Articles and Notes
Salinity Mitigation in the Murray River System

John Quiggin *

The problem of salinity and proposals to control or ameliorate it have received increasing attention in Australia in recent years. It is generally agreed that inappropriate land and water management practices, such as the excessive use of irrigation water in hydrologically unsuitable areas, are the main cause of the increasing levels of salinity which have been observed over the period of European settlement. If mitigation works are undertaken without regard to the incentive structures which generate these practices, they may encourage an extension of inappropriate land uses and ultimately be ineffectual or even counterproductive.

Analysis of these problems requires consideration of some issues which have so far received limited attention in discussions of salinity. These include the incentives which lead farmers to adopt different land management practices and the way in which institutional structures operate to generate these incentives. This change in focus has important implications for areas of analysis such as modelling. In the present paper, a model of the Murray River system, developed by Quiggin (1988a) is applied to the problem of farm responses to mitigation works and the availability of new technologies.

Introduction

The problem of salinity and proposals to control or ameliorate it have received increasing attention in Australia in recent years. This has occurred in the context of a more general resurgence of concern over issues related to land degradation, particularly in agriculture. Salinity and the associated problems of rising water tables have occurred in both irrigation and dryland agriculture. Economic aspects of the problem of dryland salinity have been studied by Hodge (1982) and Quiggin (1986). The economics of irrigation in Australia have been examined by several writers including Randall (1981), but salinity has seldom been a central concern.

There have, however, been extensive technical studies of salinity problems and their effect on agriculture. As well as documenting salinity problems and their increasing severity in some areas, studies such as Gutteridge, Haskins and Davey (1983) and Department of Resources and Energy (1983) have examined a wide range of possible remedial measures. The major emphasis of this work has been on engineering solutions aimed at mitigating the consequences of saline river flows, rather than on the land management practices which cause the problem. Salinity mitigation projects which have been undertaken include the drilling of tube wells to lower water tables, and the diversion of particularly saline flows. More ambitious projects, such as pipelines to the sea and large-scale desalinisation, have been mooted. As a result, much economic analysis of salinity problems has been concerned with measuring the costs and benefits of proposals of this kind.

Economic assessment of engineering proposals is clearly desirable. However, such approaches may be criticised for dealing with symptoms instead of causes. It is generally agreed that land and water management practices, such as the use of irrigation water in hydrologically unsuitable areas, are the main cause of the increasing levels of salinity which have been observed over the period of European settlement. The Murray-Darling Ministerial Council (1987, p. 102) notes

> "Application of excess water, lack of drainage and the use of permeable soils have all contributed to the situation where some 96000 ha of irrigation land in the Basin now has saline soils."

If mitigation works are undertaken without regard to the incentive structures which generate these practices, they may encourage an extension of inappropriate land uses and ultimately be ineffectual or even counterproductive. An equally important and closely related issue is that of the potential

* Department of Agricultural and Resource Economics, University of Maryland, College Park.

This paper is based on work undertaken at the Centre for Resource and Environmental Studies, Australian National University, and was supported by a grant from the Reserve Bank of Australia, Rural Credits Division.

for on-farm technological changes which could yield improvements in the efficiency of water use and reductions in saline accessions. Mitigation works, particularly if they are publicly funded, may act as a substitute for such on-farm improvements.

Analysis of these problems requires consideration of some issues which have so far received limited attention in discussions of salinity. These include the incentives which lead farmers to adopt different land management practices and the way in which institutional structures operate to generate these incentives.

This change in focus implies a need for a different approach to modelling, with more attention on management decisions and less on detailed representation of physical processes. Quiggin (1988a) describes a model which has been developed to illustrate the way in which different institutional structures and policies can affect farm land use decisions and the extent and severity of salinity-related problems. Among the problems examined in that paper was the effect of water pricing policies on water use and income distribution.

In the present paper, this model is applied to the problem of farm responses to mitigation works and the availability of new technologies. These responses are analysed, first in a situation where farm management decisions take no account of downstream salinity effects and then under a resource allocation satisfying an optimality condition based on maximising the net value of the resource provided by the river system. It is shown that under some incentive structures, it is possible for amelioration projects to lead to a net decline in the value of the resource to society.

Salinity and Salinity Mitigation

The Murray River system is Australia's largest irrigation area accounting for about 70 per cent of total Australian irrigated areas and irrigation water consumption (Watson et al 1983). As in other irrigation areas around the world, salinity has been an important problem, and salinity levels appear to be increasing, although there are significant year-to-year fluctuations (Gutteridge, Haskins and Davey 1983). The primary mechanism by which irrigation induces increased salinity is by increasing the rate of discharge from saline groundwater into river systems. Rising water tables can also cause damage through waterlogging. Waterlogging problems are particularly severe in the Kerang and Shepparton districts. Salinity levels in irrigation water in the river above Mildura are normally below the thresholds at which yields are affected. Yield losses arising from salinity are concentrated in the South Australian (SA) sections of the river.

The major costs of irrigation related salinity in the Murray River are those associated with downstream urban uses, primarily in Adelaide, and those associated with yield effects of saline water supplies on irrigated crops. Peck, Thomas and Williamson (1983, p. 43) estimate losses in the former category at $10.8 million per annum (1982 prices), primarily associated with reduced life expectancy for household appliances. These estimates were obtained by comparisons with experience in towns such as Perth, where salinity is not a problem. The procedure is open to the objection that Adelaide's water supply is poor for several reasons, of which irrigation-related salinity may not be the most important.

Regarding crop damage, Peck et al (1983) suggest that losses range from zero in years of low salinity to $4 million in years of high salinity. This estimate is based on farm-gate prices, but does not take account of any reductions in harvesting costs associated with lower yields. However, this estimate only measures yield losses in the crops actually planted. It does not take account of opportunity costs associated with changes in the land use pattern arising from salinity - most notably the need to choose salt tolerant crops. Quiggin (1988a) estimates that these costs are more than twice as large as the direct yield effects, yielding total losses associated with salinity of about $20 million in years of high salinity. By way of comparison, the data given by Watson et al (1983) imply a total cash operating surplus for horticultural farms in the Murray-Darling system of about $85 million for 1980-81.

A wide range of engineering projects have been introduced or proposed to mitigate salinity and its effects. Most such projects work by intercepting salt before it enters the river, and seeking to dispose of it somewhere where it will do no harm. The most common approach, exemplified by the Mildura-Merbein scheme, is to sink boreholes in areas of highly saline groundwater flows and pump the water to evaporation basins. The most difficult problem in schemes of this kind is the disposal of the effluent. In some cases, notably the Shepparton drainage scheme[1], much of the saline groundwater simply re-enters the river further downstream, so that the local benefits are offset by increased downstream costs.

The main alternative is to increase the technical efficiency of water use. This may be done either in the publicly controlled parts of the irrigation system, for example by replacing open channels with piped supplies, or by improved on-farm management. In this paper, on-farm approaches will be the major subject of concern.

Institutional arrangements associated with irrigation have historically been oriented to the maximization of the area under irrigation, without regard to economic criteria or cost-recovery. Water charges have been designed to cover the cost of operation and routine maintenance, but do not include any allowance for the capital cost of irrigation works or any opportunity cost charge for water use. Because of the low level of water charges, there is little incentive for farmers to seek improvements in the efficiency of water use. There are weak constraints on the total amounts which can be diverted in the higher levels of the river, to the detriment of downstream users (and potential users). Although there are limits on the water each farmer can use, it seems reasonable to model the existing situation as one of open access. The quality and quantity of water reaching SA has been a major bone of contention between SA and the upstream states, Victoria and New South Wales (NSW) with several state elections turning on the issue in the late 1960s. Although water quality has many dimensions, attention will be focused on salinity, as measured by milligrams of total dissolved solids per litre. Salinity is a good proxy for other aspects of water quality and for related effects of concern, such as the ecological effects of reduced stream flows.

The main reason farmers would seek to improve water use efficiency under the current policy régime is the desire to mitigate the yield effects of salinity. This is most obvious for schemes which reduce evaporation losses in water transport. Since salinity is the ratio of salt load to flow, any scheme which reduces evaporation losses directly reduces the salinity of water applied to crops. However, there are also significant potential benefits in replacing water-intensive forms of irrigation such as overhead sprinklers with more efficient systems such as trickle irrigation. There is also a possibility of improvements in biological efficiency so that the same or increased yields are achieved with reduced inputs of water. Watson et al (1983) estimate that only about 33 per cent of water released for irrigation is used by plants. They also suggest that yield improvements of up to 50 per cent could be achieved by the year 2000.

Under current institutional arrangements, it is unlikely that much of this saving in water use will be achieved. Indeed, some farm-level responses to salinity involve the use of increased amounts of water to leach salts and exacerbate the long-term problem. It is important to examine the ways in which institutional patterns interact with farm water use decisions.

The Common Property Approach

The central economic problem in Murray River salinity is the fact that farms do not individually bear the costs of irrigation decisions which cause increased salinity. Problems of this kind have typically been analysed in the externality framework pioneered by Pigou (1924). The externality concept is useful in pointing out the basis of the problem, but its analytic power is very limited in cases other than that of direct interaction between two individuals. The model used here represents an alternative approach, based on the concept of common property (Quiggin 1983, 1988b). The common property approach may be considered both as a description of institutional arrangements and as an analytic framework. This paper is concerned primarily with the second interpretation.

[1] This scheme is primarily concerned with lowering water tables rather than reducing salinity effects, but the general principles are the same.

The first requirement of this approach is that rights be defined over assets, such as air basins or lakes, rather than in terms of individual rights to undertake or preclude particular activities. The assets need not be purely physical. A given part of the atmosphere, might, for example be subject to one structure of rights when considered as an air basin, and to a different structure when considered for radio transmissions. In the asset-utilisation approach, it is asset quality which is an argument in production and utility functions and is itself affected by the actions of asset users. This representation is analytically and computationally more tractable than the externality framework and less likely to generate errors such as those discussed by Mohring and Boyd (1971).

The second requirement is the specification of a group of common owners consisting of existing and potential users of the asset. As noted above, it is important that potential and existing users (and uses) be considered. For purposes of policy analysis, the value of the asset *to* each user may be expressed in terms of changes in producer and consumer surplus with respect to some base level of asset quality and usage[2]. The pattern of usage which maximises the value of the asset to its common owners can then be identified.

The third requirement for a common property solution is the specification of institutional frameworks. This task will not be attempted here. Possible institutional frameworks for dryland salinity are considered by Quiggin (1986). The discussion of policy implications presented below gives some indication of institutional changes which might yield an outcome closer to the common property optimum. In this paper, attention will be focused on the differences between the water use pattern prevailing under conditions of open access, and that yielded by an optimal use of the common resource (in the sense of maximising asset value), without consideration of how this would be achieved.

This 'nirvana' approach has been criticised sharply by Demsetz (1969). However determination of an optimal solution provides a useful benchmark against which policies may be tested. It indicates whether there is the possibility, at least in principle, of improvements. For example, in the present model the resource allocation pattern yielded by appropriately chosen water charges may be shown to be similar, though not identical, to the optimal solution (Quiggin 1988a). If such charges were adopted, there would not be much room for further efficiency gains, although there might be interest in policies with different distributional effects.

An Outline of the Model

The purpose of the model used here is to examine the response of farm water use decisions to different sets of incentives and constraints. Because of fundamental uncertainties about underlying physical relationships, and the general difficulties of modelling economic processes, it is impossible to obtain precise and reliable numerical estimates of the costs of salinity from this, or any other model. While every effort has been made to model the Murray River system and the water use problem as accurately as possible, the primary purpose of the model must be to illustrate the underlying process and generate useful insights into the problem rather than to provide numerical estimates of costs and benefits.

The model is described in detail in Quiggin (1988a), and a shorter formal presentation is given in the Appendix. A brief description will be given here. The farm decision is characterised by the allocation of farm land between four irrigation crops - stonefruits, citrus, grapes and pasture. Stonefruits are high value crops but are highly sensitive to salinity. Pasture gives a low return per megalitre (Ml) of water applied but is relatively salt tolerant. Citrus and grapes are intermediate in both respects. The model contains four inputs to farm production - irrigable land, water, operator labour and 'other'.

The critical aspect of the problem which must be captured by the model is the relationship between upstream water users and asset quality as it affects

[2] There are a wide range of measures which could be used including consumer and producer surplus measures. For the purposes of the present study, the distinctions between these measures are not important. Prices are largely determined on world markets and are not likely to be affected by the changes considered here. Changes in the income of individual urban consumers are small and hence income effects are not likely to make much difference. Although different options may alter individual producer incomes substantially, this does not affect the validity of producer surplus measures.

downstream water users. Upstream water use tends to reduce flows and increase salinity for downstream users. Increases in salinity reduce yields, though this effect varies between crops. Increases in salinity will also affect urban water users in a variety of ways; including damage to household appliances, increased washing costs, and at high levels, directly through reduced potability of drinking water.

The system is modelled in six representative farm blocks, corresponding to successive stages in the Murray River system, and a seventh stage corresponding to downstream urban water use, primarily in Adelaide. The stages correspond to the successive stretches Albury-Echuca, Echuca-Swan Hill, Swan Hill-Mildura, Mildura-Renmark, Renmark-Kingston and Kingston-Murray Bridge. Water availability and salinity for each stage is determined by upstream usage and natural inflows and outflows.

Different policy régimes are reflected in different solution methods. The first solution method corresponds to a régime of open access. At each stage of the river, farmers will maximise their own profits without regard for downstream effects. The problem may be represented as a series of linear programming problems, linked by the fact that the solution to one problem determines the salinity and flow levels for the next.

The common property approach suggests that the solution to this problem is to seek the resource usage pattern which maximises the value of the asset to the group of users. This problem may then be formulated as a dynamic programming problem, in which the stages of the river take the place of successive time-periods in a standard dynamic programming problem.

By comparing the results yielded by the dynamic programming and sequential linear programming problems it is possible to estimate the losses associated with salinity-related externalities (or, on the asset-utilisation view, with open access to the asset). It is then possible to formulate a system of charges based on the reduction in asset value associated with activities which degrade the quality of the asset. Basic results of this kind are presented in Quiggin (1988a).

Construction of the model required estimates of parameters for aggregate water use and inflows, the relationship between water use and salt access, yield effects of salinity and farm input requirements and constraints. In many of these areas, particularly the relationship between water use and salt access, very little information was available. Gutteridge, Haskins and Davey (1983) yielded estimates of natural salt inflows and effects of salinity on plant yields. River Murray Commission Reports were used for estimates of natural water inflows and irrigated areas. A range of possible values for the parameters on water use and salt access were derived from Gutteridge, Haskins and Davey (1983) and Peck, Thomas and Williamson (1983). The runs reported here use estimates of salt levels which are higher than the median value derived from these studies, corresponding either to a bad season or to a continuation of present adverse trends. Estimates of farm input requirements were derived from Penman and Richens (1981), Watson et al (1983) and Lumley (1983). Estimates of urban salinity costs were derived from Peck, Thomas and Williamson (1983).

In this paper, the basic model is modified, first to include the possibility of a less water-intensive technology for the production of each of the crops, and then to simulate the effect of a salinity mitigation project. The mitigation project may be modelled in a straightforward fashion, by assuming that a fixed quantity of salt is intercepted before it enters the river. To illustrate the possible effects on farm water use decisions, it is assumed that the project is located near the source of the river, so that the base level of salinity is reduced for all stages.

The introduction of less water-intensive technologies poses a more significant modelling problem. If the new technology dominates the previous one, in the sense that an increased yield is obtained with reduced inputs, it will be adopted[3]. In the absence of

[3] Assuming that existing capital stocks have low scrappage values, a dominant new technology of this kind would be adopted gradually as old equipment required replacement, unless the costs of the new technology were lower than the variable costs of the old technology. The solutions derived in the present model represent a comparison of medium-term equilibria. The dynamics of adjustment between equilibria are not modelled.

strict dominance, the new technology permits a shift along the production possibility frontier, and the adoption decision will depend on relative input prices. A well-known difficulty with linear programming models of production activities is that they do not permit factor substitution within a given activity, so that responses to changes in relative factor costs can be modelled only as changes in the activity mix. The adoption of a linear programming approach is equivalent to the unrealistic assumption of fixed-proportions technology. An obvious response to this difficulty is to include two or more activities yielding the same output from different input mixes. This raises the problem of choosing alternative mixes. In this model, as in most models of this kind, the initial production mix is determined by the existing pattern of inputs and outputs. Other production patterns could be estimated from experimental evidence. However, this is costly and there is the problem of translating experimental results into actual production systems.

Another approach to the problem relies on the assumption of profit maximisation and the fact that Cobb-Douglas technology gives a first order local approximation to any differentiable production function. Using these assumptions, it is possible to estimate the coefficients of the production function from the factor cost shares by standard duality methods.

Let

$$Y = \prod X_i^{a_i} \tag{1}$$

be the Cobb-Douglas approximation to the production function where Y is output and X_i is the input of factor i. Then profit maximisation implies that

$$a_i = c_i X_i / pY = c_i X_i / \Sigma_j c_j X_j \tag{2}$$

where p is the output price and c_i is the price of factor i. Thus, given an initial vector of inputs, outputs and prices, it is possible to use the Cobb-Douglas approximation to estimate the output effects of a 'small' change in the input mix. First, equation (2) can be used to obtain an estimate of the coefficients a_i. Then equation (1) can be used to estimate Y for a vector of inputs reflecting a less water-intensive input mix. Thus, given an initial input mix, obtained from technical studies or farm surveys, this approach can be used to generate a range of input-output vectors with differing factor intensities and hence permit modelling of factor substitution at low cost.

The approach may be illustrated by an example. Choose units so that all prices equal unity and suppose there is an activity in the model which combines 20 units of each of the four inputs to yield 100 units of one of the outputs, say citrus. Then, using equations (1) and (2), it is possible to formulate an approximate Cobb-Douglas production function

$$Y = 5\prod_i X_i^{0.25} \tag{3}$$

Now consider another vector of inputs, corresponding to a shift to a less water-intensive technique, with 10 units of water and 25 units of the other three inputs. Equation (3) indicates that the output would be 99.4 units. Alternatively, for a known change in prices, the optimal input mix can be derived from (2) and the resulting output determined from (3).

Results

The basic solutions to the model are given in Tables 1 and 2. Table 1 is the linear programming solution, corresponding to a state of open access to the resource. Table 2 is the dynamic programming solution corresponding to maximisation of the asset value. The dynamic programming solution involved a reduction in water use and salinity and an increase in total profit (the value yielded by the asset to all users) from \$67.2 million to \$94.5 million. This is achieved mainly be eliminating the large-scale use of water for irrigated pasture in Stage 1 and diverting resources to stone fruits, the agricultural activity which yields the highest return per unit of water used. The resulting reductions in salinity in later stages permit further increases in stone-fruit areas and the maintenance of citrus production instead of its replacement by pasture in Stage 6. There are also gains from reductions in salinity for the downstream urban water use. The gain of \$6.3 million to downstream water users is less than the estimate of \$10.8 million cited by Peck *et al* (1983, p. 43) but the latter estimate takes as its base a situation where there are no salinity costs.

Table 1: Results of Open Access Solution

		Area[b] planted to				Water	
Stage	Salinity[a]	Stone	Citrus	Grape	Pasture	Use[c]	Asset Value[d]
1	183	0.0	171.4	0.0	228.6	2.69	19.5
2	320	0.0	173.8	0.0	176.2	2.45	19.2
3	395	0.0	140.0	0.0	0.0	1.26	13.1
4	549	0.0	140.0	0.0	0.0	1.26	8.2
5	691	0.0	0.0	48.9	91.1	0.75	2.6
6	803	0.0	0.0	48.8	91.1	0.75	1.2
7	na	0.0	0.0	0.0	0.0	0.18	3.4
TOTAL		0.0	625.2	97.7	587.0	10.0	67.2

Notes:

a: At end stage, in mg/L Total Dissolved Solids
b: Hectares * 10^3
c: Ml * 10^6
d: $m

The next two simulations involve the use of alternative technologies. These simulations may be given two different interpretations. The first is that they represent a comparative static simulation of the effects of the exogenous development of new, more water efficient technologies. The second, suggested by the previous discussion of the Cobb-Douglas approximate production functions is that they represent a refinement of the model to take account of the possibility of input substitution. Since the prevailing technology is very water-intensive, it is natural to give attention to production techniques which economise on water use. Where salinity is a problem, such techniques may be advantageous to growers even if water is not expensive.

Tables 3 and 4 contain model solutions for the case when less water-intensive production technologies, corresponding to a 20 per cent reduction in water use per hectare, are available for each of the agricultural commodities. It is assumed that these technologies involve a corresponding reduction in salinity. An example would be the case, discussed above, of a reduction in evaporation losses. The Cobb-Douglas technique described above, is used to estimate the change in yields, assuming that other input quantities are unchanged. When salinity is not a problem and prices are unchanged from the base solution, it follows from the profit-maximisation assumptions on which the Cobb-Douglas model is based that the new technology is less profitable than the old one. The introduction of this new technology has very different implications for the two solutions.

In the open access solution, the less water-intensive technology is only adopted in those sections of the river where salinity is high enough to affect yields, that is, from stages 3 onwards. The potential gains

Table 2: Results of Common Property Solution

Stage	Salinity[a]	Stone	Area[b] planted to Citrus	Grape	Pasture	Water Use[c]	Asset Value[d]
1	70	70.6	21.3	0.0	0.0	0.83	13.4
2	106	74.7	16.7	0.0	0.0	0.80	13.3
3	143	75.5	11.0	0.0	0.0	0.78	13.1
4	200	72.6	16.8	0.0	0.0	0.80	13.3
5	300	32.9	107.1	0.0	0.0	1.26	16.3
6	399	0.0	140.0	0.0	0.0	1.26	14.5
7	na	0.0	0.0	0.0	0.0	0.18	10.7
TOTAL		323.9	313.0	0.0	0.0	5.91	94.5

Notes: see Table 1.

from water savings in the earlier stages are not realised. An increase in total profits and a significant reduction in water use are still achieved. The direct local benefits from reduced salinity damages are less significant that the downstream effects of reduced salt accessions (a reduction in 'negative externalities' in Pigovian terminology). There is a reduction in costs incurred by urban water users. Also, salinity levels are kept low enough to permit the maintenance of the citrus activity in Stage 5 and delay the need to shift resources into pasture, the least water-efficient activity.

By contrast, although the global optimum solution also involves an increase in profit, this is achieved despite an increase in water use, salinity and costs to urban water users. The intuition behind this result is straightforward. If the problem of optimising resource use is compared to a consumer's decision problem, the introduction of the less water-intensive options corresponds to a reduction in the relative price of one group of goods, here the agricultural activities, as compared to another, here the urban activities. If demand is elastic, a price reduction will lead to an increase in total expenditures. Similarly, in the resource use problem, the improved water-efficiency of the agricultural activities, particularly citrus, leads to an increased allocation of resources to those activities which outweighs the reduction in unit water use.

Comparing the two results, it is noticeable that the difference in the pattern of resource allocation is much less extreme than in Tables 1 and 2. The open access solution has moved closer to the initial optimum and *vice versa*. Reduced on-farm water use is an example of a technological advance which interacts in a positive fashion with the existing institutional framework.

A contrasting example is given in Tables 5 and 6. These tables record the results of a simulation of an engineering project which reduces the initial salt load in the river by 100,000 tonnes. The benefits of this reduction are entirely captured in stage 3. There is no effect in stages 1 and 2 because, in the base solution, salt levels are too low to effect yields. In stage 3, the reduction in salinity permits a shift back to the more profitable high water-intensity technology. The resultant increase in downstream salinity outweighs the initial reduction so that final salinity is increased. The net benefits of the project

Table 3: Results of Open Access Solution (with option of less water-intensive technology)

Stage	Salinity[a]	Area[b] planted to Stone	Citrus	Grape	Pasture	Water Use[c]	Asset Value[d]
1	183	0.0	171.4(H)	0.0	228.6(H)	2.69	19.5
2	320	0.0	173.8(H)	0.0	176.2(H)	2.45	19.4
3	374	0.0	140.0(L)	0.0	0.0	1.01	13.5
4	497	0.0	140.0(L)	0.0	0.0	1.01	12.7
5	656	0.0	124.1(L)	15.9(H)	0.0	0.99	6.4
6	753	0.0	0.0	48.8(L)	91.1(H)	0.69	2.2
7	na	0.0	0.0	0.0	0.0	0.18	7.9
TOTAL		0.0	749.3	64.7	495.9	9.0	81.5

Notes: see Table 1. H denotes high water-use technology, L denotes low water-use technology

Table 4: Results of Common Property Solution (with option of less water-intensive technology)

Stage	Salinity[a]	Area[b] planted to Stone	Citrus	Grape	Pasture	Water Use[c]	Asset Value[d]
1	92	13.1(H)	152.1(L)	0.0	0.0	1.21	16.7
2	149	8.4(H)	162.7(L)	0.0	0.0	1.25	17.0
3	200	37.6(H)	96.3(L)	0.0	0.0	1.03	15.2
4	283	32.9(H)	107.1(L)	0.0	0.0	1.07	15.5
5	385	32.9(L)	107.1(L)	0.0	0.0	1.01	13.9
6	478	0.0	140.1(L)	0.0	0.0	1.01	12.1
7	na	0.0	0.0	0.0	0.0	0.18	12.9
TOTAL		124.9	765.4	0.0	0.0	6.8	103.3

Notes: see Table 3.

Table 5: Results of Open Access Solution (with option of less water-intensive technology and reduction in initial salt levels)

Stage	Salinity[a]	Stone	Area[b] planted to Citrus	Grape	Pasture	Water Use[c]	Asset Value[d]
1	171	0.0	171.4(H)	0.0	228.6(H)	2.69	19.5
2	309	0.0	173.8(H)	0.0	176.2(H)	2.45	19.4
3	384	0.0	140.0(H)	0.0	0.0	1.01	13.9
4	510	0.0	140.0(L)	0.0	0.0	1.01	12.2
5	676	0.0	124.1(L)	15.9(H)	0.0	0.99	5.7
6	777	0.0	0.0	48.8(L)	91.1(H)	0.69	2.2
7	na	0.0	0.0	0.0	0.0	0.18	7.5
TOTAL		0.0	749.3	64.7	495.9	9.3	80.3

Notes: see Table 3.

Table 6: Results of Common Property Solution (with option of less water-intensive technology and reduction in initial salt levels)

Stage	Salinity[a]	Stone	Area[b] planted to Citrus	Grape	Pasture	Water Use[c]	Asset Value[d]
1	85	4.7(H)	171.2(L)	0.0	0.0	1.27	17.2
2	146	0.0(H)	181.7(L)	0.0	0.0	1.31	17.5
3	200	33.2(H)	106.3(L)	0.0	0.0	1.06	15.5
4	283	37.0(H)	97.8(L)	0.0	0.0	1.07	15.3
5	385	32.9(L)	107.1(L)	0.0	0.0	1.01	13.9
6	478	0.0	140.1(L)	0.0	0.0	1.01	12.1
7	na	0.0	0.0	0.0	0.0	0.18	12.9
TOTAL		108.7	804.1	0.0	0.0	6.9	104.4

Notes: see Table 3.

are negative, even without taking construction costs into account. Total asset value is reduced from $81.5 million to $80.3 million. By contrast, although the optimal solution also permits the benefits to be captured in the early stages, there is no increase in downstream salinity, and total asset value is increased from $103.3 million to $104.4 million.

These results, and particularly the analysis of the engineering project, show the extent to which the problem of Murray River salinity is institutional rather than hydrological. Without appropriate institutional frameworks, measures which ameliorate the consequences of salinity may be ineffectual or even counterproductive.

Policy Implications

The common property approach has been used here primarily as a framework for analysis. The primary objective has been to illustrate the effects of technological change under alternative systems of water allocation. It is natural to consider institutional frameworks which might generate an approximation to the optimal solution derived here.

One approach would be to specify a pricing structure which would reflect the impact of water use on asset value, and therefore generate the optimal solution. Quiggin(1988a) considered the impact of a uniform increase in water charges to a level equal to the difference (expressed in $ per Ml of total water use) between the open access and common property solutions[4]. This yields an outcome close to the optimum, but does not take account of the differential impact of water use in different parts of the river system. The model presented here may be developed to generate an exactly optimal pricing system. This task is deferred for future research. However, it may be noted that the political obstacles to the achievement of opportunity cost pricing, generated by the associated redistribution of wealth, are substantial.

A second possibility would be to specify limits on total water use in each part of the river, and then develop local institutions to allocate water within this limit. A number of possibilities arise. The first is action by the existing management authorities, such as a proportional reduction in water allocations, or a program to buy back water rights from existing users. The second would be the creation of a market for water rights, combined with action to reduce total water usage to the optimal level. Water rights could be traded freely within a given region. However, the salinity implications of trade in water rights between regions would imply a need for some regulation of trade. As a practical matter, of course, any interstate transfers of water rights would require the agreement of the relevant governments. A final possible arrangement would involve the development of common property institutions at the regional level. This would be most relevant if public subsidies to capital works were removed or curtailed, and requirements for reduced saline accessions were imposed. In this case, it would be desirable for irrigators to make collective decisions on capital programs which would be funded from water charges. As in other examples of common property, such as the medieval commons, these collective institutions would co-exist with, and indeed reinforce, private property rights in land and water. A more detailed discussion of the relative merits of direct regulation, marketable property rights and common property institutions is given in Quiggin (1983, 1986, 1988b).

Concluding Comments

Economic analysis of Australian salinity problems is in its infancy. The primary purpose of the modelling exercises reported here is to illustrate the economic problems involved, rather than to provide precise numerical estimates of the costs of salinity. Some of the main points which have been raised may be summarised as follows.

First, open access to the resource represented by the Murray River system has the predictable consequence that the resource is overused and its quality degraded, relative to the socially optimal level. Second, direct costs of salinity as measured by reduction in yields may be less important than the changes in patterns of resource use which take place in response to high levels of salinity. Third,

[4] This charge approximates an opportunity cost for water. Note that, as in the present system, the capital cost of irrigation works is treated as sunk.

on-farm measures to improve the efficiency of water use may yield substantial benefits and may reduce the need for radical changes in the pattern of agricultural activity. Fourth, engineering projects which mitigate the consequences of salinity should not be undertaken without consideration of the way in which they will interact with institutional frameworks.

Despite its simplicity, the model presented here yields useful insights into the problem of salinity. There are several ways in which the model could be improved to yield a more accurate representation of the system, and to permit the analysis of features of the problem outside the scope of the present formulation. The most important is the inclusion of heterogeneity in the hydrological characteristics of land. A second possibility would be to make the model dynamic over time as well as space. This would yield important benefits, such as the ability to model a situation of fluctuating salinity levels. However, these benefits might not outweigh the cost in increased complexity and the difficulty of interpreting model results.

It is also important to consider developments on the theoretical front. The approach used here, based on the concepts of common property and asset utilisation, is still in its early stages. It has the potential to make significant changes in the ways in which environmental problems are analysed by economists.

References

AUSTRALIA, DEPARTMENT OF RESOURCES AND ENERGY (1983), *Water 2000: A perspective on Australia's water resources to the year 2000,* AGPS, Canberra.

CIRIACY-WANTRUP, S. (1952), *Conservation: Economics and Policies,* University of California Press, Berkeley, California.

DAHLMAN, C. (1980), *The open field system and beyond,* Cambridge University Press, Cambridge.

DEMSETZ, H. (1967), "Towards a theory of property rights", *American Economic Review* 57(2), 347-59.

GUTTERIDGE, HASKINS AND DAVEY LTD. (1983), *The application of salinity control techniques in Victoria,* Report prepared for the Salinity Committee of the Victorian Parliament.

HODGE, I. (1982), "Rights to cleared land and the control of dryland-seepage salinity", *Australian Journal of Agricultural Economics* 26(3), 185-201.

LUMLEY, S. (1983), Economic implications of dryland salting and stream salinity in North-Central Victoria, Unpublished M. Ec. thesis, La Trobe University, Bundoora.

MOHRING, H. and BOYD, J. (1971), "Analysing 'externalities': 'direct interaction' vs 'asset utilisation' frameworks'", *Economica* 38(4), 347-61.

PECK, A., THOMAS, J. and WILLIAMSON, D. (1983), *Salinity Issues (Water 2000: Consultants Report No. 8),* AGPS, Canberra.

PENMAN, P. and RICHENS, F. (1981), Profitability of a Murrumbidgee Irrigation Area Fruit Farm, Farm Management Bulletin 6/81, New South Wales Department of Agriculture, Sydney.

PIGOU, A. (1924), *The Economics of Welfare,* Macmillan, London.

QUIGGIN, J. (1983), The common property approach, Unpublished M.Ec. thesis, A.N.U., Canberra.

QUIGGIN, J. (1986), "Common property, private property and regulation: The case of dryland salinity", *Australian Journal of Agricultural Economics* 30(2-3), 103-117.

QUIGGIN, J. (1988a), "Murray River salinity - an illustrative model", *American Journal of Agricultural Economics* 70(3), 635-35.

QUIGGIN, J. (1988b), "Private and common property rights in the economics of the environment", *Journal of Economic Issues* 22(4), 1071-88.

RANDALL, A. (1981), "Property entitlements and pricing policies for a maturing water economy", *Australian Journal of Agricultural Economics* 25(3), 195-220.

RIVER MURRAY COMMISSION, *Annual Reports, 1976-1982,* Canberra Publishing and Printing, Canberra.

WATSON, W., REYNFOLDS, R., COLLINS, D. and HUNTER, R. (1983), *Agricultural Water Demand and Issues (Water 2000: Consultants Report No. 5),* AGPS, Canberra.

Appendix - Outline of the model

The model presented here illustrates the response of farm water use decisions to different sets of incentives, constraints, and property rights structures. A highly simplified representation of the decision problem for an irrigation farm is employed. The farm decision is characterized by the allocation of farm land among four irrigation crops: stonefruits, citrus, grapes and pasture. Remaining land is used for dryland agriculture.

The model contains four inputs to production: irrigable land, water, operator labour and "other". The major inputs are all subject to total availability constraints in each region. The water supply is constrained only by the requirement that river flow remain positive. Institutional constraints on water use are expressed primarily in the form of a requirement that the total irrigated area in each section should not increase. Similarly, the input of operator labor is constrained not to exceed the currently existing level in each area. "Other" inputs are assumed to be in perfectly elastic supply and, thus, affect the farm decision only through costs.

The salient characteristics of the four main crops are summarized as follows. Stonefruits yield the highest net profit per hectare (at full yield) and make the most intensive use of labor. They are also the most sensitive to salinity. Citrus crops are distinguished from stonefruits by lower labor-intensity, sensitivity to salt, and surplus per ha. Grapes require less water and are more salt-resistant than either citrus or stonefruits. Finally, pasture is characterized by very low labor-intensity and returns per ha. of land and per Ml of water applied.

The model may be formally specified as follows. X_{nt} denotes input of factor n at stage t; Y_{mt} denotes output of product m at stage t; θ denotes additional salt accessions per Ml water applied; α denotes the proportion of irrigation water returning to river; F_t denotes flow at stage t; S_t denotes salt load at stage t; G_t denotes natural inflow at stage t; W_t denotes water use at stage t; K_t denotes natural salt accessions at stage t; $s_t = F_t/S_t$ denotes salinity at stage t; and ϕ_{mt} denotes yield of output m at stage t.

Then the model is formulated as the following system

(1) $F_t = F_{t-1} + G_t - (1-\alpha)^* W_{t-1}$

(2) $S_t = S_{t-1} + K_t + \theta * W_{t-1}$

Yield is determined by a relationship of the form

(3) $\theta_{mt} = 1 - \gamma_m * (\max(s_t - \lambda_m, 0)$

where γ_m and λ_m are respectively yield loss and threshold parameters for product m. Thus yield for product m remains at 1 until the threshold level λ_m is reached after which it declines linearly. Input requirements are given by

(4) $X_{nt} = \Sigma A_{nm} Y_{mt} / \phi_{mt}$,

where A is an n-by-m matrix of input-output coefficients. The value of the river resource to users at stage t is

(5) $V_t = \Sigma p_m Y_{mt} - \Sigma c_n X_{nt}$,

where p and c are vectors of input and output prices, respectively. Thus, the alternative solution methods involve either maximizing the V_i sequentially or maximizing $V = \Sigma V_i$.