A Short Run Economic Analysis of the Eutrophication Problem of the Barwon and Darling Rivers in New South Wales

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(02) 385 3561

February 1995

*I have benefited from discussions with Bruce Fitzgerald, John Verhoeven and Greg White of the NSW Department of Water Resources, Bruce Cole and Jim Keary of the Hunter Water Corporation and Officers of the Dubbo and Moree offices of the NSW Department of Water Resources. I would also like to thank Jonathan Doig of the Environment Protection Authority of NSW for sending me details of the licensed point sources which discharge to the rivers in the Barwon and Darling catchments and Alan Flinders of the Department of Public Works for sending me information on costs of upgrading sewage treatment plants for phosphorus removal. The author takes full responsibility for the analysis presented in this paper.

Paper presented to the 39th Annual Conference of the Australian Agricultural Economics Society, University of Western Australia, February 1995.

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Abstract

Two short run economic solutions to the eutrophication problem of the Barwon and Darling Rivers are examined. The first is flushing algal blooms from the Rivers using reservoir releases and the second is restricting the accessions to the River of phosphorous from point sources during low flow periods. It is argued that flushing algal blooms is economic if water is available and that regardless of which solution or mixtures of solutions is employed, the phosphorus concentration in the rivers should not be permitted to reach the level where algal blooms affect the recreational use of the Rivers. This is because the marginal cost of pollution curve has a marked jump at the phosphorus concentration which can support algal blooms which affect the recreational use of the Rivers.

1 *Introduction*

Eutrophication is the nutrient enrichment of lakes, rivers and water storages at a level which can support the excessive growth of algae, aquatic plants and micro organisms under suitable conditions. The growth of algae, aquatic plants and micro organisms is considered excessive when it interferes with the normal use of water resources. The main nutrients responsible for eutrophication are soluble compounds of phosphorus and nitrogen. However, management strategies are usually based on regulating phosphorus compounds. Zajic (1971, pp. 315-316) gives three reasons for this: (i) available nitrogen occurs in three main chemical forms and also as organic nitrogen and this makes it difficult to remove from sewage. (ii) About 30% of the total nitrogen applied as fertiliser is leached out and these waters cannot be effectively treated. (iii) The blue-green algae can fix gaseous nitrogen from the air if no other nitrogen is available. The fact that nitrogen can be obtained from the atmosphere is the main reason why phosphorus is considered to be the limiting nutrient in eutrophication.

Most of the phosphorus which is applied as fertiliser is not washed through the soil but is precipitated close to the surface and negligible amounts are leached from the soil (Leeper, 1964, pp. 192-193). However, phosphorus is washed into waterways when soil is eroded and this phosphorus can play an important role in eutrophication under anoxic conditions, which for chemical reasons promote its release from sediments as soluble compounds (Canfield *et al*, 1989, pp. 77-79). Significant amounts of phosphorus can enter waterways (bound to soil particles) in run off from agricultural land during wet periods and an important determinant of the phosphorus content of this runoff is land use (Verhoeven 1993).

While eutrophication is an international problem (Ryding and Rast 1989, Zajic 1971, pp. 309-329) our focus will be the algal bloom which affected about 1000 km of the Darling and Barwon Rivers from the townships of Wilcannia to Mungindi from October to December 1991. The extent of the bloom in November and December 1991 is shown in Figure 1.

A considerable amount of information on the Darling-Barwon bloom is published in the report: "Blue-Green Algae, Final Report of the New South Wales Blue-Green Algae Task Force" which was prepared by the NSW Department of Water Resources (DWR 1993a). The bloom occurred during a drought with a return period of 15 years and a significant proportion of the algae (up to 30%) were toxic blue-green algae of the genus Anabaena. Anabaena is a photosynthetic, nitrogen fixing bacterium which can produce lethal toxins. Water for human consumption has to be treated (using activated carbon) to remove toxins and odour when Anabaena is present in concentrations of 2,000 cells/ml (or at lower concentrations if odour is detected). Water contaminated with Anabaena is considered unsuitable for stock and recreational purposes when cell counts reach 15,000 cells/ml. Anabaena cell counts as high as 256,000 cells/ml were detected in December and as high as 24,000 cell/ml in November (Bowling *et al*, 1991, p. 2).

The waters of Australian rivers are considered eutrophic when total phosphorus is in the range 0.02mg/l to 0.05mg/l and hypereutrophic when total phosphorus exceeds 0.05mg/l. During the bloom, concentrations of total phosphorus exceeding 0.2mg/l were found in 50% of samples. Over the period October to December 1991, the Darling and Barwon rivers ceased to flow or had irregular low flows with most water held in town weir pools along the rivers. These stagnant water conditions coupled with the eutrophic status of the waters produced conditions favourable to the development of the bloom. The low turbidity and high nutrient status initially promoted the growth of non-toxic algae which increased the pH of the water by removing carbon dioxide and reduced the nitrogen concentration, producing the high pH and low nitrogen to phosphorus ratio which favour the growth of Anabaena.

Available evidence indicates that total phosphorus concentrations in the major streams draining into the Darling are hypereutrophic with median values ranging from 0.12mg/l to 0.27mg/l over the period 1975-1985 (DWR, 1993a, p. 63). Much of this phosphorus is thought to originate in the effluent of sewage treatment plants.

Thus, it seems that the normally eutrophic waters of the Darling and Barwon rivers were trapped in stagnant pools during the 1991 drought. During this drought, the phosphorus concentration of these rivers was boosted by effluent from point sources such as sewage treatment plants and concentrated by evaporation. These are the key factors that most likely produced the boom. Field studies reported by Bowling *et al* (1991) do not support the hypothesis that large amounts of phosphorus were released from sediments trapped behind the walls of the town weirs which occur along the Darling and Barwon rivers.

Solutions to the blue-green algae problem of the Darling and Barwon Rivers fall into two categories: (i) long term and (ii) short term. Long term solutions include: (a) reducing the phosphorus content of point sources. This can be done by upgrading wastewater treatment through tertiary treatment which involves precipitating phosphorus out of solution using lime or alum combined with filtration (Zajic, 1971, pp. 316-328) or passing the effluent from secondary treatment through specially designed wetlands. The artificial wetland which has been constructed at the Carcoar reservoir is a recent example of the wetland approach to removing nutrients from wastewater treatment plant effluent (White *et al* 1994). The Carcoar wetland removes nutrients (mainly phosphorus) from the effluent of a town sewage treatment plant and treated abattoir effluent. (b) Introducing a comprehensive regime of environmental flows to enhance water quality and meet conservation aims (Fitzgerald 1993). (c) Reducing the nutrient status of non-point source accessions to the river systems. This can be done through a comprehensive land management strategy which aims to reduce erosion and minimise the impact of animal industries on the river system.

These long term solutions will take some time to implement because of high information requirements and the high capital costs of upgrading sewage treatment plants. The long term picture is complicated by the growth in river nutrient levels. DWR (1993a) reports that over the past 18 years to 1993 total river phosphorus levels have risen by about 5% per year in NSW with higher growth levels recc ded in some of the tributaries of the Darling and Barwon Rivers. The growth in phosphorus loads will make planning more difficult. For example, White (1975) in discussing strategies for tackling the eutrophication problem of Lake Rotorua, to which the effluent from the Rotorua sewage treatment plant is a major contributor, rejected upgrading the sewage treatment plant as a solution, because even after upgrading the plant, growth in sewerage connections would raise the phosphorus load in Lake Rotorua to eutrophic levels by 1983. For this reason, it was decided to discharge the effluent from the Rotorua sewage treatment plant outside the catchment.

Short term solutions which can be applied once the conditions which predispose the Barwon and Darling Rivers to toxic algal blooms occur fall into two categories. The first is using releases from the major reservoirs in the headwaters of the Darling-Barwon Rivers to flush the rivers once toxic blooms begin to develop and before any major bloom related costs are incurred. This is likely to be effective because increased river flows due to heavy rains in December dispersed the 1991 algal blooms. The second short term strategy involves restricting the release of phosphorus from point sources once conditions conducive to toxic bloom formation become apparent. It is well known that concentration of algal cells is an increasing function of the concentration of total phosphorus (Dillon *et al* 1978, Oliver 1990), so that reducing the accessions to river phosphorus from point sources in critical periods can be expected to delay the onset of a toxic algal bloom, thus lessening the time over which the economic costs of any toxic algal bloom which may develop are incurred.

At present the sewage treatment plants in the Darling-Barwon Rivers catchment are not designed for the chemical removal of phosphorus, although some phosphorous can be removed using existing plant. The Public Works Department of NSW is currently costing different ways of upgrading the sewage treatment plants in NSW so that cost efficient removal of phosphorus can be achieved (Public Works Department, 1993). In section 4 we present an economic analysis of the strategy of phosphorus removal in the context of the blue-green algae problem and in this analysis, it is assumed that the treatment plants have been upraded. The analysis presented in section 4 is short run because we do not consider the problem of choosing the optimal plant size.

The remainder of the paper is organised as follows. In the following section, we present material on hydrology and property rights which is required in subsequent sections. Section 3 contains an economic analysis of the strategy of using reservoir water to flush the algal blooms. In section 4 the strategy of reducing the phosphorus load from point sources to reduce the economic impact of algal blooms is analysed. This section contains a discussion of the likely shape of the marginal cost of pollution curve attributed to the agal blooms. It is concluded that because the marginal cost of pollution curve is likely to have a jump at the level of phosphorus that reduces the recreational value of the Barwon and Darling rivers, the optimal phosphorus load is likely to be less than that which will cause recreational effects. The strategies of flushing flows and phosphorus removal from the discharge of point sources are not considered jointly because phosphorus removal acts by lowering the phosphorus concentration whereas flushing flows provide phosphorus dilution and also affect the growth of algae by increasing turbidity and lowering the retention time of water in pools. Motion in the water generally inhibits algal growth. The fifth and final section of the paper contains a summary of the conclusions of the study.

2 Background: Hydrology and Property Rights

The Barwon-Darling River passes through lands in the Western Division of NSW which have a harsh arid climate. Average annual rainfall varies from 495 mm (19.5 inches) at Mungingi to 245 mm (9.65 inches) at Menindee and the average potential evaporation ranges from 1750 mm (68.9 inches) at Mungindi to 2180mm (85.82 inches) at Louth (see Figure 1 for the town location.

Monthly and annual streamflow statistics for Bourke are shown in Table 1. These statistics show that streamflow at Bourke is highly positively skewed, median annual streamflow being 22GL, about 12.2 per cent of average annual streamflow (180GL). Streamflow at Bourke is highly regulated because reservoirs which supply mainly irrigation water have been built at the headwaters of all major Darling-Barwon tributaries. Water Resources Commission (1986) estimates that 25 per cent of the average annual streamflow of the Barwon and Darling Rivers is lost to irrigation, so that the skewness of the streamflow distribution under unregulated conditions would be higher than that shown in Table 1.

The catchments of the Barwon and Darling Rivers are subject to prolonged drought. The longest drought lasted from 1895 to 1902 and the Darling River at Bourke stopped flowing for over a year in 1902 and 1903. The drought ended in January 1903. Periods of no flow along the Barwon and Darling Rivers occur frequently, for example between June 1943 and February 1983 there were 11 periods when these rivers stopped flowing for at least 5 days, 4 of these no flow periods lasted at least 20 days at Bourke and 8 lasted at least 20 days at Mungindi. (Water Resources Commission 1986, pp.8, 12).

Figure 1 shows that there are 15 weirs on the Darling and Barwon Rivers upstream from Bourke; of these, 10 were built between 1949 and 1980 (Water Resources Commission 1986, p.4). Water Resources Commission (1986) notes that the weirs provide town and farm water supplies and also offer recreational amenities for boating, skiing, fishing and picknicking (pp. 10, 14) and also mentions that in periods of no flow, water quality is **higher** in weir pools in regard to hardness and poisonous blue green algae (p.16). Thus, it seems that severe outbreaks of blue-green algae in the stagnant water of weir pools along the Barwon and Darling Rivers in 1991 have no historical precedent. The fact that town water treatment plants along the Barwon and Darling Rivers and tributaries did not have the facilities to remove blue green algae (activated carbon and filtration tanks) during the 1991 outbreak also supports this conclusion.

The growth in the phosphorus concentration of about 5% per annum is one factor which contributed to the appearance in 1991 of toxic blue green algae blooms; another likely contributing factor is the increase in off-allocation water entitlements in the 80s which supported the concurrent increase in the area of irrigated cotton. For example, King (1994) notes that the area of irrigated cotton in the local government areas of Moree Plains, Walgett and Bourke grew from 29,902 to 70,073 hectares; 1,149 to 3,592 hectares and 2,590 to 4,633 hectares respectively over the period 1982-83 to 1986-87. Alvarez *et al* (1989) commented on the growth of off-allocation water licences as follows: "However this raises a wide range of issues from responsibilities to the environment and to users in downstream river systems". The extent to which the removal of off allocation water from the Darling and Barwon rivers has contributed to the formation of the 1991 algal bloom is not known, however any removal of off allocation water from this river system during a low-flow period is likely to contribute to conditions which promote the growth of algal blooms by reducing the dilution effect of the flows and lengthening the duration of the no-flow period.

There is also recent evidence of pilfering of riparian water. Since the Barwon and Darling Rivers and their tributaries are regulated by reservoirs in the headwaters of tributaries, the water supplies of towns along these rivers are maintained by the Department of Water Resources. For example, the water supply of Walgett (1991 census population: 8,208 persons) is maintained by reserves held in the Keepit Dam on the Namoi River. In September 1994, during the most recent drought (accompanied by a no flow period for the Barwon and Darling Rivers lasting from August 1994 to January 1995) Walgett was close to running out of town water supplies. The Department of Water Resources released sufficient water from the Keepit Dam to replenish the town water supply, however this water did not reach Walgett because it was stolen by upstream irrigators who have pumps in place to extract their legal water entitlements from the river.

Cheung (1970) and Randall (1975) define an unattenuated property right as one possessing the attributes if being completely specified, exclusive, enforceable and enforced and transferable. Since the entitlements to town water supplies of town along the Barwon and Darling Rivers are volumetric in nature and do not specify quality, these entitlements are attenuated on two grounds (i) they are not completely specified, and (ii) they are not enforceable and enforced since the water entitlement may not arrive when required. However, it should be noted that a subsequent release from the Keepit Dam did arrive at Walgett, so that the lack of enforceability of the original allocation could possibly reflect that enforcement procedures were not in place because theft was not anticipated.

Turning now to point source polluters, the NSW Environmental Protection Authority has licensed 18 point source polluters to discharge into streams in the Darling-Barwon catchment. Of these, 7 are sewage treatment plants, 1 is engaged in processing oilseeds, 4 store, distribute and process petroleum products and discharge "oily wastes", 1 is a piggery, 1 is a feedlot, 1 is a metallurgical firm, 1 discharges irrigation tailings and 2 discharge sludge from water treatment.

Some information on point sources in Queensland is contained in Murray Darling Basin Commission (1992). Apparently there are 12 sewage treatment plants in Queensland which are licensed to discharge into tributaries of the Darling and Barwon Rivers. There are no industrial discharges into these tributaries and as piggeries and cattle feedlots in Queensland are required to have appropriate waste processing facilities no discharge into streams from these sources is expected during dry periods.

No licensed point sources of effluent into the Darling and Barwon Rivers and their tributaries in New South Wales and Queensland have nutrient levels specified in their discharge licences. Thus, these entitlements are attenuated. The New South Wales Environment Protection Agency is planning to specify nutrient levels in discharge licences for sewage treatment plants in the Darling and Barwon River catchments once the plants are upgraded for phosphorous removal.

3 *Externalities and Flushing*

The blue-green algae problem of the Darling-Barwon Rivers in 1991 was caused by the eutrophic status of the water in these rivers and low flows. These factors resulted in the rivers becoming a sequence of stagnating pools at the weirs which are situated on major towns along the rivers. High temperatures and low turbidity combined with these factors to precipitate the blooms. Direct economic costs of $1,260,000 were incurred in providing potable water supplies to towns along the Darling and Barwon Rivers and the loss to providers of tourist and recreational facilities was estimated at $1,500,000 giving a total of $2,760,000 in estimated costs attributed to the algal bloom (DWR 1993a, pp.32-33).

The estimate of $1,500,000 as the monetary loss to providers of tourist and recreational facilities due to the 1991 blue green algae outbreak on the Darling and Barwon Rivers was obtained by Walker and Greer (1992). Their method of estimation was based on estimating the loss in gross revenues from beer sales during the blue green algae outbreak in two of the smallest towns along the river (Louth and Tilpa each with a permanent population of less than 50 persons). Each town has one hotel and losses of beer revenue were obtained by interviewing the publican. The losses for each hotel were averaged and the average loss ($61,600) was then assumed to apply to the 22 hotels in the other towns along the afflicted stretch of river. The estimate of $1,500,000 reported in DWR (1993a) is therefore the estimated aggregate loss in gross revenue from beer sales, calculated in the above manner for the affected stretch of river.

This estimate obviously has some deficiencies. The first being that it is an estimate of the gross value of lost beer sales, whereas the net value of loss lost beer sales is a better measure of the economic loss to the region from lost beer sales attributed to the algal bloom. The second deficiency is that it ignores the other expenditures made by tourists, such as spending on food, lodging, fuel and recreational equipment and fees. We are probably justified in assuming that $1,500,000 grossly underestimates the monetary losses to providers of tourist and recreational facilities along the Barwon and Darling Rivers during the blue green algae outbreak. Despite this, the estimated loss in gross revenue from beer sales is useful as an indicator of the gross monetary losses in the sales of one commodity during the 1991 blue green algae outbreak. Finally, it should be mentioned that monetary losses do not include the utility lost by the permanent inhabitants who use the Darling and Barwon Rivers for recreational purposes, so that any monetary costs which can be attributed to the blue green algae outbreak will underestimate the total cost of the outbreak.

Since the algal bloom can be attributed to the actions of economic agents, it may be regarded as an externality. We shall obtain an estimate of the cost of preventing the externality associated with the 1991 algal bloom by estimating the opportunity cost of providing water to flush the bloom.

The algal bloom occurred on the highly regulated part of the Darling and Barwon rivers in the irrigation regions of Macquarie Western and Barwon. In the 1991 irrigation season 717,500 ML was allocated to irrigation in the Barwon Region and all was taken up, whereas of the 635,000 ML allocated to irrigators in the Macquarie Western Region only 510,000 ML was taken up. The main cash crop in the Barwon Region is cotton, whereas in the Macquarie Western Region, cotton forms about 50% of the cash crops with horticultural crops, sunflower, sweet corn and livestock making up the remainder.

In the 1991 season, about 69, 296 ML of water was transferred on a temporary basis in the Barwon Region, while 23,555 ML was transferred in the Macquarie Western Region (DWR 1993b, p. 30). Prices for transferred water in the Barwon Region ranged between $100 to $200 per ML and were in the range $10 to $20 per ML in the Macquarie Western Region.

DWR (1993a, p. 113) estimated that a flow of 2,000 ML per day for 5 days is sufficient to suppress the development of an algal bloom. Using the upper bound of the range of prices for water transfers in the Barwon Region as an estimate of the opportunity cost of water in the 1991 season, we obtain $200 x 10,000 = $2,000,000 as an upper bound on the cost of flushing the algal bloom. If 50% of the flushing water was obtained form the Macquarie Western region and 50% from the Barwon region, the upper bound on the opportunity cost of a flush in the 1991 season would be: $(200 x 5,000 + 20 x 5,000) = $1,100,000. Both estimates are below the

$2,760,000 the 1991 bloom was conservatively estimated to cost for the provision of potable water and lost tourism. Thus, it would seem that the provision of 10,000 ML of water to flush the Barwon and Darling rivers in the event that conditions which favour the development of algal blooms develop, as recommended in DWR (1993a, p. 113), can be justified on economic grounds. This conclusion is based on the assumption that the water released for flushing reaches the afflicted sections of the river. Theft of significant amounts of water (as described in section 2) could change this conclusion.

The use of flushing as a solution to the blue-green algae problem of the Darling and Barwon rivers is dependant on the availability of water. While the probability that no irrigation water will be available in any one season is negligible for the Macquarie Western Region, it is not negligible for the Barwon Region. Alvarez *et al* (1989, p. 255) note that for the Barwon Region there is a 50% chance that no water would be available for irrigation and that 100% of water entitlements would be available in about 50% of seasons. Water from either the Barwon Region or the Barwon Region and the Macquarie-Western Region must be used for flushing because water from the Macquarie Western Region cannot be used to flush the Barwon River. Thus, in some years the option of flushing will not be available unless a carryover is maintained for this purpose. Carryover water would be very valuable in years when no irrigation water is available in the Barwon Region. For this reason we will examine the option of reducing the phosphorus from point sources during periods when conditions are favourable for the development of blue-green algal blooms.

4 *Externalities and Phosphorus Control*

Introduction

In this section of the paper we shall develop and analyse a simplified economic model of the blue green algae problem of Darling and Barwon Rivers. The model can be described as follows.

Phosphorus is released in the river system by firms and sewage treatment plants. Firms are assumed to have a wastewater treatment plant which removes phosphorus which is a by product of production. Each firm is assumed to have two inputs, one which generates waste containing phosphorus and another composite input which is a surrogate for all other variable inputs. The production function of each firm is assumed to have a negative definite hessian matrix and its treatment cost function is assumed to be a strictly convex increasing function (of removed phosphorus) with a positive second derivative. Thus the treatment cost functions are assumed to exhibit increasing marginal treatment costs. The assumption of increasing marginal treatment costs has been found to hold generally in empirical studies of pollution control at high levels of treatment (Kneese and Schultz, 1975, pp.18-22) and for phosphorus removal from sewage (Harper 1992, p.223). The sewage treatment plants are also assumed to have strictly increasing cost functions which exhibit increasing marginal treatment costs.

The model is solved for two contiguous time periods. In the first period, the river system is assumed to be flowing slowly and to be not flowing by the end of the period. The first period has a duration which is sufficient for the phosphorus load in the river system to be in an equilibrium (by the end of the period) which corresponds to a given level of production and effluent treatment which is maintained during the first period.

In the second period, the river system is assumed to be not flowing and the phosphorus load at the start of the second period is entirely determined by the phosphorus producing and treatment activities of the first period. When not flowing, the river system is assumed to comprise of a number of stationary bodies of water. In the second period, extra phosphorus is added to each of the stationary bodies of water solely by the phosphorus generating and treating activities which are located on each body of water.

The second period has a fixed duration which includes a time interval when the river system is used for recreational purposes by tourists. Each level of phosphorus at each location is assumed to have a corresponding blue green algal concentration which is an increasing function of the phosphorus load. At each location, it is assumed that when the phosphorus load exceeds a given threshold, town water supplies require treatment for blue green algae contamination and income is lost from tourism. Thus the cost of pollution function has two components: the cost of water treatment and income losses from lost tourism. We shall initially assume that the cost of pollution function is (after a threshold level of phosphorus is reached) an increasing, strictly convex function with a positive second derivative. Thus, it is assumed that increased marginal costs of pollution characterise the cost of pollution function. Because time preference is incidental to the theme of the paper, second period revenues and costs are not discounted to simplify the notation.

The assumptions listed above ensure that calculus can be used to analyse this simplified pollution problem. Two types of problems are tackled in this framework. The first involves finding an expression for the marginal abatement cost (of phosphorus abatement) function at a specified location for the second period. The second problem involves finding the production and treatment levels which characterise the optimal solution to the blue green algae pollution problem.

It can be argued that when a given location has a significant tourist industry, the assumption that the cost of pollution curve at this location is differentiable is unrealistic. The argument goes as follows. Assume that when a phosphorus level of a in Figure 2 is reached at location q, the blue green algae concentration is such that town water needs to be treated and that the curve aj in Figure 2 is the marginal cost of water treatment at phosphorus levels exceeding a.

Now assume that when the phosphorus load reaches b, the blue-green algae concentration is such that tourism is reduced until the point c is reached when all tourism is lost. The loss in tourist income is represented by the marginal cost curve ef in Figure 2, so that the aggregate marginal cost of pollution curve is represented by the discontinuous function $a\ d\ g\ h\ i\ j$. The implication of having a discontinuous marginal cost of pollution function is that the cost of pollution function is not differentiable and an economic solution to the simple problems outlined above cannot be obtained using calculus.

We shall explore the implications of a discontinuous marginal cost of pollution curve (with the shape given in Figure 2) for the solution to the pollution problem by using the marginal abatement cost curve for location q, derived using calculus and the marginal cost of pollution function shown in Figure 2, to obtain an idea of the likely equilibrium (optimal phosphorus load) at location q.

TABLE 1

Monthly and annual stream flows statistics for the Darling River at Bourke 1895-1972 (Gigalitres)

Month	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Average	135	174	308	190	86	105	218	313	191	111	144	190	180
Median	25	67	55	33	10	10	23	32	20	15	3	22	22

Source: Water Resources Commission (1986, p.7)

Notation and Constraints

In our problem, when the River system stops flowing it becomes $j = 1,\ldots,q$ disconnected bodies of water, which we shall call locations. At location j there are n_j firms which are point sources for phosphorus and the total number of polluting firms on the River system is n, where

$$n = \sum_{j=1}^{q} n_j.$$

Also, at each location j there are m_j sewage treatment plants which are point sources of phosphorus and the total number of polluting sewage treatment plants on the River system is m, where

$$m = \sum_{j=1}^{q} m_j$$

Each firm has a production function f_{ijt} which yields output for firm i at location j in period t, where $t = 1, 2$. The production function for firm i at location j has a time subscript because the two periods may be of different duration. Output for firm i at location j in period t may be written:

$$y_{ijt} = f_{ijt}\left(x_{ijt}, z_{ijt}\right)$$

where:

y_{ijt} is the output of firm i at location j in period t

x_{ijt} is the amount of a first input used by firm i at location j in period t, and

z_{ijt} is the amount of a second input used by firm i at location j in period t.

For firm i at location j the price of output is p_{ij} and the prices of each input are p_{xij} and p_{zij}. All prices are assumed to be invariant across time periods.

The phosphorus containing liquid waste generated by each firm depends on the amount of input x_{ijt} used. The amount of phosphorus generated is $\gamma_{ij} \cdot x_{ijt}$, where γ_{ij} is a parameter which is specific to firm i at location j.

Each firm is assumed to have a wastewater treatment facility which removes phosphorus. The cost function of the wastewater treatment facility is $C_{1ijt}\left(P_{1ijt}\right)$, where C_{1ijt} is cost of treatment function and P_{1ijt} is the amount of phosphorus removed from the wastewater of firm i at location j in period t.

We shall assume that the hessian matrix of the production function of each firm in each period is negative definite, and that $\partial C_{1ijt} / \partial P_{1ijt} > 0$, $\partial^2 C_{1ijt} / \partial P_{1ijt}^2 > 0$.

The constraints on production are as follows: $x_{ijt} \geq 0$, $z_{ijt} \geq 0$ (inputs are non-negative) and $\gamma_{ij} \cdot x_{ijt} - P_{1ijt} \geq 0$ (phosphorus removal by each firm in each period is constrained to be less than or equal to the phosphorus produced by each firm in each period).

Sewage treatment plants at location j in period t have the following cost function: $C_{2ijt}\left(P_{2ijt}\right)$, where P_{2ijt} is the amount of phosphorus removed by sewage treatment plant i at location j in period t. Phosphorus is removed from wastewater which contains I_{ijt} units of phosphorus. It is assumed that $\partial C_{2ijt} / \partial P_{2ijt} > 0$ and $\partial^2 C_{2ijt} / \partial P_{2ijt}^2 > 0$. Sewage treatment is subject to the following constraints: $P_{2ijt} \geq 0$ and $I_{ijt} - P_{2ijt} \geq 0$ the first constraint is a non-negativity constraint on phosphorus removal and the second constraint ensures that sewage treatment plant i at location j in period t cannot remove more phosphorus than is in its wastewater inflow in period t.

We now need to define a set of parameters that convert phosphorus which is released into the river system in period 1 by sources at each location to phosphorus at the start of period 2 at each location. Let α_{jk} denote the units of phosphorus in location $k, (k = 1,\ldots,q)$ in period 2 per unit of phosphorus released in location $j, (j = 1,\ldots,q)$ in period 1. Evidently, $\alpha_{jk} \geq 0$, with $\alpha_{jk} = 0$ if location j is downstream from location k.

We can now give an expression for P_j, the phosphorus load in period 2 at each location j $(j = 1,\ldots,q)$:

$$P_j = \sum_{k=1}^{q} \alpha_{kj} \left\{ \sum_{i=1}^{n_k} \left(\gamma_{ik} \cdot x_{ik1} - P_{1ik1}\right) + \sum_{i=1}^{m_k} \left(I_{ik1} - P_{2ik1}\right) \right\}$$
$$+ \sum_{i=1}^{n_j} \left(\gamma_{ij} \cdot x_{ij2} - P_{1ij2}\right) + \sum_{i=1}^{m_k} \left(I_{ij2} - P_{2ij2}\right), \quad j = 1,\ldots,q. \tag{1}$$

The first term in 1 represents the contribution to the second period phosphorus load at location j attributed to the first period activities of all firms and sewage treatment plants. The second and third terms represent the phosphorus load in the second period at location j attributed to the activities of firms at location j in the second period and sewage treatment plants at location j in the second period respectively.

We shall assume that when the phosphorus load at location j exceeds a threshold a_j, the town water drawn from location j requires treatment for blue green algae contamination, and that the recreational value of location j is adversely affected. Let $C_j(P_j)$, $P_j \geq a_j$ denote the cost pollution function at location j in period 2. We shall assume that $\partial C_j / \partial P_j > 0$ and $\partial^2 C_j / \partial P_j^2 > 0$ for $P_j > a_j$. The assumption that the cost of pollution function is differentiable is made for mathematical convenience and will be relaxed for location q later in this section.

Having defined the relevant functions, variables, parameters and constraints we now turn to the deviation of the marginal abatement cost function at a specified location.

The Marginal Abatement Cost Curve

In this section we shall derive an expression for the marginal cost of abatement of phosphorus (MAC) curve at a specified location in the second period. This curve gives the marginal cost of phosphorus reduction, assuming that this reduction is achieved in an economically efficient manner for a given set of phosphorus loads at the chosen location. For convenience we shall derive the curve for location q which we assume to be downstream from the remaining $(q-1)$ location. Choosing this location implies that in principle (from equation 1) that each location contributes phosphorus to the second period phosphorus load at location q.

We shall show that the marginal abatement cost curve can be obtained by maximising a variable net revenue function whose components include all production and treatment activities subject to a given level of phosphorus load at location q.

This optimisation problem may be written:

Choose:

$$x_{ijt}, z_{ijt} P_{1ijt}, \quad (j = 1,\ldots,q;\ i = 1,\ldots,n_j;\ t = 1,2)$$

and $\quad P_{2ijt}\ (j = 1,\ldots,q;\ i = 1,\ldots,m_j;\ t = 1,2)$

to maximise:

$$\phi = \sum_{j=1}^{q}\sum_{i=1}^{n_j}\left(p_{ij}\cdot y_{ij1} - w_{xij}\cdot x_{ij1} - w_{zij}\cdot z_{ij1} - C_{1ij1}\right) - \sum_{j=1}^{q}\sum_{i=1}^{m_j} C_{2ij1}$$
$$+\sum_{j=1}^{q}\sum_{i=1}^{n_j}\left(p_{ij}\cdot y_{ij2} - w_{xij}\cdot x_{ij2} - w_{zij}\cdot z_{ij2} - C_{1ij2}\right) - \sum_{j=1}^{q}\sum_{i=1}^{m_j} C_{2ij2} - \sum_{j=1}^{q-1} C_j \qquad (2)$$

subject to:

$$P_k = \sum_{j=1}^{q}\alpha_{jk}\left\{\gamma_{ij}\cdot x_{ij1} - P_{1ij1}\right\} + \sum_{i=1}^{m_j}\left(I_{ij1} - P_{2ij1}\right)$$
$$+\sum_{j=1}^{n_k}\left(\gamma_{ik}\cdot x_{ik2} - P_{1ik2}\right) + \sum_{i=1}^{m_k}\left(I_{ik2} - P_{2ik2}\right),\ k = 1,\ldots,q \qquad (3)$$

$$\gamma_{ij}\cdot x_{ijt} - P_{1ijt} \geq 0, \qquad \left(j = 1,\ldots,q;\ i = 1,..,n_j;\ t = 1,2\right) \qquad (4)$$

$$I_{ijt} - P_{2ijt} \geq 0, \qquad \left(j = 1,\ldots,q;\ i = 1,..,m_j;\ t = 1,2\right) \qquad (5)$$

$$x_{ijt} \geq 0,\ z_{ijt} \geq 0,\ P_{1ijt} \geq 0, \qquad \left(j = 1,\ldots,q;\ i = 1,..,n_j;\ t = 1,2\right) \qquad (6)$$

$$P_{2ijt} \geq 0, \qquad \left(j = 1,\ldots,q;\ i = 1,..,m_j;\ t = 1,2\right) \qquad (7)$$

We shall assume that this problem has an interior maximum, so that constraints (6) and (7) are not binding at the maximum. Furthermore, we shall assume that marginal costs of phosphorus removal rise rapidly so that (4) and (5) also do not bind at the optimum. A consequence of the assumption that the problem has an interior maximum is that all phosphorus treatment plants remove some phosphorus and for this to occur, $P_j > a_j,\ j = 1,\dots,q-1$ because phosphorus would not be removed unless its presence incurred a cost and in this problem the cost is the cost associated with townwater treatment and lost tourism.

It may be verified that the hessian matrix of ϕ, for all values of the choice variables in the interior of the feasible region and for which $P_j > a_j,\ j = 1,\dots,q-1$, is negative definite so that the maximum of the constrained optimisation problem is unique.

Now substituting the expression for $P_j, j = 1,\dots,q-1$ given in (3) into the corresponding C_j terms of (2), the first order conditions which the unique solution to the constrained optimisation problem must satisfy may be obtained by differentiating the following Lagrangean expression:

$$L = \phi + \lambda\left[P_q - \eta\right] \tag{8}$$

where η is the right hand size of the expression for P_q given in (3), and λ is a Lagrangean multiplier. Differentiating L with respect to each of the choice variables (including λ) and setting each derivative equal to zero yields the first order conditions:

$$p_{ij} \cdot \partial y_{ij1} / \partial x_{ij1} - w_{xij1} = \gamma_{ij}\left(\alpha_{jq} \cdot \lambda + \sum_{k=1}^{q-1} \alpha_{jk} \cdot \partial C_k / \partial P_k\right) \tag{9}$$

$$\partial C_{1ij1} / \partial P_{1ij1} = \gamma_{ij}\left(\alpha_{jq} \cdot \lambda + \sum_{k=1}^{q-1} \alpha_{jk} \cdot \partial C_k / \partial P_k\right) \tag{10}$$

$$p_{ij} \cdot \partial y_{ijt} / \partial z_{ijt} - w_{zij} = 0 \tag{11}$$

$$\left(j = 1,\dots,q;\ i = 1,\dots,n_j;\ t = 1,2\right)$$

$$\partial C_{2ij1} / \partial P_{2ij1} = \alpha_{jq} \cdot \lambda + \sum_{k=1}^{q-1} \alpha_{jk} \cdot \partial C_k / \partial P_k \tag{12}$$

$$\left(j = 1,\dots,q;\ i = 1,\dots,m_j\right)$$

$$p_{ij} \cdot \partial y_{ij2} / \partial x_{ij2} - w_{xij} = \gamma_{ij} \cdot \lambda \tag{13}$$

$$\partial C_{1ij2} / \partial P_{1ij2} = \lambda \tag{14}$$
$$\left(j = q;\ i = 1,\ldots,n_q\right)$$

$$p_{ij} \cdot \partial y_{ij2} / \partial x_{ij2} - w_{xij} = \gamma_{ij} \cdot \partial C_j / \partial P_j \tag{15}$$

$$\partial C_{1ij2} / \partial P_{1ij2} = \partial C_j / \partial P_j \tag{16}$$
$$\left(j = 1,\ldots,q-1;\ i = 1,\ldots,n_j\right)$$

$$\partial C_{2ij2} / \partial P_{2ij2} = \lambda \tag{17}$$
$$\left(j = q;\ i = 1,\ldots,m_q\right)$$

$$\partial C_{2ij2} / \partial P_{2ij2} = \partial C_j / \partial P_j \tag{18}$$
$$\left(j = 1,\ldots,q-1;\ i = 1,\ldots,m_j\right)$$

$$P_q = \sum_{j=1}^{q} \alpha_{jq} \left\{ \sum_{i=1}^{n_j} \left(\gamma_{ij} \cdot x_{ij1} - P_{1ij1}\right) + \sum_{i=1}^{m_j} \left(I_{ij1} - P_{2ij1}\right) \right\}$$

$$+ \sum_{i=1}^{n_q} \left(\gamma_{iq} \cdot x_{iq2} - P_{1ij2}\right) + \sum_{i=1}^{m_q} \left(I_{iq2} - P_{2ij2}\right) \tag{19}$$

Assuming the conditions of the implicit function theorem hold, the first order conditions (9) to (19) may be solved for the optimal values of the choice variables:

$\left(x_{ijt}^*, z_{ijt}^*, P_{1ijt}^*, j = 1,\ldots,q; i = 1,\ldots,n_j; t = 1,2\right)$, $\left(P_{2ijt}^*, j = 1,\ldots,q; i = 1,\ldots,m_j; t = 1,2\right)$ and λ^* as differentiable functions of the parameters of the problem. The parameter of interest is P_q and we shall show that $\lambda^*\left(P_q\right)$ can be interpreted as the marginal abatement cost of pollution at location q.

Let ϕ^* be ϕ as defined by (2) evaluated at the optimal values of the choice variables, then ϕ^* is a differentiable function of P_q (as well as the other parameters of the problem). It is well known (from the envelope theorem) that:

$$\partial \phi^* / \partial P_q = \lambda^*\left(P_q\right) \tag{20}$$

where $\lambda^*(P_q) > 0$ from (14) or (17) because marginal costs of phosphorus removal are positive. Thus $\lambda^*(P_q)$ represents the marginal change in ϕ^* as P_q is increased at the margin and hence represents the marginal abatement cost function at location q.

Differentiating (17):

$$\partial^2 C_{1iq2} / \partial P_{1iq2}^2 = \partial\lambda^* / \partial P_q \cdot \partial P_q / \partial P_{1iq2} = -\partial\lambda^* / \partial P_q,$$

hence:

$$\partial\lambda^* / \partial P_q = -\partial^2 C_{1iq2} / \partial P_{1iq2}^2 < 0 \qquad (21)$$

We shall assume that $\lambda^*(P_q)$ is a strictly convex function of P_q; this will give it the shape usually assumed for marginal abatement cost functions. The third derivatives of the production functions and treatment cost functions could be specified to guarantee the strict convexity of $\lambda^*(P_q)$, but the required conditions are non-intuitive.

We shall now examine the first order conditions for the optimal solution to our simplified problem. This analysis will enable us to characterise the optimal solution at location q in terms of $\lambda^*(P_q)$ and $\partial C_q(P_q) / \partial P_q$ (the marginal cost of pollution at location q).

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The Optimal Solution

The optimal solution to our extrenality problem may be found by solving the following variable net revenue maximisation problem.

Choose:

$$\left(x_{ijt}, z_{ijt}, P_{1ijt}, j = 1,\ldots,q;\ i = 1,\ldots,n_j;\ t = 1,2\right) \text{ and } \left(P_{2ijt}, j = 1,\ldots,q;\ i = 1,\ldots,m_j;\ t = 1,2\right)$$

to maximize:

$$\pi = \sum_{j=1}^{q}\sum_{i=1}^{n_j}\left(p_{ij}\cdot y_{ij1} - w_{xij}\cdot x_{ij1} - w_{zij}\cdot z_{ij1} - C_{1ij1}\right) - \sum_{j=1}^{q}\sum_{i=1}^{m_j} C_{2ij1}$$

$$+\sum_{j=1}^{q}\sum_{i=1}^{n_j}\left(p_{ij}\cdot y_{ij2} - w_{xij}\cdot x_{ij2} - w_{zij}\cdot z_{ij2} - C_{1ij2}\right) - \sum_{j=1}^{q}\sum_{i=1}^{m_j} C_{2ij2}$$

$$-\sum_{j=1}^{q} C_j\left(P_j\right) \qquad (22)$$

subject to: (3), (4), (5), (6) and (7).

We shall assume this problem has an interior solution, so that constraints (6) and (7) do not bind. We shall also assume that not all phosphorus generated at each site is removed by the treatment plant at that site so that constraints (4) and (5) do not bind at the optimum. Arguing as before, phosphorus is only removed if its release generates costs, so that at the optimum we must have $P_j > a_j$ for $j = 1,\ldots,q$. Thus, the first order conditions obtained from maximising (22) with the expressions for P_j given in (3) substituted into the $C_j(P_j)$ terms of (22), will yield a set of equations which the optimal solution must satisfy. It may be verified that over the domain defined by positive value^r of the choice variables and $P_j > a_j$ for $j = 1,\ldots,q$, the hessian matrix of π is negative definite so that the optimal solution is unique.

The first order conditions for maximising (22) may be written:

$$p_{ij}\cdot\partial y_{ij1}/\partial x_{ij1} - w_{xij} = \gamma_{ij}\left(\sum_{k=1}^{q}\alpha_{jk}\cdot\partial C_k.\partial P_k\right) \qquad (23)$$

$$\partial C_{1ij1}/\partial R_{ij1} = \sum_{k=1}^{q}\alpha_{jk}\cdot\partial C_k/\partial P_k \qquad (24)$$

$$p_{ij}\cdot\partial y_{ijt}/\partial z_{ijt} - w_{zij} = 0 \qquad (25)$$

$$\left(j = 1,\ldots,q;\ i = 1,\ldots,n_j;\ t = 1,2\right)$$

$$\partial C_{2ij1} / \partial P_{2ij1} = \sum_{k=1}^{q} \alpha_{jk} \cdot \partial C_k / \partial P_k \tag{26}$$

$\left(j = 1,\ldots,q;\ i = 1,\ldots,m_j\right)$

$$p_{ij} \cdot \partial y_{ij2} / \partial x_{ij2} - w_{xij} = \gamma_{ij} \cdot \partial C_j / \partial P_j \tag{27}$$

$$\partial C_{1ij2} / \partial P_{1ij2} = \partial C_j / \partial P_j \tag{28}$$

$\left(j = 1,\ldots,q;\ i = 1,\ldots,n_j\right)$

$$\partial C_{2ij2} / \partial P_{2ij2} = \partial C_j / \partial P_j \tag{29}$$

$\left(j = 1,\ldots,q;\ i = 1,\ldots,m_j\right)$

Let $\left(\bar{x}_{ijt}, \bar{z}_{ijt}, \bar{P}_{1ijt}, j = 1,\ldots,q;\ i = 1,\ldots,n_j;\ t = 1,2\right)$ and $\left(\bar{P}_{2ijt}, j = 1,\ldots,q;\ i = 1,\ldots,m_j;\ t = 1,2\right)$ satisfy the first order conditions (23) through to (29) inclusive, then these values of the choice variables maximise (22). By substituting the optimal values the choice variables into the expressions for $P_j, j = 1,\ldots,q$ given in (3), we obtain $\bar{P}_j, j = 1,\ldots,q$, which are the optimal phosphorus loads at each location in the second period.

Examining the first order conditions for the constrained optimisation problem (used to obtain the marginal abatement cost curve) given by equations (9) through to (19) inclusive; it is evident that if the constrained problem was solved subject to the constraint that $P_q = \bar{P}_q$, the solution to the constrained optimisation problem may be obtained from the solution to the unconstrained problem given above. This follows because the optimal solution to the unconstrained problem plus the following condition:

$$\lambda^*\left(\bar{P}_q\right) = \partial C_q\left(\bar{P}_q\right) / \partial P_q \tag{30}$$

will satisfy the first order conditions for the constrained problem.

Thus, the optimal level of phosphorus at location q may be found at the intersection of the marginal abatement cost curve $\lambda^*(P_q)$ and the marginal cost of pollution curve $\partial C_q(P_q)/\partial P_q$. This optimal solution is shown in Figure 3.

Now, if we relax the assumption that the marginal cost of pollution curve at location q is continuous and assume that it has the shape given in Figure 2, then we obtain the result that there is a range of marginal abatement cost curves that will yield an equilibrium phosphorus load at location q (in the second period) which does not exceed the level that will cause losses due the loss of the recreational amenities provided by river at location q. This result is shown in Figure 4.

Our analysis has some implications for the setting of the phosphorus load standards of the effluent from point sources during low flow periods. As a rough guide to setting standards, the marginal cost of removing the unit of phosphorus which precipitates losses due to the deterioration of the recreational value of locations along the River should be compared to the marginal cost of lost recreation plus the marginal cost of treating town water attributed to that unit of phosphorus. If the marginal abatement cost is less than the marginal pollution cost, the standards should be set at a level lower than that which will precipitate recreational losses.

5 Summary and Conclusions

Two short term strategies were considered for controlling the blue green algae problem of the Barwon and Darling Rivers. The first is using releases from the major reservoirs in the headwaters of the Barwon and Darling Rivers to flush the Rivers once toxic blooms develop.

The second strategy involves restricting the release of phosphorus from point sources once conditions conducive to toxic bloom formation become apparent.

Based on data available from the 1991 bloom, it appears that flushing the River system once toxic blooms begin to form is an economic strategy. However this conclusion needs to be qualified. Firstly, flushing is only viable if water is available and the hydrological evidence suggests that there will be low flow periods when the required water is not available. The second qualification is that the amount of water required to flush the river system may be underestimated (and hence the costs of the required water may be underestimated) because of theft of water by irrigators. This is a recent development but if enforcement of entitlements needs to be upgraded to protect environmental flows, then the resulting increase in costs needs to be taken into account in any benefit cost analysis. Enforcement costs were not taken into account in the analysis of section 3.

In analysing the strategy of controlling algal blooms by restricting phosphorus from point sources during low flow periods, we argued that the marginal cost of pollution curve has a discontinuity at the phosphorus load which causes loss of income from tourism and recreation at locations on the river system where tourism is important. The discontinuity of the marginal cost of pollution curve is important because it allows a range of marginal abatement cost curves to yield an equilibrium phosphorus load equal to that which precipitates income losses from degraded recreational amenities. It was therefore concluded that in setting phosphorus load standards for point sources in load flow periods, the marginal cost of removing the unit of phosphorus which precipitates recreational losses should be compared to the marginal cost of lost recreation plus the marginal cost of townwater treatment and if the marginal abatement cost is found to be less than the marginal cost of pollution, standards for phosphorus loads in the effluent of point sources should be set at a level lower than that which will precipitate economic losses from degraded recreational amenities. At locations where tourism is a major industry, the equilibrium level of phosphorus is likely to be below that which would precipitate losses from reduced tourism.

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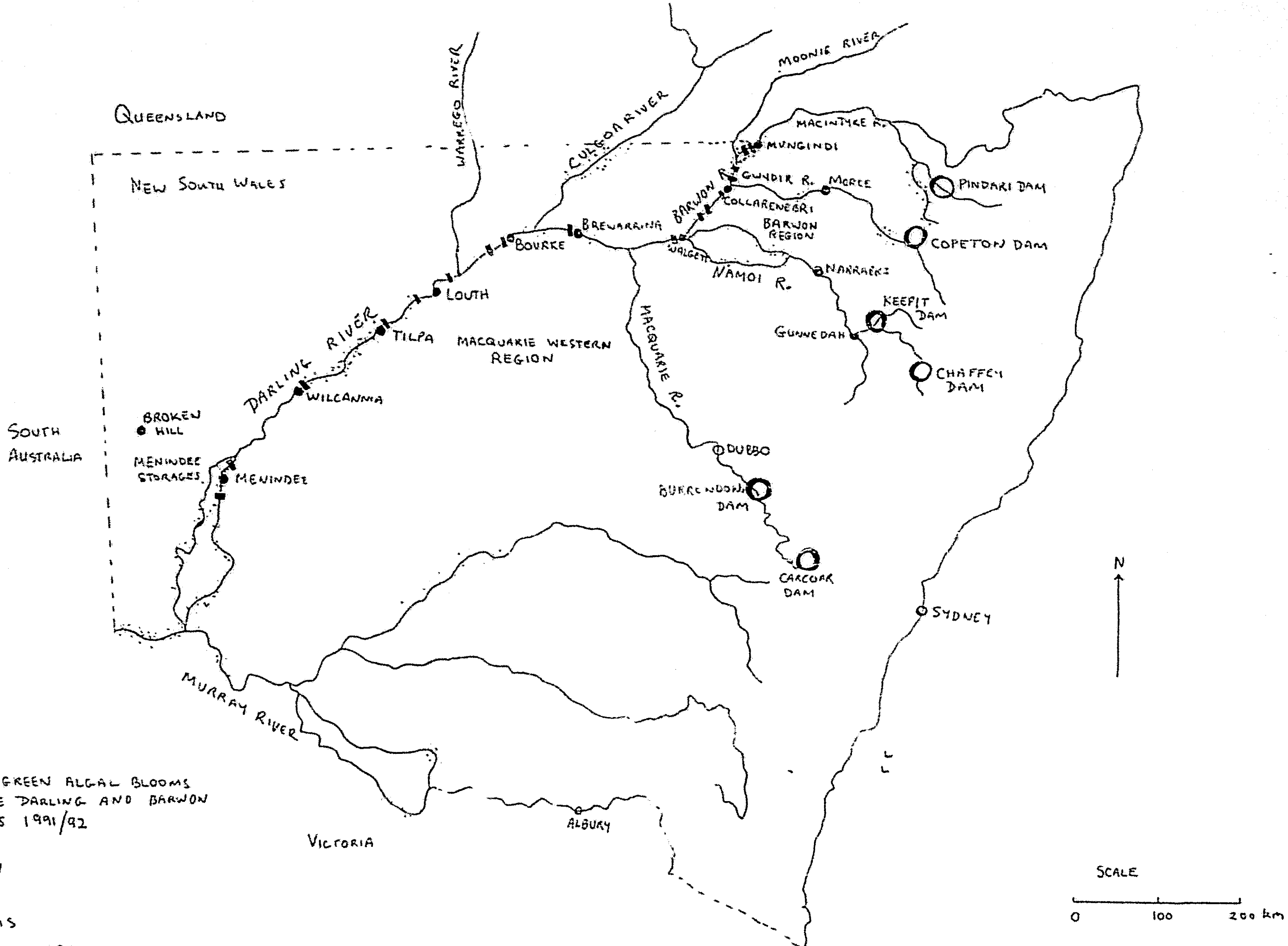

FIGURE 1: BLUE-GREEN ALGAL BLOOMS IN THE DARLING AND BARWON RIVERS 1991/92

- MAJOR TOWN
- WEIR POOL
- ALGAL BLOOMS
- MAJOR WATER STORAGE

Source : Water Resources Commission (1991), Department of Water Resources (1993a)

Figure 2: A discontinuous marginal cost of pollution curve

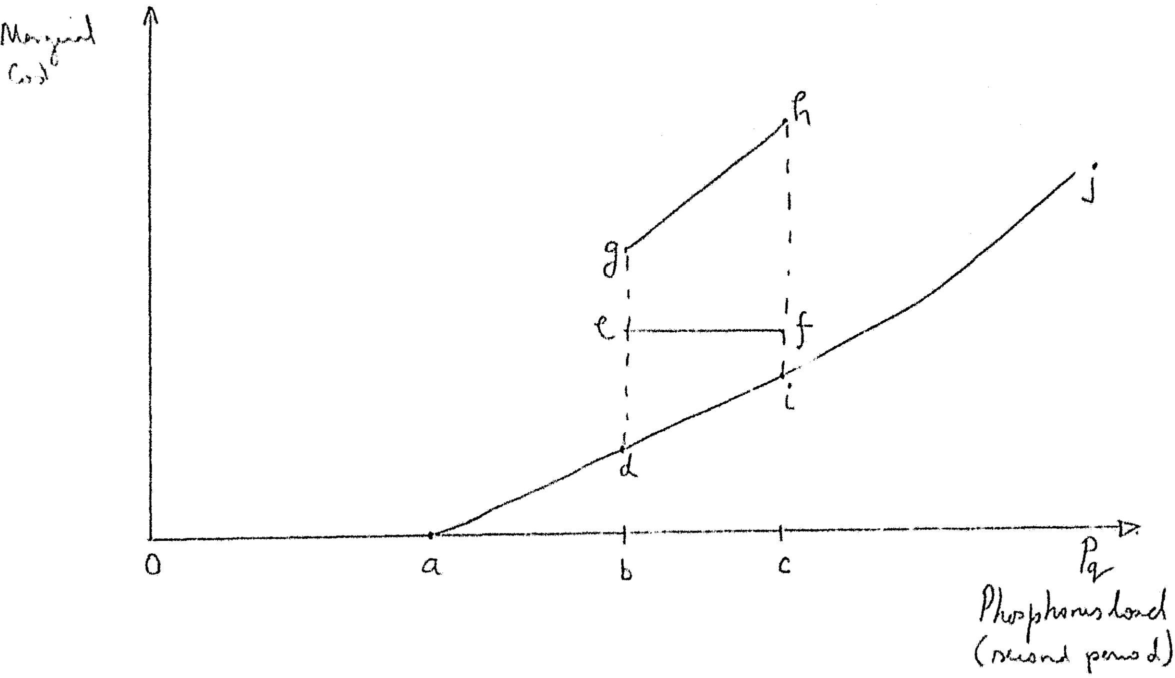

Figure 3

The optimal solution at location q when the marginal cost of pollution curve at location q is continuous

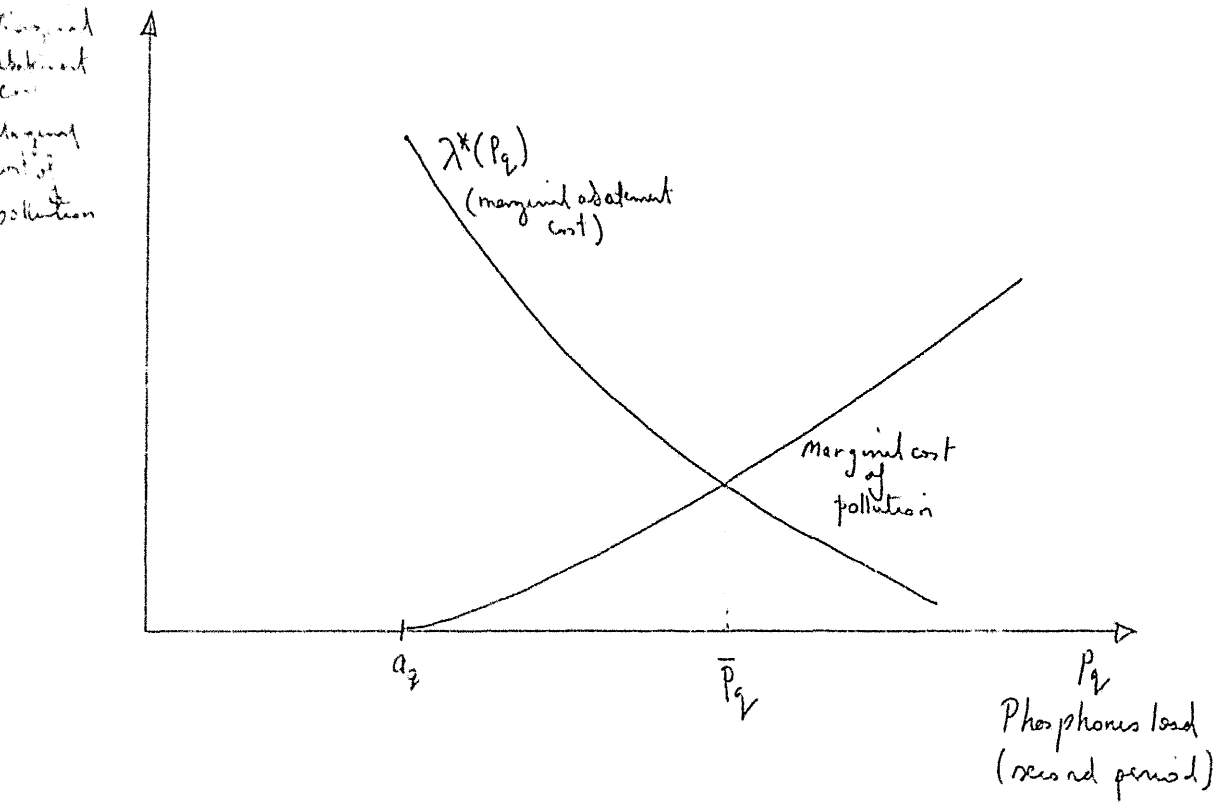

Figure 4

<u>A hypothetical optimal solution at location q when the marginal cost of pollution curve is discontinuous</u>