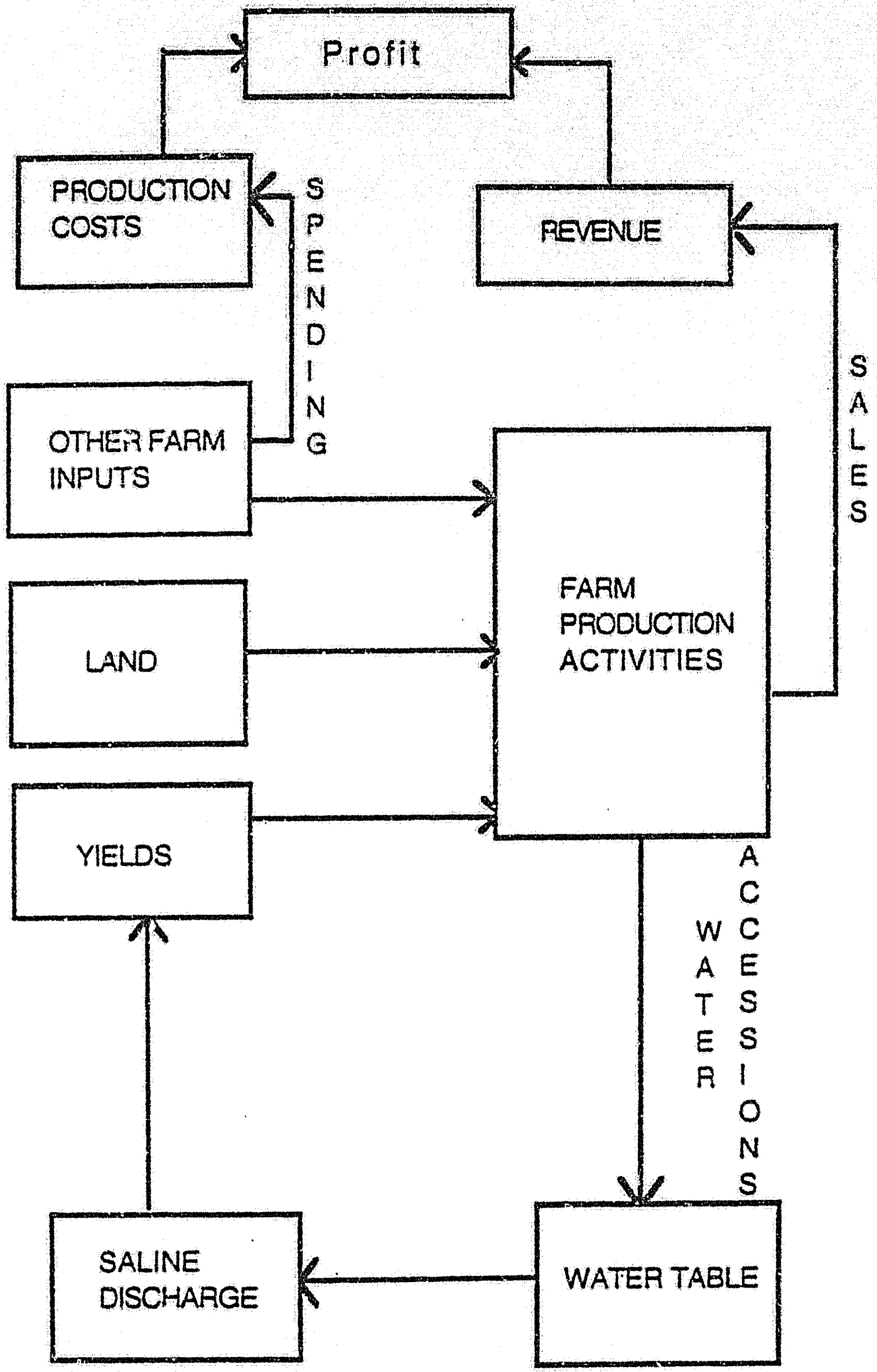


Table 1: Groundwater accession rates

	Sands and gravel	Clay loam	Heavy clay
	ML/ha	ML/ha	ML/ha
Rice	na	2.2	1.4
Irrigated wheat	1.6	0.8	0.6
Low irrigation wheat	0.5	0.4	0.3
Irrigated annual pasture	2.0	0.6	0.4
Low irrigation annual pasture	1.0	0.3	0.2
Irrigated perennial pasture	1.7	0.6	0.3
Low irrigation perennial pasture	0.8	0.3	0.15

Source: Murray–Darling Basin Commission.

appendix A). Groundwater salinity levels were obtained from maps of the salinity at the top of the aquifer provided by the New South Wales Department of Water Resources. Salinity at this level of the aquifer was chosen because this would be the salt that would be brought to the surface if groundwater tables rose (Evans, R., Australian Geological Survey Organisation, personal communication, July 1992). In table 2 the effect of salinity on different plant yields used in the model are presented. As can be seen, annual pasture and rice are more susceptible to salinity effects than wheat or permanent pasture.

Accessions to the groundwater table from irrigation were assumed to only affect groundwater tables directly beneath each crop, without influencing groundwater levels of

Table 2: Soil salinity effect on crop yields

	Threshold dS/m	Productivity fall per dS/m a
		%
Wheat	6.0	7.1
Rice	3.0	12.2
Annual pasture	1.5	12.1
Perennial pasture	5.6	7.6

a Productivity fall per dS/m beyond the threshold salinity level.
Source: Landsberg et al. (1991).

adjoining areas. This is a strong assumption. However, information on groundwater flows is scarce and the way aquifers affect each other is too complex to consider within the framework presented here. Nevertheless, information that is available for the area indicates that aquifers do, in general terms, fill like a bucket from the bottom up and there appears to be little neighbourhood effects until the aquifers become highly pressured (Evans, R., Australian Geological Survey Organisation, personal communication, July 1992). In these circumstances the assumption of no neighbourhood effects from groundwater accessions seems reasonable.

Waterlogging is assumed to occur when the groundwater table reaches the root zone of plants (Grieve, Dunford, Marston, Martin and Slavich 1986). Different plants have different root depths, and tolerance to waterlogging varies (table 3). Therefore the timing and extent of yield losses from waterlogging can be expected to vary depending on plant type.

Table 3: Effects of waterlogging on yields

	Reduction in yield from waterlogging
	%
Wheat	20.0
Rice	0.5
Annual pasture	10.0
Perennial pasture	16.0

Source: Grieve et al. (1986).

The model is disaggregated into representative farms. Using the available information on the West Berriquin District, the region is divided into four different farm models to represent different farm types. Because there are many dairy farms in the region a farm model representing dairy farming is included. Two farm models representing irrigated broadacre agriculture are included. The first has a higher proportion of heavy clay, on which a great deal of rice growing is conducted — this farm type is referred to as the rice farm in this study. The second representative irrigated farm model has a higher proportion of lighter soils and is referred to as a mixed farm. The rice farm and the mixed farm have a similar enterprise mix in the 1990 model results. However, it was felt that disaggregation was necessary because of the different physical resource characteristics of the two farm types. There are also some dryland farms in the area, particularly in the north of the district. Therefore, a representative farm model of dryland broadacre farming is included for completeness. The physical characteristics of each farm type are presented in table 4.

Each representative farm model is run recursively for twenty years. The results of each year's run that affected the farm's resources were saved and used as an input for the following year's run of the model. In this way the changing physical characteristics of the representative farms and changing farm responses can be simulated over time. The assumption is that farmers make decisions on the basis that their present resource situation will continue into the future. They will modify their management decisions only as they become aware of changes in their resources — for example, when yields fall because of a rising groundwater table. This approach differs from that of multiperiod models like that used in Mallawaarachchi, Hall and Phillips (1991) which assume perfect knowledge of the future and optimise over the whole period. Neither approach fully represents the decision framework because farmers have more foresight than is implied by the approach used in this paper but do not have the perfect knowledge and ability to optimise over time that is implied by the multiperiod approach.

A further simplifying assumption that should be noted is that in reality there will be other influences on farm profitability, such as changing input and output prices as well as technological change. These influences are not modelled. If prices and technology were

Table 4: Model farm characteristics

	Unit	Dairy	Rice	Mixed	Dryland
Area					
Sand and gravel	ha	222	8	78	87
Clay loam	ha	126	253	260	0
Heavy clay	ha	0	86	11	713
Groundwater depth					
Sand and gravel	m	1.50	2.05	1.18	3.47
Clay loam	m	1.89	2.91	2.17	na
Heavy clay	m	na	3.11	0.24	8.14
Groundwater salinity					
Sand and gravel	d/Sm	1.02	5.00	1.02	2.00
Clay loam	d/Sm	1.00	3.86	1.00	na
Heavy clay	d/Sm	na	3.78	1.05	5.00

na Not applicable.

assumed to change, and particularly if these changes had different time profiles, the results of this study could be significantly affected.

The sensitivity of the model results to variation in assumptions about the physical characteristics of the representative farms was tested. The results were most sensitive to a change in groundwater salinity. When this was increased, large changes in profit and enterprise mix resulted. Changes in other physical coefficients and constraints did not have major effects on the results.

Results

Farmers' response to rising groundwater tables

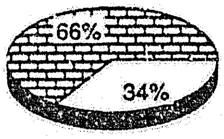
Using the groundwater settings specified in table 4 for the first year of the model, the four representative farm models were run for twenty years. The rise in the groundwater table for each year was fed into the model for the following year and yields were recalculated depending on the effects of irrigation salinity and waterlogging that had occurred. In this way the reactions of farmers to rises in the groundwater table can be estimated and the implications for economic viability and resource sustainability in the district seen. The enterprise mixes of the dairy, rice and mixed farm types in 1990, the base year, and 2009 are shown in figures 3.1, 3.2 and 3.3 respectively.

The results for the representative dairy farm in the first year, 1990, are that all the land available for irrigation is used for growing irrigated pasture. The remainder of the farm is taken up by dryland pasture. The pasture is used to run mainly dairy and beef cattle and some sheep. The dairy farm already has high groundwater tables on all soil types (less than 2 metres from the surface) and these rise even further over subsequent years (figure 4.1). A small drop in earnings occurs in the 1993 and 2003 runs of the model as irrigation salinity and waterlogging cut pasture yields so that stocking rates fall (figure 5.1). Rising groundwater does not change the optimal combination of enterprises mix. Therefore land use in 2009 remains the same, although carrying capacity has been reduced.

The rice farm has about 10 per cent of the farm area growing rice and 13 per cent allocated to irrigated wheat in 1990. The remainder of the farm is allocated to irrigated and dryland pasture which carries beef and sheep. This combination of land was found to continue until 1999, although livestock carrying capacity falls slightly in response to pasture yield losses that result from the effects of salinity and waterlogging (figure 3.2).

Figure 3: Effect of groundwater table rise on enterprise mix on three farm types: base case

Figure 3.1: Dairy 1990



Dairy 2009

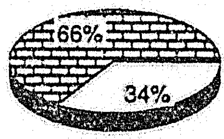
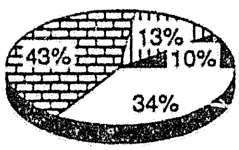


Figure 3.2: Rice 1990



Rice 2009

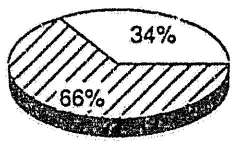
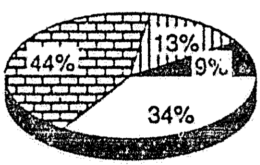
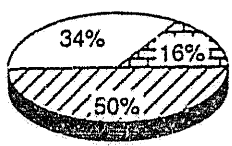


Figure 3.3: Mixed 1990



Mixed 2009



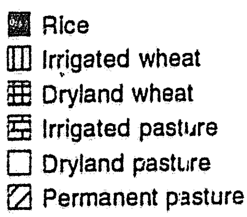


Figure 4: Groundwater table level in the base case for three farm types

Figure 4.1: Dairy farm

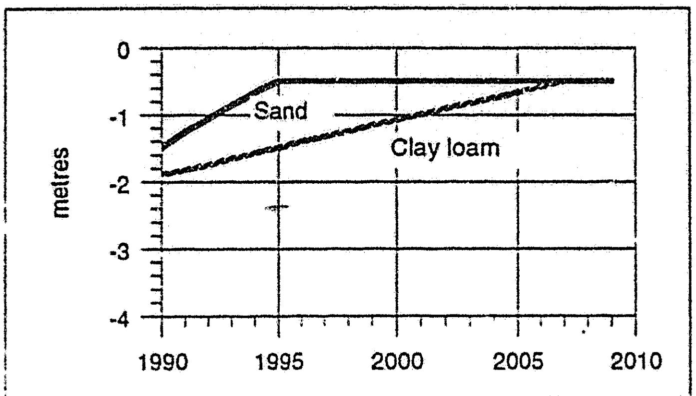


Figure 4.2: Rice farm

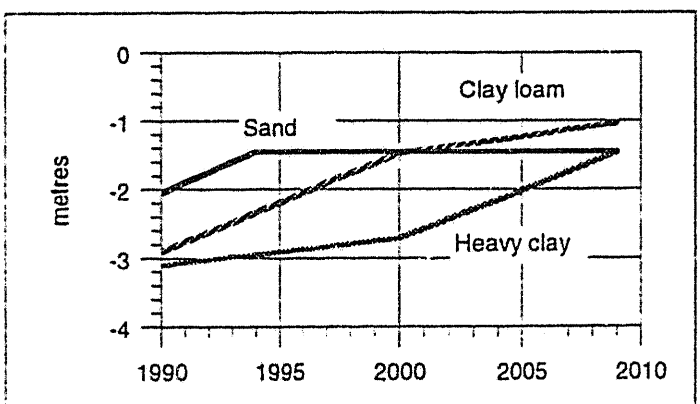
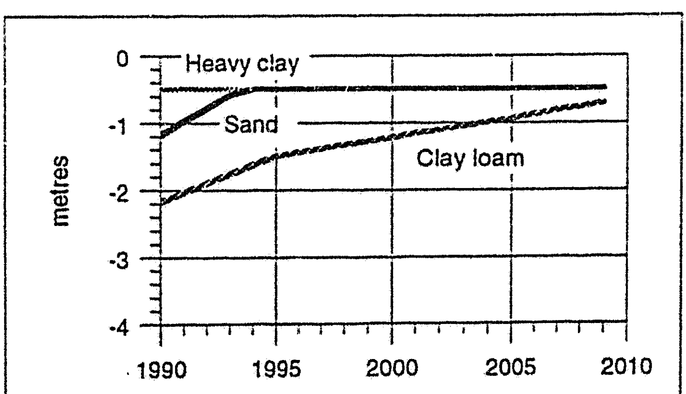


Figure 4.3: Mixed farm



From the year 2000, the groundwater table on clay loam soils rises to less than 1.5 metres from the surface (figure 4.2). At this point the effects of irrigation salinity become more severe and the result is that it is no longer optimal to maintain the same land use. The area planted to rice falls by around 35 per cent, irrigated wheat by around 90 per cent and irrigated pasture by around 80 per cent. The model indicates that it is optimal to replace these enterprises with permanent pasture, which is more salt tolerant. The level of dryland pasture is maintained. However, the farm enterprise changes are not enough to entirely offset the effect on income, and pre-tax profit falls to a lower level (figure 5.2). From 2000 to 2008 the enterprise mix remains constant, with some loss of stock carrying capacity and crop yields resulting from the effects of salinity and waterlogging. In the final year the groundwater table for heavy clay rises to less than 1.5 metres from the surface, rice and irrigated wheat production cease and are replaced with permanent pasture. There is a further reduction of pre-tax income.

The mixed broadacre farm has a similar initial production mix to the rice farm (figure 3.3). However, this farm starts with higher groundwater tables than the rice farm and so the effects of rising groundwater tables occurs in 1994 (figure 4.3). This is earlier than on the rice farm. Between 1994 and 1995, the amount of irrigated pasture grown falls by about 65 per cent, production of irrigated wheat ceases and the area of rice falls by nearly 90 per cent. This reflects the fact that nearly all irrigated cropping on this farm is conducted on clay loam soils. Therefore, the effect of a rise in the groundwater table on this particular area of the farm has more impact on total farm production than is the case for the rice farm model.

For the dryland farm, because there is no irrigation, there are no groundwater rises and therefore enterprise mix remains constant at 800 ha of dryland pasture over the twenty year period. However, this model run is based on the assumption that there is no general groundwater rise caused by land clearing and no groundwater rise as a result of spillover effects from irrigators in the area. If these assumptions did not hold, the results for the dryland farm may be different. Pre-tax profit on this farm remain unchanged over the twenty year period (figure 5.4).

There is a clear incentive for farmers in the region to respond to rising groundwater tables. If farmers do not respond and enterprise mixes are fixed at 1990 levels, then the present value of pre-tax profit in 2009 for the rice farm is estimated to be 33 per cent lower than if the enterprise mix is flexible. Pre-tax profit on the mixed farm is estimated to fall by 7 per cent if enterprise mix is fixed. Clearly the viability of remedial works will be overestimated if the 'do nothing' option in economic assessments assumes that farmers will conduct business as usual. In addition the relative merits of alternative works may be wrongly estimated.

District drainage

The effect of district drainage being installed in the area is simulated in the model for each representative farm by restricting groundwater tables to rise to no higher than 2 metres

Figure 5: Net pre-tax profit on the four farm types

Figure 5.1: Dairy farm

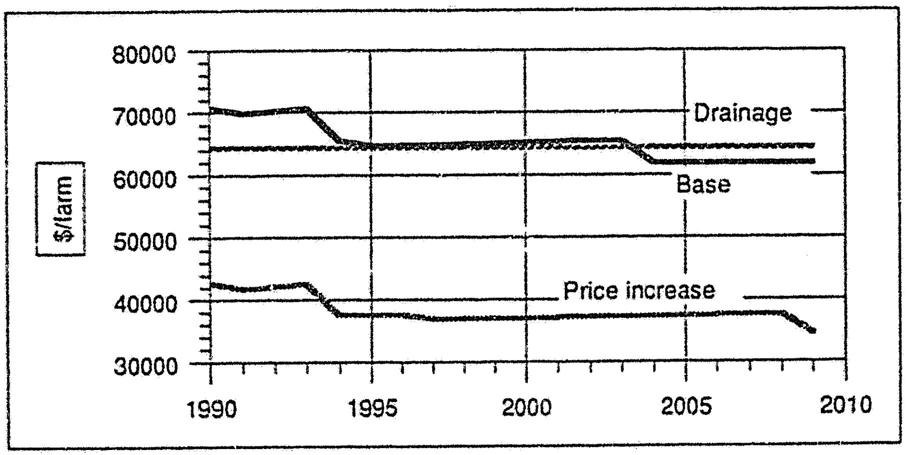
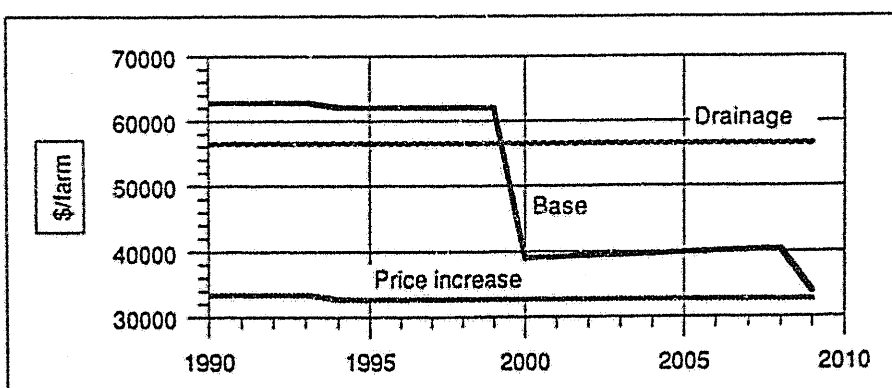


Figure 5.2: Rice farm

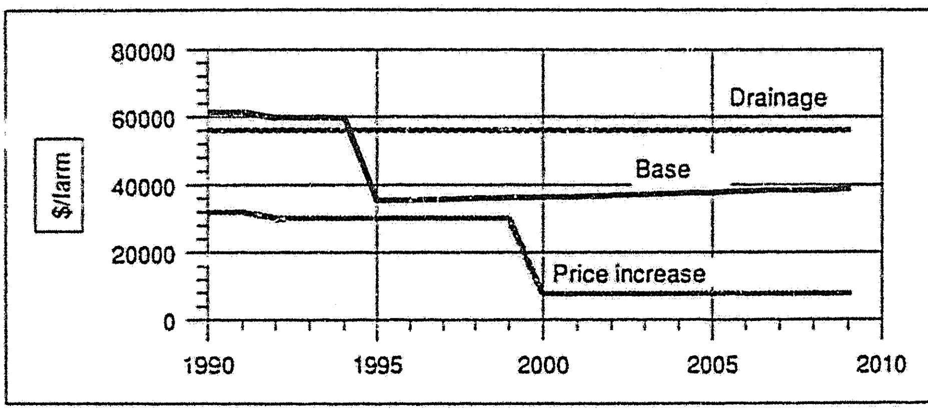


from the surface. The cost of district drainage was simulated by levying a charge on each farmer based on the total area of each irrigated farm. The levy was calculated as an annuity of the capital cost plus the estimated annual running cost of the drainage scheme. The per hectare cost of district drainage estimated by ACIL Australia Pty Ltd and P.J. Hallows and Associates (1990) was $250/ha capital cost and $3/ha ongoing costs.

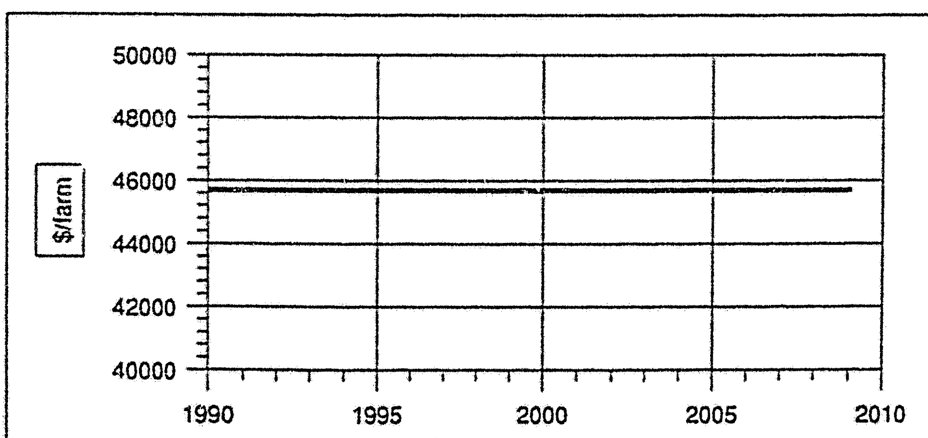
By comparing the results of this simulation with the base simulation, an estimate of the benefits of implementing district drainage on irrigation farms in the West Berriquin

Figure 5 *(continued)*

Figure 5.3 : Mixed farm



Figur 5.4: Dryland farm



Irrigation District can be made. The benefits of district drainage for each type of irrigation farm are estimated as the present value of the difference between the sum of pre-tax profit over twenty years plus the present value of the farm in year 20 with and without drainage. Discount rates of 3, 5 and 7 per cent are used, and the estimate expressed as a per hectare present value (table 5). Present value is measured as the stream of pre-tax profit over 20 years plus the present value of the capital value of the farm in year 20 using a discount rate of 5 per cent. The capital value of a farm in year 20 is the value of the expected future stream of incomes in that year.

The effect of installing district drainage for the representative dairy farm is that estimated pre-tax profit remains constant over the twenty year simulation period at a lower level than the first year of the base run. This compares with a decline in pre-tax profit of around 6 per cent without district drainage (figure 5.1). No effects of irrigation salinity or waterlogging are experienced over the twenty years and therefore productivity and enterprise mix for this farm are maintained. The farm is able to maintain carrying capacity for the twenty years. Despite this, the additional cost of drainage results in a net loss to the dairy farm (table 5).

The effect of district drainage on the rice farm is, again, that enterprise mix and production are maintained at their 1990 levels. This results in pre-tax profits being maintained at 1990 levels (figure 5.2). Similar results are observed for the mixed farm (figure 5.3). For these two representative farms there is a positive return from district drainage. On average, over the three representative farms district drainage is profitable.

If the reaction of farmers to rising groundwater tables is not taken into account in economic assessments of the benefits of district drainage, errors can occur (table 6). For

Table 5: Present value of the benefits of district drainage

	Discount rate		
	3 per cent	5 per cent	7 per cent
	$/ha	$/ha	$/ha
Dairy	21	-6	-22
Rice	546	355	226
Mixed	812	597	445
Average value of drainage	479	329	226

Table 6: Estimated increase in farm profit from district drainage assuming fixed and variable enterprise mix

	Increase in pre-tax profit over the period, compared with the base run	
	Fixed enterprise mix a	Variable enterprise mix
	%	%
Dairy	-0.2	-0.2
Rice	15.2	13.5
Mixed	31.0	25.3

a 1990 enterprise mix applied to all future years.

the rice farm, the benefits from district drainage are reduced from a 15.2 per cent increase in pre-tax profit to 13.5 per cent and for the mixed farm from 31.0 per cent to 25.3 per cent if farmers' reaction to rising groundwater tables is taken into account. The benefits are measured as the difference between the present values of the farms with and without drainage.

Increase in water price

The delivery cost of water to farmers as specified in the base run of the model is $6.45/ML (Crean 1992b). It is possible that groundwater table problems are exacerbated by low water charges which encourage higher levels of irrigation. This is explored in the model by increasing the water price and examining the impact on land use, production, the extent of irrigation, water use and pre-tax profits. Delivery prices of water between $10/ML and $40/ML were examined. It was not until the price of water increased to $40/ML that enterprise mix and water use were found to change for each of the representative farms. This indicates that there is a high gross margin for water for irrigation in the region.

With a water price of $40/ML, the dairy farm continues to irrigate all the land available for irrigation. However, instead of growing irrigated pasture with the same high water application rate as at the lower price, water use per hectare is reduced. The remainder of the farm remains dryland pasture. The pasture is used to run dairy and beef cattle and some sheep but there is a decrease in beef and sheep carrying capacity of around 10 per cent as a result of lower feed supply from low water application to irrigated pasture. Pre-tax profit in 1990 was found to decline from the base case (figure 5.1). Groundwater tables under clay loam and heavy clay soils do not rise as quickly over the twenty years as they do in the base run. Water tables under these two soil types rise 60 per cent over twenty years in this scenario, compared with a 73 per cent rise over the same period in the base run.

When the delivery price of water is increased to $40/ML for the rice farm, large changes in enterprise mix occur. The most significant of these changes is that rice is no longer grown. Instead, irrigated wheat and pasture are grown. However, this is low water application irrigation. The same amount of dryland pasture is grown as in the base case. Carrying capacity after twenty years is 12 per cent higher than in the base case. This can be attributed to a delay of the effects of salinity and waterlogging on yields caused by groundwater tables rising only 43 per cent under clay loam soils and 23 per cent under heavier clay soils. This compares with 63 per cent and 53 per cent respectively in the base run case. Pre-tax profit in 1990 on the rice farm is 47 per cent lower than in the base case because of the higher water price but the rise in the groundwater table is delayed because of the lower rate of application of irrigation water.

No rice is grown on the mixed broadacre irrigated farm when the water price is increased to $40/ML because the high water requirement of this crop makes it unprofitable. Low water application irrigated wheat is grown on 69 ha of land in 1990 but this drops significantly in the year 2000 to 23 ha. Low water application irrigated pasture is also grown on 151 ha of the farm in 1990 but this drops 88 per cent by the year 2000, replaced by dryland pasture.

The rate of rise in groundwater tables under sand and heavier clay soils does not change from that in the base run. However, under clay loam soils the ground watertable rises at a slower rate over twenty years than for the same period in the base run. Groundwater tables for clay loam soil reach 1.5 metres below in 2000, compared with reaching the same level five years earlier in the base run.

In summary, raising the water delivery price results in a reduction in water use, which delays the impact of rising groundwater tables for around five years. While the slowing of groundwater rise increases farm income, the effect of the higher water delivery price is to reduce the present value of the farm relative to the base run, by 37 per cent for the dairy farm, 29 per cent for the rice farm and 54 per cent for the mixed farm.

Conclusions

In this study a bioeconomic linear programming model based on representative farms in the West Berriquin Irrigation District was developed. The model includes the effects of farm decisions in any year on groundwater tables and yields in following years. As yields are reduced because of the rising groundwater tables, farmers can be expected to adjust their farm enterprise mix. The adjustment takes the form of reduced irrigation rates or switches in enterprises to others, such as perennial pasture, which are less affected by high groundwater tables. Often, however, on-farm responses are not accounted for in benefit–cost analyses of groundwater management options. This has led to a tendency to focus on technical solutions such as drainage, and to overestimating the likely benefits.

The development of the model in this paper demonstrates the importance of on-farm production decisions when assessing policies to deal with environmental problems affecting agricultural industries. As only some of the benefits and costs of the alternative policies have been estimated, it is not possible to rank one ahead of another. Clearly, however, the economic merits of any option in absolute or relative terms may be affected by assumptions about farmers' responses to rising groundwater levels. The analysis illustrates the errors that can occur if farm enterprise mix is assumed to be fixed. If adjustment in enterprise mix is not allowed for, then production losses and consequent income losses of farms to rising groundwater will tend to be overestimated.

The model contains several simplifying assumptions because of the limited information available and to simplify the analysis. The most important of these assumptions is not allowing for a general rise in the groundwater table as a result of factors other than irrigation. Other factors could include channel leakages, and groundwater rises caused by land clearing in recharge areas or from the irrigation of neighbouring land. In addition, as physical and economic data were collected separately, they can only be used at an aggregated level. Combined data collection would have greatly improved the specification and precision of the model. Nevertheless, while models of the type developed in this paper require simplifications, they can be useful tools for examining policy where both economic and physical considerations are involved.

The model was used to examine two possible policy option to address rising groundwater levels. The first option is the installation of drainage in the area. From the analysis, it can be seen that significant benefits are possible but that the benefits may vary depending on the groundwater salinity, water table height and the original type of farm enterprise. It should be noted that the results do not include the costs of damage to roads or from increased salt loads in the river system. Therefore, these results should not be regarded as a full benefit–cost analysis of district drainage in the West Berriquin Irrigation District.

The second policy option examined focused on what happens when farm enterprise mix is changed in response to an increase in the delivery price of water. In the analysis it was shown that the representative farms changed their water use and enterprise mix little until the water delivery price was raised markedly above current levels. The introduction of a $40/ML water delivery price was found to reduce pre-tax profit on each of the three irrigated farms by a significant amount. This arose from a switch in enterprise mix, lower yields associated with lower water application rates and higher water delivery costs. However, because less water was applied to crops in the region, the groundwater tables did not rise as quickly, resulting in a delay in waterlogging and salinity.

Further development of this model would aim to allow more realistic modelling of policy options such as drainage. This would involve more detailed physical specification of the representative farms and the bioeconomic relationships involved including improved specification of groundwater and salinity relationships and of the interaction of different crops and management systems with changes in groundwater levels. This preliminary version of the model is sufficient to indicate broad responses to the two policies examined. A fuller analysis of the impacts of district drainage and water pricing policies would be possible with a more refined model.

The analysis presented in this paper is aimed at developing ways of incorporating the effect of the changing productivity of land into an economic model. However, the model is only preliminary and this study does not include all the research issues that could be examined. This leaves several issues for further research. As stated above, in this study farmers do not take into account the effects of rising groundwater tables in their production decisions until the productivity of their farms is affected. This assumption is simplistic and further research could examine how production decisions vary as this assumption is relaxed. Also, it is increasingly likely that water rights will become tradable between regions and so farmers would be able to buy more water. The possible effect that this could have on farmer's production decisions may be a possible avenue of further research. As mentioned above, the model does not include any effect of externalities, either on other farms from rising groundwater levels within a district or the effects on river salinity. This raises a number of policy options to deal with these externalities which could be topics of further research.

Appendix A

Specification of the model

The economic model of agriculture in the West Berriquin Irrigation District used in this study is based on four representative linear programming farm models which are run recursively for twenty years. Each model represents a single farm type in the region and includes both economic and physical activities so that optimisation each year takes account of the impact of past decisions on levels of groundwater and salinity and of current prices and other resource levels. The models are a development of those of Hall, Mallawaarachchi and Batterham (1991) and incorporate information on groundwater and crop yield behaviour supplied by the Murray–Darling Basin Commission. The GAMS language (General Algebraic Modelling System; Brooke, Kendrick and Meeraus 1988) was used to specify and run the models. The model equations are given in appendix B.

Income for each representative farm is separately optimised each year. Resource endowments that are changed in a year are reinitialised for the next year. Thus, for example, closing cash balance for year 1 becomes opening cash balance for year 2. The model represents about 280 farms with four representative farms. This involves a substantial degree of aggregation at the farm level and an even higher degree for soil groups and water tables. The base data set for these variables (Naninga, P.M., Murray–Darling Basin Commission, personal communication, 1991) divides the region into 24 polygons each with its own level of groundwater. The average groundwater table under each soil type on each representative farm is the weighted average of the groundwater tables under its component polygons. Each representative farm is based on a combination of polygons.

Agronomic specifications

Soil types are important to the region because of the different agronomic requirements of rice and other crops. Rice requires shallow soils with an impervious layer which can be kept continually wet. Three soil types are represented: sand, clay loam and clay.

The growing of crops in rotations is of considerable agronomic importance. The approach used here is to combine the individual activities into rotation packages (Heady and Candler 1958). For example, one rotation package of the matrix is a combination of two years of rice, no wheat and three years of pasture. The rotations are based on combinations of pasture and cropping. Rice is commonly grown for up to two years, but three years is relatively rare and is not an option included in this model specification. Cereals may be grown for up to two years. Pasture, which has a regenerative effect on the soil, is grown as an integral part of the cropping system. Other farm activities modelled included permanent irrigated pasture, dryland pasture, merino wethers, prime lambs, dairy production and beef cows producing vealers.

The level of water use can be varied in the model. A set of low water use activities was developed for cereals, pasture, tree crops and vines. However, it was assumed that rice could not be grown at any but the normal water use. Rice was not allowed to be grown on sandy soils because of the excessive water losses from this soil type.

The constraint rows of the model include capital use, cash costs, water activities and the water allocation, seasonal labour use activities, machinery use and harvesting activities. There are also constraint rows for the land types, for areas of irrigated land on each soil type and for the feed activities.

Objective function

The structure of the objective function is designed to maximise the present value of an infinite stream of after-tax consumption — that is, the capital value of the farm, less the net debt position. Farm income and off-farm income (from investments and off-farm work) together with cash costs generate net pre-tax income. This income is then fed through a submatrix which simulates the progressive income tax system. The after-tax income is then split between consumption and investment. The annual consumption return is fed to the objective function through an activity which compounds it by the real rate of interest to obtain the capitalised value of an infinite stream of consumption expenditure at that rate.

The other financial activities in the model are borrowing and investment activities, land transactions and the purchase of capital equipment. Borrowing is in the form of an annual overdraft which adds to opening cash for investment and to cash costs of interest, and is a cost in the objective function.

Investment activities of the model include activities for buying general purpose machinery (defined as a package of tractors and associated equipment) and harvesting equipment. The return from capital purchases is in increased future income flows, which are capitalised in the objective function. Thus capital spending is compared with the capitalised value of the benefits from the investment.

Water tables

Each activity which uses water also supplies water to a soil water pool which receives the net additions of water to the subsoil from each activity in each year. These water table additions and irrigation rates were supplied by the Murray–Darling Basin Commission (Naninga, P.M., personal communication, May 1992). Water enters the soil from the top through irrigation, and from below if the regional groundwater table is rising independently of irrigation; it is lost through evaporation and drainage. This model attempts to integrate water table height, salinity in the root zone, water logging and plant yield. In this paper, it is assumed that there is no external addition of water to the system other than through irrigation; that there is no drainage out of the water table; and that evapotranspiration keeps the water table below 0.5 metres on average over the year.

The assumption that water tables are not rising independently of irrigation is not justified for dryland farms, where the rise is approximately 20 cm a year because of clearing in recharge areas. On irrigated areas this rise is masked by the irrigation water (Evans, R., personal communication, August 1992). In this model the impact of this rise in the groundwater table on the dryland representative farm is disregarded. If it were taken into account it would bring water tables nearly to the surface in twenty years time on about 11 per cent of the representative farm's area.

The water table rise under irrigation in a year is simulated as follows for each soil type on each representative farm:

$$GA_s = \Sigma(C_{is} * A_{is})$$

$$GR_s = GA_s / P_s$$

$$GW_{st+1} = GW_{st} + GR_{st}$$

where GA_s is accession to groundwater on soil type s in ML; C_{is} is the production of crop i on soil type s; A_{is} is the accession rate for crop i on soil type s in ML/ha; GR_s is the rise of groundwater on soil type s in metres a year; P_s is the permeability of soil type s; and GW_{st} is the level of groundwater on soil type s in year t in metres.

In this way continued irrigation leads to annual increases in the groundwater table, which rises to an upper limit of 0.5 metres at which evapotranspiration is assumed to balance out the additional increments of groundwater so that further rises do not occur. As groundwater rises toward the surface it has two effects on crop growth. The salinity of the soil increases where the salinity of the groundwater exceeds that of the soil surface, and waterlogging reduces yields when the water table reaches the root depth of each crop.

The soil salinity at various plant root depths is calculated using a set of functions supplied by the Murray–Darling Basin Commission (Naninga, P.M., personal communication, May 1992). These nonlinear functions interpolate between surface and groundwater salinity to estimate salinity at the root depth for each crop. As the water table approaches the surface, this function indicates that salinity at root depth begins to increase very rapidly. The impact of salinity on crop yields is shown in table 2. For each crop there is a threshold concentration below which salinity has no impact on yields. Above this concentration yields are assumed to decline linearly with increasing salinity. Each crop has a different rate of decrease of yield.

As water tables rise they eventually reach the root depth of each crop. These root depths are specified for each crop in the model (table 3). When the water table reaches root depth it is assumed that crop yields diminish by fixed amounts. Water logging and salinity yield losses are assumed to be independent and additive.

Time dimension

The representative farm models are run recursively. That is, the resource base is changed in each year on the basis of the previous year's solution. This approach of year by year adaption to resource changes, which are the result of previous management decisions, was developed by Day (1963). It is assumed that farmers make decisions on the basis that their present resource situation will continue into the future. They will modify their management decisions only as they become aware of changes in their resources — for example, when yields decline because of rising groundwater tables. Thus farmers are assumed to take a short term view (Day 1978). This is unlike the assumption of perfect knowledge in multiperiod models such as the one used by Mallawaarachchi, Hall and Phillips (1991). In a situation of perfect knowledge farmers would be able to internalise the effects of rising groundwater on their own farms, although the external impacts on other farms and regions would still remain. It is unlikely that farmers will have perfect knowledge of the groundwater situation on their own farms either now or in the future and so the assumption of short term behaviour seems more justified than one of perfect knowledge.

Appendix B

Equations of the model

The General Algebraic Modelling System (GAMS) was used to build and run this model and the equ ,tions are set out here using GAMS notation (Brooke et al. 1988). There are three equations in the model that represent three sets of equations. These are the *PROFIT* equation which defines the objective function; the *SALES* matrix which defines the selling of commodities; and the *PRODN* matrix which defines the production relationships of the farm model.

There are four variables in the equations: *Z*, the vector of net revenues; *X*, the vector of rotation activities relating to cropping and pastures; *Y*, the vector of other production activities, mainly the livestock activities; and *B*, the vector of market variables involving sales of commodities, taxation and investment and purchases of financial inputs.

Variables

Z is net revenue; *X*(*R*) are the rotation quantities; *Y*(*Q*) are the other production quantities; and *B*(*S*) are the quantities market variables. Where *R* is a set of possible rotations, *Q* is a set of production activities and *S* is a set of market activities.

Equations

SALES(*U*) is the sales matrix; *PRODN*(*H*) is the production matrix; and *PROFIT* defines the objective function. Where *U* is a set of sales constraints and *H* is a set of production constraints.

$$PROFIT \,..\, Z \; = E = \; SUM[(S, B(S) * PLAN(S)]$$

The objective is to maximise the value of *PROFIT*, which is the sum of quantities of market variables times their weights. These weights allow for the compounding of incomes over time. The values of variable *B* are those of after-tax consumption income, debt and off-farm assets. These are weighted by the values in *PLAN* that are 1 for debt and off-farm assets and 37 for consumption income. This is the present value of an infinite stream of income. A real interest rate of 4 per cent is used throughout the analysis.

$$PRODN(H) .. SUM[R, X(R)*ROTN(H,R)] + SUM[Q, Y(Q)*STOCKD(H,Q)] =L= RL(H)$$

Where STOCKD is a set of livestock activities and RL is a set of resource limits.

The *PRODN* group of equations integrate the farms' production activities that are constrained by the physical resource limits *RL(H)* that include land areas and labour availability. Crops and pasture activities are included as rotation activities *ROTN* that are combinations of individual crop and pasture activities. The possible combinations are specified in the GAMS program. This system allows activities to be specified individually, which is easier to check and simplifies recalculating yields each year but prevents unrealistic cropping combinations being specified. The first term of the summation states that each rotation is multiplied by its resource requirements. In the second term the livestock and other physical activities are multiplied by their resource requirements. The whole equation ensures that the total use of resources does not exceed the resources available to the farm.

$$SALES(U) .. SUM(R, X[R)*ROTC(U,R)] + SUM(R, X[R)*ROTY(U,R)] + SUM[S, B(S)*REV(U,S)] + SUM(Q, Y[Q)*STOCKN(U,Q)] + SUM[Q, Y(Q)*STOCKY(U,Q)] + SUM(S, B[S)*MARKET(U,S)] = L = SL(U)$$

Where *ROTC* is a set of cash costs of rotation activities; *ROTY* is a set of commodity yields of rotation activities; *REV* is a set of revenues per unit of product sold; *STOCKN* is a set of cash costs of livestock; *STOCKY* is a set of yield coefficients for livestock; *MARKET* is a set of taxation and investment coefficients; and SL is a set of resource limits.

The *SALES* group of equations ensures that the use of financial and sales resources by the financial and sales activities of the farms do not exceed the available resources. There are six groups of summations in the equation system. The first relates to the production of crops from the rotation activities and the second to corresponding production of livestock products such as wool. The third set of equations represents the sale of the farm products. The sets of equations in *STOCKN* and *STOCKY* relate to crop and livestock yields per unit while the final term refers to the equations that describe the financial, taxation, borrowing and investment behaviour of the model. Thus, the set of equations taken together ensures that the output of the productive system of crops and livestock is sold and the revenue distributed to pay farm costs, taxation, investment and consumption.

References

ACIL Australia Pty Ltd and P.J. Hallows and Associates 1990, *Study of Surface / Subsurface Drainage for the Murray-Darling Basin*, Report to the Murray–Darling Basin Commission, Canberra, May.

Brooke, A., Kendrick, D. and Meeraus, A. 1988, *GAMS: A Users Guide*, Scientific Press, Redwood City, California.

Crean, J.J. 1991, *Summer Irrigation Cropping, Murray Valley 1991*, Farm Budget Handbook, New South Wales Agriculture, Yanco, July.

—— 1992a, *Winter Irrigation Crop Budgets 1992, Murray Valley*, Farm Budget Handbook, New South Wales Agriculture, Yanco, March.

—— 1992b, *Winter Crop Budgets 1992, Western Riverina*, Farm Budget Handbook, New South Wales Agriculture, Yanco, March.

Day, R.H. 1963, *Recursive Programming and Production Response*, North Holland, Amsterdam.

—— 1978, 'Adaptive economics and natural resource policy', *American Journal of Agricultural Economics*, vol. 60, no. 2, pp. 276–83.

Grieve, A.M., Dunford, E., Marston, D., Martin, R.E. and Slavich, P. 1986, 'Effects of waterlogging and soil salinity on irrigated agriculture in the Murray Valley: a review', *Australian Journal of Experimental Agriculture*, vol. 26, 761–77.

Hall, N., Mallawaarachchi, T, and Batterham, R. 1991, The market for irrigation water: a modelling approach, ABARE paper presented at the 35th Annual Conference of the Australian Economics Society, University of New England, Armidale, 11–14 February.

Heady, E.O. and Candler, W. 1958, *Linear Programming Methods*, Iowa State University Press, Ames.

Landsberg, J.J., Hirst, K.M. and Nanninga, P.M. 1991, *Draft 20 Year Profile Pilot Study*, Murray–Darling Basin Commission Draft Report, Canberra, December.

Mallawaarachchi, T., Hall, N. and Phillips, B. 1991, Investment in water saving technology on horticultural farms, ABARE paper presented at the 35th Annual Conference of the Australian Agricultural Economics Society, University of New England, Armidale, 11–14 February.

New South Wales Department of Water Resources 1991, Berriquin Irrigation District, Deniliquin (unpublished).

Young, M. 1992, Effects of increasing resource management costs on pressure for structural adjustment in the Shepparton Region, Paper presented to the 36th Annual Conference of the Australian Agricultural Economics Society, Canberra, 10–12 February.