Australian Journal of Agricultural Economics, Vol. 33, No. 3 (December 1989), pp. 203–218

A MIXED INTEGER LINEAR PROGRAMMING EVALUATION OF SALINITY AND WATERLOGGING CONTROL OPTIONS IN THE MURRAY–DARLING BASIN OF AUSTRALIA

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Pollution of the River Murray by salt imposes costs on domestic and industrial users in Adelaide and to irrigators on the River Murray. Salt enters the Murray–Darling system through saline ground water aquifers and from irrigation and drainage of saline land. Irrigation and drainage generate benefits from improved agricultural productivity and impose costs through increased salt loads to the Murray–Darling system. The salinity of the River Murray can be reduced by pumping highly saline ground water into evaporation basins before it enters the River Murray. This paper presents a mixed integer linear programming model which is used to determine the mix of ground water interception schemes and land improvement schemes that minimises the net present value (over a time horizon of 30 years) of total Murray–Darling Basin costs due to salinity and waterlogging. By varying a target salinity level, the mix of works that yields various salinity targets in the River Murray at minimum cost is obtained. The sensitivity of the optimal solution to prescribed changes in costs and benefits of projects and to a longer planning horizon is examined.

The Murray–Darling Basin covers about one-seventh of Australia and spans four of the eastern states. It supports about 25 per cent of the nation's cattle and dairy farms, contains about 50 per cent of its sheep and cropland and around 75 per cent of its irrigated land. Total output from natural resource-based industries is valued at about $A10 billion (1987) per annum. The Basin accounts for around 74 per cent of Australia's irrigation water consumption and the River Murray supplies between 60 and 90 per cent of Adelaide's annual water supply (population about 1 million).

The rivers of the Basin become increasingly saline as they flow westward and this creates major water quality problems for human consumption. In addition, land salinisation and waterlogging problems are becoming evident in the Basin due to rises in water-tables caused by past land clearing, overwatering, lack of surface drainage, leaky channels, irrigation of unsuitable land and other inappropriate manage-

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*We would like to thank John Paterson and Peter Sutherland for useful comments and encouragement throughout the course of the project. The data used in the study were assembled by a panel of experts from the Commonwealth Government and some of the state governments. The membership and affiliation of this data working group were: Don Blackmore (River Murray Commission), Clive Lyle (Department of Agriculture and Rural Affairs, Vic.), David Marston (Department of Agriculture, NSW), Stuart Wood (Department of Agriculture, SA), Ralph Young (Commonwealth Department of Primary Industry) and Campbell Fitzpatrick. The data and methodology used in the paper were reviewed by R. G. Dumsday and ACIL who acted as independent consultants to the project. The views expressed in the paper do not necessarily reflect those of any Australian federal or state government agency. The authors accept responsibility for the opinions and analysis presented in the paper.

ment practices. Land salinisation is caused by the accumulation of salts in the root zone; this is due, in most instances, to capillary rise in saline moisture from shallow water-tables. This reduces the productivity of most plants. Waterlogging occurs when the water-table rises into the root zone. This produces anaerobic conditions which reduce plant growth and may kill plants. The annual loss in agricultural production due to salinity and waterlogging is conservatively estimated at $A39 million per annum in irrigation areas and is expected to increase if current trends in water-table rises and water use continue (Murray–Darling Basin Ministerial Council 1987*b*).

Unfortunately, economic policy measures such as increasing water prices and transferable water entitlements are not likely to provide acceptable or effective solutions to the waterlogging and salinity problems of the Basin. The price of irrigation water in the Basin has been set to recover the costs of operating and maintaining the water supply networks and water has tended to be rationed at the price charged. The evidence for this is that farmers tend to purchase all of their entitlements. Thus, substantial increases in water charges may be required to reduce water use significantly in the Basin, and this is likely to prove politically unpalatable.

Transferable water entitlements, which were introduced into New South Wales in 1983–84 (Alvarez, Cleary and Wood 1989) and Victoria in 1987–88, have the potential to reduce the adverse economic effects of salinity and waterlogging because transfers are only permitted out of affected areas. Since transferability of entitlements has only been recently introduced, an accurate assessment of its environmental impact is not feasible; however, two limitations can be identified. First, transferable water entitlements can only have a positive direct environmental impact if water is worth more outside affected areas; second, experience has shown that the volume transferred is low in wet years because of the higher availability of irrigation water and higher levels of soil moisture, and this is precisely the type of season when salinity and waterlogging problems are likely to be exacerbated. Thus, it is tentatively concluded that transferable water entitlements are not likely to produce a significant reduction in the salinity and waterlogging problems of the Basin.

The current level of salinity in the River Murray imposes economic costs on domestic and industrial users in Adelaide and Whyalla and to irrigators on the River Murray. Past irrigation development in the states of New South Wales and Victoria has contributed to these costs. Land salinisation and waterlogging problems primarily occur in Victoria and New South Wales. Control of these problems using physical measures such as grading and drainage works, which do not depend on factors such as the demand for water or seasonal conditions to be effective, would benefit the upstream states but would impose additional costs on South Australia and other irrigators on the River Murray by increasing its salinity levels.

This increased salinity would impose a unidirectional externality (Dasgupta 1983) on downstream users of River Murray water (including those in South Australia) if physical circumstances are considered in the absence of property rights. However, as Coase (1960) has argued, the direction of the economic externality depends on property rights.

The River Murray Waters Act, 1915 successfully provided an instrument for sharing River Murray water resources between South Australia, Victoria and New South Wales for more than 70 years. However, the Act was silent on the property rights of the states with respect to water quality.

The River Murray Waters Act, 1982 amended the previous act and includes water quality provisions. This act empowered the River Murray Commission to make recommendations to the states on water quantity and quality (clause 28) and required the states to inform the Commission of new proposals which may affect flow, use, control or quality of the water (clause 29). This was a major step forward which has subsequently been reinforced by the enactment of the Murray–Darling Basin Act, 1988. However, the 1988 act suffers from the same defect as the 1982 act in that it does not specify the states' rights as to water quality.

The Murray–Darling Basin Commission (formerly the River Murray Commission) has used an arbitrary interim salinity objective of maintaining salinity levels in the River Murray at less than 800 electrical conductivity units (EC) at Morgan, South Australia for 90 per cent of the time. However, this objective does not define the rights and responsibilities of the states as regards to River Murray salinity. The analysis reported in this paper was undertaken as part of the negotiations to develop a salinity and drainage agreement for the River Murray (Murray–Darling Basin Ministerial Council 1988, 1987*b*).

Data on proposed works which reduce River Murray salinity or reduce land salinisation and waterlogging problems within the Basin were collected to assist the Murray–Darling Basin Ministerial Council in preparing the salinity and drainage agreement. The mixed integer linear programming model described in this paper was used to determine the package of works that minimises the net present value of costs associated with salinity and waterlogging over a planning horizon of 30 years, as well as the packages of works that produced specified environmental objectives (expressed as target salinity levels in the River Murray at Morgan, SA) at minimum cost.

The difference between the minimised net present value of costs over the planning horizon and the minimised net present value of costs over the planning horizon associated with meeting each specified target salinity level is an estimate of the direct cost of meeting the environmental objective rather than the economic objective. To the best of our knowledge, this is the first application of operations research methods to a large-scale environmental problem.

The fifteen schemes presently being considered to alleviate the salinity and waterlogging problems of the Murray–Darling Basin are listed in Table 1, and their locations in the Basin are shown in Figure 1, together with their (estimated) salinity impact on the River Murray, measured in EC at Morgan, SA. The first seven projects listed in Table 1 are ground water interception schemes. These reduce River Murray salinity by pumping highly saline ground water into evaporation basins before it reaches the River Murray. The remaining schemes listed in Table 1 are land protection schemes.

The four land protection schemes that increase River Murray salinity are drainage schemes. Three of the land protection schemes that reduce River Murray salinity improve the effectiveness of applied

TABLE 1

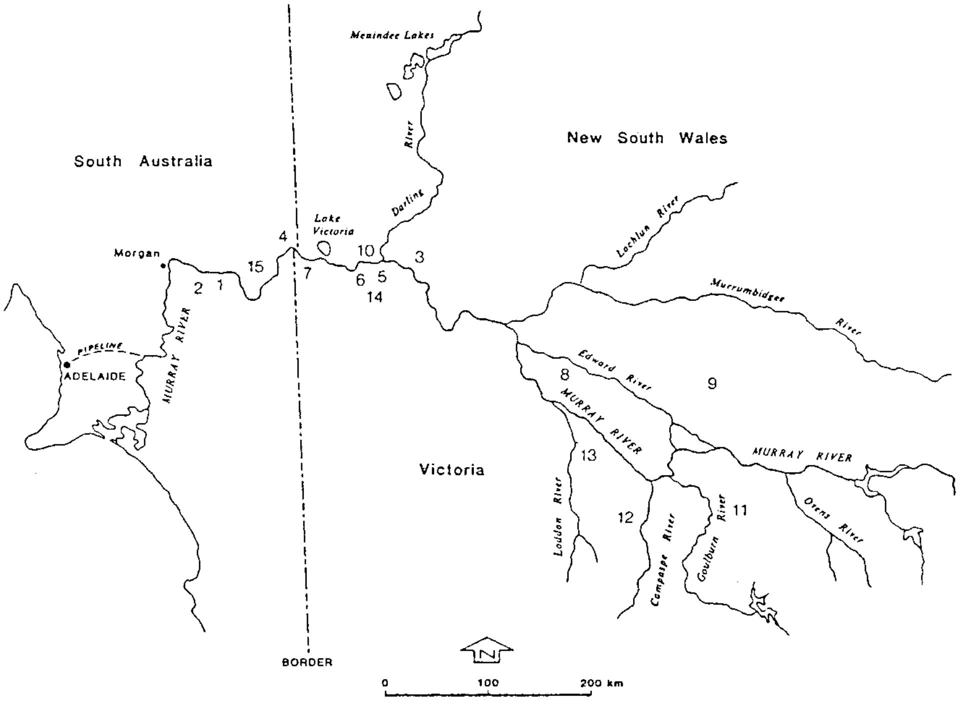
Proposed Works for Alleviating the Salinity and Waterlogging Problems of the Murray-Darling Basin[a]

Scheme	Salinity effect on Murray at Morgan, SA	Programme variable type	Implementation period (years)
Interception scheme			
1. Woolpunda	−39·8 EC[b]	Integer (0, 1) and continuous if chosen	4
2. Waikerie	−15·9 EC	Integer (0, 1) and continuous if chosen	3
3. Mallee Cliffs	−7·5 EC	Integer (0, 1) and continuous if chosen	2
4. Chowilla	−10·5 EC	Integer (0, 1) and continuous if chosen	2
5. Mildura/Merbein/Buronga	−5·7 EC	Integer (0, 1) and continuous if chosen	1
6. Sunraysia	−4·0 EC	Integer (0, 1) and continuous if chosen	3
7. Lindsay River	−7·0 EC	Integer (0, 1) and continuous if chosen	3
Land protection scheme			
8. Wakool/Tullakool/Deniboota	10·9 EC	Integer (0, 1)	30
9. Berriquin Phase A	4·0 EC	Integer (0, 1)	5
10. NSW Sunraysia	−2·0 EC	Integer (0, 1)	30
11. Shepparton	13·5 EC	Proportion	30
12. Campaspe	0·8 EC	Proportion	12
13. Barr Creek	−6·5 EC	Integer (0, 1)	7
14. Vic. Sunraysia	−2·0 EC	Proportion	30
15. SA Riverland	−21·4 EC	Proportion	20

[a] Maximum EC reduction of all the schemes: 122·3 EC; maximum EC addition of all the schemes: 29·2 EC.
[b] EC, electrical conductivity unit.

irrigation water through land forming and associated improved agricultural practices. Land forming involves contouring paddocks to promote efficient flood irrigation, and this usually requires laser grading to achieve precise slopes. The Barr Creek scheme is the fourth land protection scheme that reduces the salinity of the River Murray. This scheme combines land forming and improved management practices to reduce drainage into Barr Creek, thus increasing the efficiency of an existing scheme which diverts highly saline Barr Creek water into an evaporation basin before it reaches the River Murray. More detailed information on the Basin salinity and waterlogging problems and the proposed control measures may be found in the Murray-Darling Basin Ministerial Council publications cited in the bibliography and in Macumber and Fitzpatrick (1986).

The problem of choosing which of the above projects to implement has been addressed in a number of reports: River Murray Commission (1984*a*, *b*, *c*) and Murray-Darling Basin Ministerial Council (1986, 1987*a*, 1988). These reports present an economic evaluation of some of these projects and indicate which of the projects studied appear viable.



SALT INTERCEPTION SCHEMES

1	WOOLPUNDA	(-39.8 EC)
2	WAIKERIE	(-15.9 EC)
3	MALLEE CLIFFS	(-7.5 EC)
4	CHOWILLA	(-10.5 EC)
5	MILDURA/MERBEIN/ BURONGA	(-5.7 EC)
6	SUNRAYSIA	(-4.0 EC)
7	LINDSAY RIVER	(-7.0 EC)

LAND MANAGEMENT SCHEMES

8	WAKOOL/TULLAKOOL/ DENIBOOTA	(10.9 EC)
9	BERRIQUIN PHASE A	(4.0 EC)
10	N.S.W. SUNRAYSIA	(-2.0 EC)
11	SHEPPARTON	(13.5 EC)
12	CAMPASPE	(0.8 EC)
13	BARR CREEK	(-6.5 EC)
14	VICTORIA SUNRAYSIA	(-2.0 EC)
15	S.A. RIVERLAND	(-21.4 EC)

NOTE - THE ESTIMATED SALINITY EFFECT OF EACH SCHEME ON THE MURRAY RIVER AT MORGAN SOUTH AUSTRALIA APPEARS IN BRACKETS NEXT TO THE SCHEME

FIGURE 1—Proposed Salinity Control Schemes in the Murray–Darling Basin of Australia.

The economic evaluation in these studies was carried out using cost–benefit analysis on a project-by-project basis. This approach is similar to that adopted by Gardner and Young (1985, 1988) in their economic evaluation of the Colorado River Basin salinity control programme.

Since each of these projects has an impact on the salinity of the River Murray, the Murray–Darling Basin can be treated as an integrated economic unit for the purposes of the project selection exercise. This suggests that the selection exercise should aim to choose the set of projects that minimises the net present value of total Murray–Darling Basin costs due to salinity and waterlogging over the planning horizon. Because there are a large number of projects, each of which is complex in nature and generates both benefits and costs, a mathematical programming model is an appropriate tool for solving the problem of project selection. Examples of this approach to project selection may be found in Mishan (1982, pp. 273–82).

There are many advantages in formulating the project selection exercise as a mathematical programming problem. This approach requires the problem to be rigorously defined and provides a framework for data collection. The sensitivity of the optimal solution to changes in technical assumptions and financial estimates can be readily explored. A range of interesting sub-optimal solutions can be generated by varying a nominated salinity constraint on the aggregate impact of the selected projects on the River Murray. This allows the water quality problem (which impacts mainly on South Australia) to be examined concurrently with the cost minimisation problem. The project selection problem can also be solved subject to constraints on available capital (Alaouze and Fitzpatrick 1987). In formulating the mixed integer linear programming model we have followed the advice of Beale (1980) and attempted to construct a simple model that captures the essential features of the problem.

The remainder of the paper is organised as follows. The mixed integer linear programming model is developed in the next section, which also contains some details on the data used in the study. The results of the study are presented in the third section. The fourth section of the paper presents a summary of the paper and the conclusions of the study.

The Mixed Integer Linear Programming Model

Introduction

The projects described in the first section are implemented in stages over a maximum period of 30 years, and this is the length of the planning horizon for which the data base was assembled. Details on the implementation profile of schemes are given in Table 1. For example, the Woolpunda interception scheme is built in the first 4 years of the planning horizon and the scheme is not operated until the fifth year. In years 5 to 30 the scheme can be operated in its design range. The financial impact of the scheme involves capital expenditure in the first 4 years, and in years 5 to 30 only operating and maintenance costs, which are related to the level of operation of the scheme, are incurred. Benefits to South Australia due to reduced River Murray salinity are obtained in years 5 to 30 and are related to the level of operation of the scheme.

The land protection schemes have a more variable implementation profile. For example, the Campaspe scheme is implemented progressively over 12 years, so that capital costs are incurred in the first 12 years and operating costs are incurred in each of the 30 years. Benefits to South Australia due to reduced River Murray salinity and local benefits from improved productivity and water re-use accrue in each year.

In the mixed integer linear programming model developed below, the chosen mix of schemes is implemented in the first period of the planning horizon and each selected interception scheme is operated at a level which is fixed in each operating period.

The net present value of the schemes is calculated by discounting the annual benefits/costs occurring in each of the 30 years. All costs and benefits are expressed in constant 1985–86 dollars and were discounted using a 5 per cent real interest rate. The 5 per cent real interest rate chosen for discounting is our estimate of the average real interest rate over the life of the projects.

The annual salinity cost or benefit of each scheme was calculated for us by the River Murray Commission (1984*c*) using a computerised version of the salt cost model. This model calculates benefits and costs based on changes in salinity along the length of the River Murray (including domestic and industrial users in Adelaide and Whyalla) throughout the year. However, for the purpose of solving the linear programming models, the salinity impact of each project is described in terms of the change in average salinity at Morgan, SA.

The planning horizon for which the data were collected is somewhat shorter than the economic life of the projects. For example, it is likely that with regular maintenance, the bore component of the interception schemes could last for 50 years and that some evaporation basins could last indefinitely (due to leakage). The useful life of some land protection schemes is not known, but with regular maintenance, these too could have lives substantially longer than 30 years. In order to test the sensitivity of the mix of works that minimises the net present value of Basin costs due to salinity and waterlogging to the length of the planning horizon, the present value of benefits and costs of each project for a 50 year horizon was calculated by assuming the benefits and costs of each scheme in year 30 are applicable for an additional 20 years. These data were used in the sensitivity analysis reported below.

Mathematical formulation

A mixed integer linear programming model is developed because the interception schemes and some of the other projects can only be implemented wholly; these are modelled using a (0, 1) integer choice variable. Other projects can be partially implemented, and the choice variable in this case is a proportion (see Table 1). The level of operation of each selected interception scheme is a continuous variable which is chosen in the operating range of the interception scheme (Table 1).

The data requirements and structure of the interception scheme component of the mixed integer linear programming model are outlined below. Since there are seven interception schemes the subscript j runs from 1 to 7 for this component of the model.

Parameters: E_j, Annual EC impact at Morgan per ML of operation of scheme j, (EC/ML)/annum; b_j, present value of operating costs per ML of operation of scheme j, \$/ML; a_j, present value of investment cost of scheme j, \$; M_j, upper bound of operating range of interception scheme j, ML/annum; m_j, lower bound of operating range of interception scheme j, ML/annum; B_j, present value of EC removed per ML of operation of scheme j, \$/ML.

Choice variables: Z_j is an integer which takes the value 1 if scheme j is implemented, 0 otherwise ($j=1, \ldots, 7$). X_j is a variable representing the level at which scheme j is operated ($j=1, \ldots, 7$). X_j is chosen in the operating range of the scheme if the scheme is selected, otherwise it is set at 0.

Contribution to objective function (net present value of costs and benefits):

$$\sum_{j=1}^{7} a_j Z_j + \sum_{j=1}^{7} (b_j - B_j) X_j$$

Constraints:

$$\left.\begin{aligned} M_j Z_j - X_j &\geq 0 \\ -m_j Z_j + X_j &\geq 0 \\ Z_j \quad &\leq 1 \\ X_j &\geq 0 \\ Z_j \quad &\geq 0 \end{aligned}\right\} j = 1, \ldots, 7$$

The above set of constraints is structured so that if X_j is chosen to be non-zero Z_j must take the value 1, and X_j is constrained within the operating range of the interception schemes. If X_j is chosen to be 0 then, by construction, Z_j must be 0. A similar example may be found in Loucks, Stedinger and Haith (1981, p. 59).

The salinity impact of the interception schemes may be written:

$$\sum_{j=1}^{7} E_j X_j$$

and this is a component of the target EC constraint.

The land protection scheme component of the model has the following data requirements and structure. Since there are eight land protection schemes, the subscript j runs from 1 to 8 for this component of the model.

Parameters: G_j, Annual EC impact of scheme j at Morgan at the end of the planning horizon (G_j is positive if salt is removed, negative if salt is added), EC/annum; C_j, present value of EC benefit or cost of scheme j (C_j is positive for benefits, negative for costs), \$; K_j, present value of capital plus operating costs of scheme j, \$; R_j, present value of benefits to agriculture of scheme j, \$.

Variables: Y_j ($j = 1, \ldots, 4$) is an integer which takes the value 1 if scheme j is implemented, 0 otherwise. Y_j ($j = 5, \ldots, 8$) is the proportion of scheme j which is implemented.

Contribution to objective function (net present value of costs and benefits):

$$\sum_{j=1}^{8} (K_j - C_j - R_j) Y_j$$

Constraints:

$$\left.\begin{aligned} Y_j &\leq 1 \\ Y_j &\geq 0 \end{aligned}\right\} j = 1, \ldots, 8$$

The salinity impact of the land protection schemes may be written:

$$\sum_{j=1}^{8} G_j Y_j$$

and this is a component of the target EC constraint.

Specification of the EC-constrained mixed integer linear programming model: This linear programming model involves choosing the mix of interception schemes, land protection works and the level of operation of the selected interception schemes that minimise the net present value of Basin salinity and waterlogging costs and satisfy a specified salinity target. The target salinity level is expressed as a deviation from the average River Murray salinity level at Morgan, SA. The mix of works and the level of operation of the chosen works that minimise the net present value of Basin salinity costs are found by solving the model without the EC constraint. The EC constraint is achieved at the end of the planning horizon.

The model can be written:

Choose:

Integers: $Z_j\ (j=1, \ldots, 7)$, $Y_j\ (j=1, \ldots, 4)$ and
Variables: $X_j\ (j=1, \ldots, 7)$, $Y_j\ (j=5, \ldots, 8)$

To minimise:

$$\sum_{j=1}^{7} a_jZ_j + \sum_{j=1}^{7} (b_j - B_j)X_j + \sum_{j=1}^{8} (K_j - C_j - R_j)Y_j$$

Subject to:

$$\left.\begin{array}{rr} M_jZ_j - X_j & \geq 0 \\ -m_jZ_j + X_j & \geq 0 \\ Z_j \qquad & \leq 1 \\ X_j & \geq 0 \\ Z_j \qquad & \geq 0 \end{array}\right\} j=1, \ldots, 7$$

$$\left.\begin{array}{ll} Y_j & \geq 0 \\ Y_j & \leq 1 \end{array}\right\} j=1, \ldots, 8$$

$$\sum_{j=1}^{7} E_jX_j + \sum_{j=1}^{8} G_jY_j = T$$

where T is the target deviation from average salinity conditions.

Data, assumptions and software

The data used in calculating the parameters required for the solution of the linear programming model outlined above for the 30 year planning horizon may be found in the appendix of Alaouze and Fitzpatrick (1987). Specific information on the assumptions used in compiling the data used in the study, together with a more detailed description of each project, can be obtained from the authors on request.

A specialist working group consisting of representatives from the states of Australia and the Commonwealth was convened to compile the data for each salinity control project considered. The membership of the data working group is listed in the acknowledgements. Costs and benefits of the land protection schemes were estimated by local experts but were not necessarily based on rigorous experimental data. Benefits were calculated assuming that markets for agricultural products would be maintained into the future.

Despite some limitations, the data used in this study are the most comprehensive set of economic data on salinity control projects for the

Murray–Darling Basin compiled to date. The data are constantly being revised as improved information becomes available on each project, and the version used in the analysis reported in this paper was compiled in April 1987.

The linear programming model developed above was solved using the mixed integer linear programming module BBMIP of MPOS (Multi Purpose Optimisation System). BBMIP uses a branch and bound algorithm for solving mixed integer linear programming problems. An account of the specific algorithm used may be found in the user manual (Cohen and Stein 1978, pp. 48–50). This software was validated by solving a sample problem using APEX (version iv) which is the standard mathematical programming package used by the CSIRO. MPOS and APEX produced an identical solution to the sample problem.

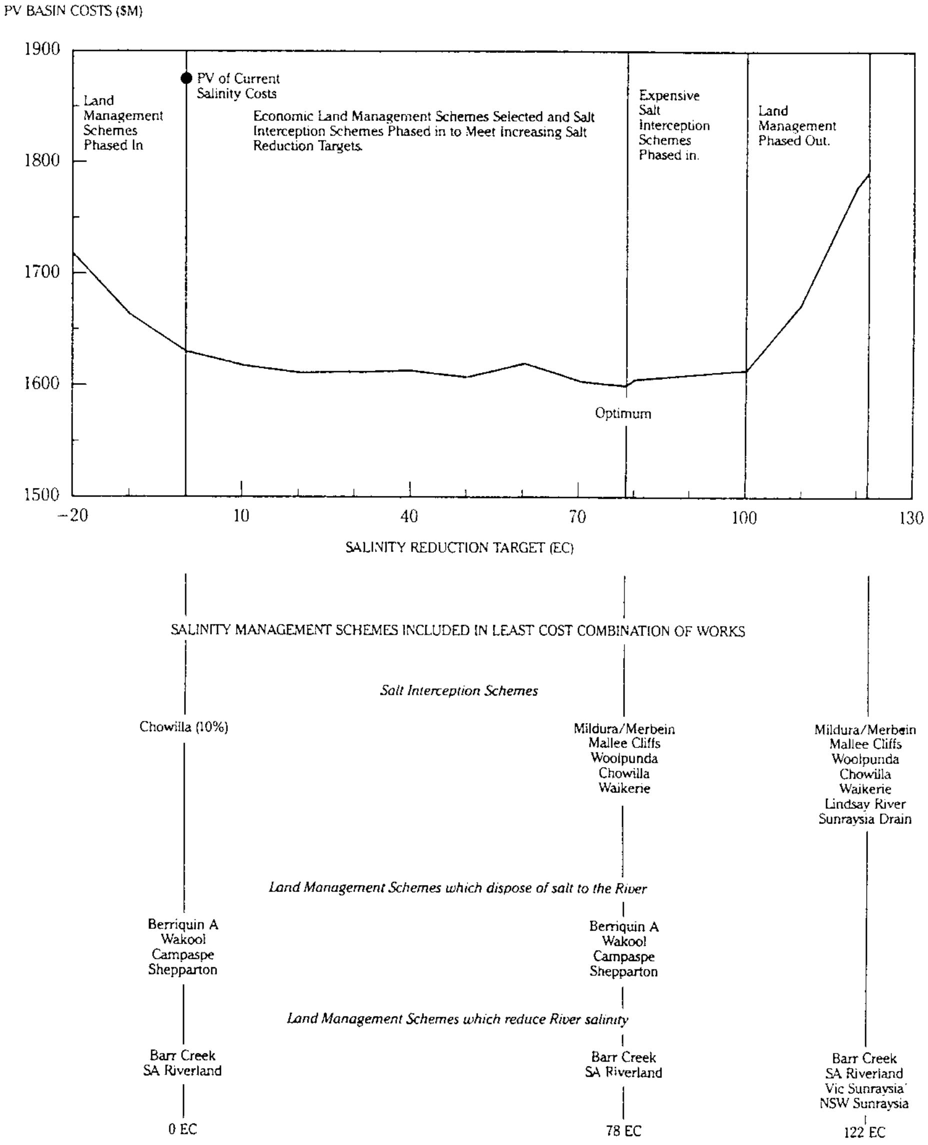
Results

From Table 1 it can be seen that the range of salinity impacts on the River Murray of the projects ranges from an addition of 29·2 EC to a maximum reduction of 122·3 EC. The EC-constrained linear programming model was solved over the range of 20 EC to −122·3 EC change in River Murray salinity, in steps of 10 EC for all but the last step which was a 2·3 EC change. The change in salinity level that minimises the net present value of total Murray–Darling Basin salinity costs over the 30 year planning horizon was found by solving the linear programming problem without the salinity constraint. The change in salinity level associated with this solution corresponds to a reduction in River Murray salinity of 78 EC.

The present value of total Murray–Darling Basin costs due to salinity and waterlogging over the 30 year planning horizon was estimated at $1875 million, and this is reduced as economically efficient salinity and waterlogging projects are implemented.

Figure 2 shows the net present value of Basin costs associated with the mix of works that produces each target salinity level at minimum cost and the cost-minimising solution; the projects chosen for achieving the cost minimum for the Basin, and the 0 EC and 120 EC salinity reduction targets are also shown. It can be seen from Figure 2 that the present value of Basin costs decreases rapidly as the River Murray salinity target changes from a 20 EC increase in salinity to maintaining the current level. This decrease in Basin costs occurs because, over this range, the linear programming model is introducing land protection schemes that provide substantial local productivity benefits but dispose of salt to the River Murray. This increased salt load is balanced by introducing an interception scheme and two land protection schemes which reduce River Murray salinity.

Figure 2 shows that the net present value of Basin costs decreases gradually between a salinity reduction target of 0 EC to the 78 EC salt reduction level. Over this range of salinity reduction targets, the linear programming model selects additional interception schemes to meet the progressively more stringent targets. Land protection schemes which dispose of salt to the River Murray but have net benefits are retained in the package of works. The shape of the curve in Figure 2 shows that Basin costs increase as the salt reduction targets increase from 78 EC to 122·3 EC, with a rapid increase between 100 EC and



* Salinity Costs = Cost of reduced Productivity + Cost of Land Management − Benefits of Land Management Measures + Costs of River Salinity + Costs of Interception Schemes − Benefits of Interception Schemes.
(Present value assumes 30 year period, 5% Discount Rate)

FIGURE 2—Minimised Present Value of Salinity Costs to the Murray–Darling Basin* Versus Salinity Reduction Targets at Morgan, South Australia.

122·3 EC. The economic data for the least cost combination of works are summarised in Table 2.

Comparison between the schemes selected to meet the 0 EC reduction target and the minimum cost package of works shows that four additional salt interception schemes are selected by the LP to minimise the net present value of Basin costs. The inclusion of these four interception schemes requires an additional $21·2 million of

TABLE 2

Net Present Value ($ millions) of Benefits and Costs and Salinity Impact of Schemes Selected in the Package of Works that Minimises the Net Present Value of Total Murray–Darling Basin Costs Due to Salinity and Waterlogging

Scheme	Salinity impact (EC)	Costs			Benefits		
		Capital	O. & M.	Total	Local	River	NPV
Interception scheme							
Woolpunda	−39·8	10·9	12·7	23·6	0·0	31·0	7·4
Waikerie	−15·9	7·3	5·1	12·4	0·0	13·2	0·8
Mallee Cliffs	−7·5	2·8	1·6	4·4	0·0	8·3	3·9
Chowilla	−10·5	3·7	1·4	5·1	0·0	11·3	6·3
Mildura/Merbein	−5·7	0·2	0·3	0·5	0·0	6·4	5·9
Sub total	−79·4	24·9	21·0	45·9	0·0	70·2	24·2
Vic. land protection scheme							
Shepparton	13·5	50·3	12·5	62·8	147·2	−7·0	77·4
Campaspe	0·8	1·1	0·8	1·9	7·6	−0·8	4·9
Barr Creek	−6·5	28·3	0·3	28·6	42·5	6·7	20·6
Sub total	7·8	79·7	13·6	93·3	197·3	−1·0	103·0
NSW land protection scheme							
Wakool	10·9	53·3	9·0	62·3	73·6	−4·8	6·5
Berriquin	4·0	43·3	10·2	53·5	111·9	−4·1	54·3
Sub total	14·9	96·6	19·2	115·8	185·5	−8·8	60·9
SA land protection scheme							
SA Riverland	−21·4	46·7	33·8	80·5	169·2	13·4	102·1
Total							
Interception	−79·4	24·9	21·0	45·9	0·0	70·2	24·2
Land protection	1·3	222·9	66·7	289·6	551·9	3·6	265·9
Grand total	−78·1	247·8	87·7	335·5	551·9	73·7	290·1

capital and provides benefits to water users of $58·9 million. Taking operating costs into account, the additional investment in these interception schemes increases net present value by $18·0 million. These benefits primarily accrue to water users in South Australia.

The package of works selected to maximise salt reduction in the River Murray differs from the works selected for the economic optimum in that the Sunraysia drainage scheme, Lindsay River interception scheme and improved irrigation technology schemes in the New South Wales and Victorian Sunraysia are included. Each of these schemes has a negative net present value, indicating that costs exceed benefits, but they all reduce River Murray salinity. In addition, it is necessary to drop the land protection schemes that dispose of salt to the River (Wakool, Berriquin, Shepparton and Campaspe) from the package of works for the salt reduction target to be met. The significant productivity benefits to the Basin of these schemes are lost. The net present value of Basin costs due to salinity and waterlogging exceeds the minimised value of these costs by $176·1 million, thus showing that substantial monetary benefits can be lost if projects are selected to meet arbitrary water quality constraints.

Sensitivity analysis

The data on which the preceding results are based are subject to considerable uncertainty. This stems from attempting to cost projects on a regional basis when costs depend on local conditions. In addition, agricultural productivity benefits were estimated assuming that appropriate management practices are adopted concurrently with the physical land protection proposals. There is some evidence from past experience that not all farmers adopt management practices appropriate to improved infrastructure. The data were reviewed by two independent expert consultants (see acknowledgements) and both concluded that the data for the land protection schemes erred on the optimistic side for benefits and tended to underestimate costs.

The impact on River Murray salinity of each of the proposed projects was selected as the most likely value from a range of possible values. The range of possible values is due to uncertainties in extrapolating from situations where precise measurements were available, to other situations involving land protection and interception schemes which would operate under similar conditions but for which inferior or no data were available. In addition, revised estimates of the capital and operating costs of some of the interception schemes suggest that these costs were underestimated in the base data.

These points suggest that some sensitivity analysis is warranted, and to this end the data working group was asked to suggest changes to the base data which could possibly correct for any biases that might be present. The data working group suggested the following changes to the base data for sensitivity analysis.

(1) Increase all capital and operating costs by 25 per cent.
(2) Reduce the annual salinity effect of each salt interception scheme as shown in brackets in column 2 of Table 3. These can be compared with the salinity effect of each scheme assumed in the base data reported in Table 1.
(3) Reduce the increase in productivity estimated for the New South Wales Sunraysia, Victorian Sunraysia and South Australian Riverland from 15 per cent (for the base data) to 10 per cent. Reduce the estimated productivity increase of the remaining land protection schemes by 30 per cent as compared with the base data.

The data were modified accordingly and the mixed integer linear programming model (without the EC constraint) was solved for a 50 year planning horizon with the base data, and for both the 30 year and 50 year horizons using data modified as described above. The mixed integer linear programming solutions to these problems are all integer solutions and the results are presented in Table 3.

Referring to Table 3, it can be seen that modifying the data causes the Woolpunda and Waikerie interception schemes and the Wakool/Tullakool/Deniboota land protection scheme to be dropped from the optimal package of works. Increasing the planning horizon to 50 years using the base data causes all schemes except the Sunraysia interception scheme and the New South Wales Sunraysia land protection scheme to be included in the optimal package of works. A 50 year horizon with the base data is the most favourable combination for project selection considered; thus, these two schemes can be regarded as uneconomic. For the 50 year horizon with the modified data the

TABLE 3

Sensitivity Analysis Results[a]

Scheme	1 30 year horizon base data	2 30 year horizon modified data	3 50 year horizon base data	4 50 year horizon modified data
Interception scheme				
1. Woolpunda	X	– (−29·9)	X	–
2. Waikerie	X	– (−11·9)	X	–
3. Mallee Cliffs	X	X (−5·625)	X	X
4. Chowilla	X	X (−7·87)	X	X
5. Mildura/Merbein/Buronga	X	X (−4·275)	X	X
6. Sunraysia	–	– (−3·0)	–	–
7. Lindsay River	–	– (−5·25)	X	–
Land protection scheme				
8. Wakool/Tullakool/Deniboota	X	–	X	–
9. Berriquin	X	X	X	X
10. NSW Sunraysia	–	–	–	–
11. Shepparton	X	X	X	X
12. Campaspe	X	X	X	X
13. Barr Creek	X	X	X	X
14. Vic. Sunraysia	–	–	X	–
15. SA Riverland	X	X	X	X
Value of objective function ($million, PV)	−290·1	−63·95	−511·0	−154·2
Annual salinity effect on River Murray (EC)	−78·1	−27·37	−87·1	−27·37

[a]The symbol X indicates that the proposed scheme is chosen by the linear programme as part of the package of works to be implemented; – indicates the scheme was not selected. The numbers in parentheses in column 2 are the modified annual salinity impacts (in EC units) of each scheme. These can be compared to those in Table 1 which displays the value of annual salinity effect of each scheme assessed in the base data.

linear programming model chooses the same projects as for the 30 year horizon with the modified data. Increasing the length of the horizon does not compensate for the changes to the base data so far as the optimal plan is concerned (although net Basin benefits are increased); thus, the schemes shown in columns 2 and 4 of Table 3 appear to be quite robust to changes in the length of the planning horizon, increases in their costs and reductions to their benefits. It would therefore seem that these schemes are economically viable and should be implemented.

For the Woolpunda, Waikerie and Lindsay River interception schemes, the Wakool/Tullakool/Deniboota and Victorian Sunraysia land protection schemes, increasing the length of the planning horizon does not compensate for the modifications to the data. Thus, we conclude that the data for these schemes should be examined closely and the linear programming model be re-run with revised data before any decision to implement or discard these projects is made.

Summary and Conclusions

In this paper, a mixed integer linear programming model was developed to evaluate a number of proposed salinity and waterlogging control schemes in the Murray–Darling Basin. This model was used to select the mix of projects that minimises the net present value of total Basin costs from a number of perspectives: River Murray salinity (water quality), cost minimisation and the sensitivity of this optimal solution to prescribed changes in the data and length of planning horizon.

The results suggest that if water quality in the River Murray and capital are not limiting factors, eight of the fifteen projects should be implemented, two should be discarded and the data for the remaining five be reviewed and further analysis undertaken before the decision to implement or discard these projects is made. The net present value of the recommended package of works is conservatively estimated at between $A63·95 million and $A154·2 million in 1985 dollars, depending on the actual useful lives of the projects. This package of works also provides an average reduction of River Murray salinity which is conservatively estimated at 27·4 EC.

To undertake this type of analysis using cost–benefit techniques would have been extremely tedious, and the answers obtained could not claim to be optimal in any formal sense. Thus, our approach illustrates the superiority of formal mathematical programming techniques over cost–benefit ratios, calculated on a project-by-project basis, in analysing complex project selection problems.

In addition, the model developed in the paper provides a framework for the collection of data on river protection, land salinisation and waterlogging schemes and provides a better understanding of how proposed works and measures interact. The results presented here formed the basis of negotiations between the states of New South Wales, Victoria and South Australia and the Commonwealth in drafting the Murray–Darling Basin salinity and drainage agreement.

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