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The Economics of Algal Bloom Control

by

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ABSTRACT

Concern over the appearance of algal blooms in Summer months on Australian waterways has been increasing in recent years. Some algae are toxic to humans and livestock when ingested. To avoid the dangers of contaminated drinking water, costs must be incurred, either by eliminating nutrient loadings, or taking action to disperse blooms. Such costs may also be worth incurring to prevent the loss of recreation use of waterways and consequent loss of tourism revenue.

The aim is to consider the formulation of models to aid in the control of outbreaks of algal blooms, so as to maximise the net present value of social net returns. The complexity of determining the triggering of blooms is discussed. Results from regressing algal cell counts on possible explanatory variables such as water flow, water temperature, and nutrient loadings for three sites on the River Murray are presented.

Dynamic programming models are formulated with phosphorus in sediments, algal cell count, and water in storage as alternative state variables. The role of rainfall as an important stochastic variable is considered, because flood events lead to substantial nutrient runoff, and dry periods are associated with low river flow and conditions favourable for the outbreak of blooms.

Keywords: Algal Bloom, Dynamic Programming, Risk

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1.0 Introduction

Algae are a normal component of life in waterbodies the world over. They play an important part in the ecological balance of water systems, and usually are beneficial rather than a menace to people However, in some circumstances a population of algae can explode exponentially for a time, breaking down the normal ecological balance. If the algae are toxic, they can be a considerable nuisance to people, and finding means of preventing population explosions, often manifested as blooms, becomes a high priority

The need to study the causes of algal blooms adversely affecting inland waterways has been recognised in many countries, and led to large scale international investigations, mainly restricted to the northern hemisphere and to reservoirs and lakes (e.g. OECD, 1982 and Ryding and Rast, 1989).

There are many species of algae in Australian inland waterways and storages. The type that has led to particular concern in recent years is blue-green algae, or cyanobacteria, which can be toxic to humans and livestock. A major outbreak of blooms and scum of blue-green algae on various parts of a 1000 km stretch of the Darling River in the summer of 1991 focussed national attention on the problem. The outbreak was attributed to warm calm weather conditions, low turbidity permitting light penetration, high concentrations of phosphorus, and low flows resulting from a prevailing drought. Although the bloom did not result in any known human deaths, about 1600 sheep and 40 cattle died (New South Wales Department of Water Resources, 1992). Alternative sources of drinking water had to be found, and recreation on the water was adversely affected.

Dangerous levels of toxic algae occur from time to time throughout the river and water storage systems of south-east Australia. Their occurrence is very difficult to predict, which makes policy prescriptions likewise very difficult. Governments have responded at various levels in setting up bodies to recommend or implement programs and strategies, such as the National Eutrophication Management Program, the National Water Quality Management Strategy (Agriculture and Resource Management Council of Australia and New Zealand), the Murray-Darling Basin Commission's Algal Management Strategy, and the Nutrient Management Strategy for Victorian Inland Waters. Bodies involved in research include the CSIRO, the Murray-Darling Basin Commission, the Land and Water Resources Research and Development Corporation, State Water Departments and various Cooperative Research Centres.

It is clear that agricultural practices and human settlement have markedly changed the ecology and quality of the water systems. The phosphorus and nitrogen loads have been increased by point source pollution from sewage treatment works, intensive livestock and fish farms, and non-point source from pastures and urban land. These loads are a source of nutrients for algae. Also, the collection and regulated release of water from reservoirs and weirs have altered the flow of water throughout the year. In many parts of the system, flows are much less in winter months, and faster in summer months when water for irrigation is transmitted. There are many suggestions as to how these changes may have affected the incidence of algal blooms, but many are still matters of conjecture

If we are interested in how to best tackle the algal bloom problem from an economics perspective, we need to know the damage costs of blooms, the causes of blooms, measures for countering the causes, and the costs of the measures. All these measures and costs are difficult to identify and quantify. Two basic approaches for attempting to reduce the probability of outbreaks are: the reduction of nutrient loads into water systems, or catchment management; and increasing water flows at critical times, or flow regulation. The first approach has probably had the most attention, tending to feature in the various national and state programs, and leading to prescriptions for taxes and quotas on nitrogen and phosphorus in fertilisers and detergents. The second perhaps offers prospects of more immediate control. Both approaches are very costly. The aim of this paper is to consider these two approaches, and the prospects for formulating economic strategies. Policy issues are considered in more detail in Section 2. The results of analysing biological, physical and chemical data for three sites on or near the Murray to attempt to gauge the importance of each approach are reported in Section 3. The scope for dynamic optimisation models is considered on Section 4.

2.0 Technical and policy issues

The special characteristics of blue-green algae and their effects which are relevant for policy are introduced in Section 2.1. References to different policy approaches and estimates of damage costs and avoidance costs are presented in the following two sections.

2.1 Special characteristics of blue-green algae

Useful introductions to the biology and health effects of blue-green algae may be found in the works of the Victorian Blue-Green Algae Team (undated), Ressom et al. (1994), and the DPIE (1995), which provides the current understanding of the algae in much more detail than the title would suggest.

Conditions favouring the growth of the algae are: i) abundant phosphorus and nitrogen, obtained from external (to the affected water body) sources such as urban, industrial and agricultural activities, and from internal sources such as the release from sediments (when there is little oxygen in the bottom layers, during thermal stratification of storages) and algal decomposition; ii) long periods of sunlight and warm temperatures which provide the energy for photosynthesis; iii) reduced water flow, due to lack of rain, or diversion of water for irrigation; iv) high pH (pH 8-10) and low carbon dioxide concentration; v) moderate turbidity levels; and vi) abundant zooplankton which preferentially graze other algae.

Blue-green algae have the following unique abilities enabling them to exploit environmental conditions and dominate other algae: i) to form internal pockets of gas for buoyancy regulation, enabling them to seek light at the surface, or nutrients at lower depths; ii) to fix atmospheric nitrogen, and so able to out compete other algae when nitrogen is limiting; and iii) to ingest large amounts of phosphorus (luxury consumption), and store it for when supplies are short.

Some species of blue-green algae produce toxins, creating problems if affected water is ingested by humans or livestock, if people are in contact with water through boating or swimming, and if tourists are deterred from spending time around an infected waterway. Toxins include: i) hepatoxins which can cause liver damage and gastrointestinal problems; ii) neurotoxins which can cause paralysis and respiratory arrest in animals, and iii) endotoxins which can cause various allergic reactions on contact

2.2 Alternative explanations for the outbreak of blooms

In common with all living organisms, algae must ingest nutrients to survive, grow and reproduce. Important sources of nutrients are various forms of nitrogen and phosphorus. One way of reducing excessive populations of blue-green algae would therefore appear to be to reduce the nitrogen and phosphorus loads in affected waterway and storages by imposing various regulatory controls or pricing incentives on the management of point and non-point sources.

A study carried out by UNESCO (Ryding and Rast, 1989) found that average annual concentrations of phosphorus in North American and European lakes and reservoirs played a greater role in determining algal biomass (as determined by chlorophyll α) than nitrogen. Results from double log regressions of algal biomass on phosphorus enable target levels of phosphorus load to be estimated to achieve ceiling levels of algal biomass. The question arises as to whether this approach can be applied successfully to the catchments of the Murray-Darling system. This is considered in some detail by Harris (1994). Reducing the phosphorus load is likely to be beneficial, but there are many caveats. Compared with North America and Europe, in Australia soil is generally poor in phosphorus, and the seasonal distribution of rainfall is highly variable resulting in floods and droughts which significantly affect both flows and nutrient transport, and hence the conditions conducive for algal blooms. River systems are more open than lakes and reservoirs, so that assumptions which may hold reasonably well for lakes and reservoirs may not hold for rivers.

Discussion of the impact of nutrients on algae populations usually includes the concept of limiting nutrients, and whether control can be effected by reducing the availability of the limiting nutrient (e.g. OECD, 1982; Harris, 1986; and Ryding and Rast, 1989). Based on the composition of algae, the mass ratio of nitrogen to phosphorus (N:P) in algae is estimated to be 7.2:1. Thus if the ratio in a waterbody is greater than 7.2, phosphorus is indicated as limiting, and *vice versa*. However, because blue-green algae can often fix nitrogen, nitrogen is not necessarily a limiting nutrient. Low N:P may beneficially affect blue-green algae as against other algae which cannot grow for lack of nitrogen. This has led some to advocate reducing blue-green algae by increasing nitrogen availability in a waterbody to raise N:P. Others have counselled that the minimum concentration of phosphorus should be determined first, and then nitrogen concentration adjusted.

The availability of phosphorus to algae could be controlled by regulating phosphorus inflows into waterways if these external sources were the main sources. However, there are storages of phosphorus which can be tapped by algae, the internal sources. Phosphorus attaches to the particles which form bottom sediments, and accumulates over time. It is released under anoxic conditions when stratification of the waterbody occurs during calm warm weather. Further, blue-green algae may be able to draw on reserves of phosphorus stored in their cells when phosphorus would otherwise be limiting. This leads to many questions about policy on reducing phosphorus inflows. For example, if sewage works release phosphorus waste during periods of high flow, does this reduce the probability of blooms, or is it trapped in storages down river? Are stocks of phosphorus in sediments so high that even marked reductions of inflow would have little effect in reducing blooms over many years?

Another approach besides attempting to reduce nutrient availability is to increase water flow at times when temperatures are high and flows are low. The feasibility of such an approach has been reported recently by Webster et al. (1996) in an intensive study at the Maude Weir pool on the Murrumbidgee River in central New South Wales. It was hypothesised that without vertical mixing of water during stratification in summer, blue-green algae dominate other species of algae by increasing their buoyancy, floating to higher water levels which receive more of the light necessary for population growth. Mixing would destroy this comparative advantage for blue-green algae. Some important findings were: over four years of monitoring, 14-day averaged discharge (i.e. flow, measured in ML per day) explained about 60 per cent of *Anabaena* (a species of blue green algae) abundance; abundances of > 5000 cells per ML occurred only when discharges had been < 500 ML per day for 14 days; total reactive phosphorus was observed to decrease over a key period of *anabaena* bloom, presumably because it was ingested by the algae; the specific growth rate for *anabaena* was estimated to be 0.37 per day, implying a doubling time of about two days, and an increase in cell concentration from 4 cells per ML to 10000 cells per ML in three weeks (level 2 alert). It was concluded that maintaining discharge through Maude Weir at 1000 ML per day would almost certainly eliminate the problem of *anabaena* blooms in the weir in summer. Recognising that a continuous increase in flow would be expensive, a pulsed discharge of 1500 ML per day for one day at three-day intervals is suggested.

Questions which arise with this approach are: is the problem of blooms just flushed further down river?; how feasible is the pulsing option, in terms of the cost of required water when water is typically scarce?; could other indigenous water life be adversely affected by exacerbating the change in flow regime compared with flows before regulation?

Evidence for the impact on blue-green algae cell concentration of variables such as flow, temperature, nutrient levels and nutrient ratios for three sites near Swan Hill on the Murray are considered in Section 3. Another factor in the relative promise of either approach is the cost of the regulation of nutrient inflows and instream flows.

2.3 Cost estimates

It is reported in the DPIE (1995) study that the ARMCANZ (1993) estimated the costs of treating and preventing algal blooms in Australia in 1992-93 to be about $10 million, excluding costs to agriculture, the environment, and for health and tourism, which are "more difficult to estimate". Some references which do value these items are listed below.

Read Sturgess and Associates (1996) have produced a useful report on rapid appraisal methods of valuing various types of loss associated with algal blooms or their avoidance, such as: reduced recreation and tourism; use of algicides; water restrictions; carting in water; on-farm water for drinking and irrigation; and environmental and amenity impacts.

Herath (1996) documents the costs of alternative means of removing phosphorus from Australian waterways. Alaouze (1995) considers the policy implications of the nature of marginal cost of lost recreation, the marginal cost of townwater treatment, and the marginal cost of phosphorus pollution. Herath and Jackson (1994) estimate the loss of a day's recreation at Lake Mokoan after the outbreak of blooms, using a travel cost approach. Hill (1994) estimates the willingness to pay by the public for improved water quality in the Darling River, taking a contingent valuation approach.

There is thus a reasonably rich fund of studies for estimating the costs and benefits of algal bloom control measures, and for use in dynamic optimisation models.

3.0 An empirical study

A data bank of relevant biological, physical and chemical variables was compiled for three sites on or near the Murray. The sites were Torrumbarry weir, Swan Hill down river from the weir, and Capel's crossing, on a tributary of the Murray between the weir and Swan Hill. Sites on or near the Murray were chosen because algal cell count data are available for these sites but not for sites in other Victorian catchments feeding into the Murray. Observed variables are listed in Table 1, and explanatory variables computed from them in Table 2.

The data covers the period 1978 to 1996. Cell, physical and macronutrient observations are mainly weekly, with micronutrients (ions) monthly. Some observations were missing for all variables. In order not to lose much data when many explanatory variables were included in regression runs, missing values were replaced by linear interpolation of values on either side of the missing values, but only in cases where at most three observations were missing. Some observations fell in the same week. In these cases average values were used for the week for physical and chemical data. In the case of cell observations, aggregate values were used where observations were for different species of blue-green algae. Further work is probably required on the cell data, partly because it may be possible to find a system of weighted aggregation of blue-green algae of different species for the purposes at hand, and because 'zero' observations may in fact relate to positive values too low to be reported.

The main objective of regression analysis was to attempt to find relationships between blue-green algae cell concentration and posited explanatory variables such as phosphorus, nitrogen, N:P, flow and temperature, with various transformations of the variables, such as natural logarithms and lags, allowance for interactive effects, and dummy variables for seasons. A useful starting position is the time series graphs of major variables. Plots of weekly observations for the sample period of cell concentration, flow, total nitrogen and total phosphorus are shown in Figures 1 to 3 for Torrumbarry weir, Capel's crossing and Swan Hill. Vertical scales are the same for Figures 1 and 3 to permit easy comparisons. Flow and nutrient observations for Figure 2, Capel's crossing, the site off the Murray, are of a different order of magnitude, and has different vertical scales. Flows on the tributary are much lower but whether water velocity is lower depends on the relative cross sectional river areas of the sites. Nutrient concentrations are much higher at Capel's crossing.

The incidence of algal blooms at the three sites are obtained by reading off the first panel of Figures 1 to 3, in conjunction with the designated alert levels shown in Table 3. To aid placement within the year, the autumn period has been marked on all panels, plotting values of the autumn dummy variable. Over the sample period of 17 years, there were 1, 2 and 4 blue-green algae outbreaks above 15000 cells per mL, levels high enough to be considered toxic.

Table 1: Observed variables[a]

Observed variables[b]	Units	Frequency of observations [c]
Blue-green algae[d]		
Cell concentration (*cells*)	cells/mL	weekly
Physical factors		
Discharge (*flow*)	ML/day	weekly
Stream temperature (*temp*)	°C	"
Turbidity (*turb*)	NTU	"
Electrical conductivity at 25°C (*ec*)	uS/cm	"
pH (*ph*)		"
Alkalinity (total) (*alk*)	mg/L	monthly
Colour (filtered) (*col*)	Pt/Co	"
Macronutrients		
Oxidised nitrogen (*nox*)	mg/L	weekly
Total Kjeldahl nitrogen (*tkn*)	mg/L	"
Total phosphorus (*tp*)	mg/L	"
Filterable reactive phosphorus (*frp*)	mg/L	"
Silicate (*sio2*)	mg/L	"
Dissolved organic carbon (*doc*)	mg/L	monthly
Micronutrients		
Chloride (*cl*)	mg/L	monthly
Sulphate (*so4*)	mg/L	"
Calcium (*ca*)	mg/L	"
Magnesium (*mg*)	mg/L	"
Sodium (*na*)	mg/L	"
Potassium (*k*)	mg/L	"

[a] Data sources. Water Ecoscience, Mt Waverley, Victoria and Murray Darling Basin Commission
[b] Variable names in brackets
[c] Sometimes intermittent and irregular
[d] Descriptors microcystis, anabaena, anabaenopsis, aphanizomenon and other cyanophyceae

Table 2: Computed variables

Variable	Name and derivation
Total nitrogen concentration	$tn = nox + tkn$
Nitrogen/phosphorus ratio	tn/tp
Phosphorus load over n weeks	$loadn = \sum_{i=1}^{n} tp_i$
Natural logarithm of variables	e.g. *lntemp*
Variables lagged n weeks	e.g. *tempn*
Season dummy variables	*autumn*, *winter*, *spring*

Figure 1: Torrumbarry weir weekly profiles
Cell count, flow and nutrient concentrations

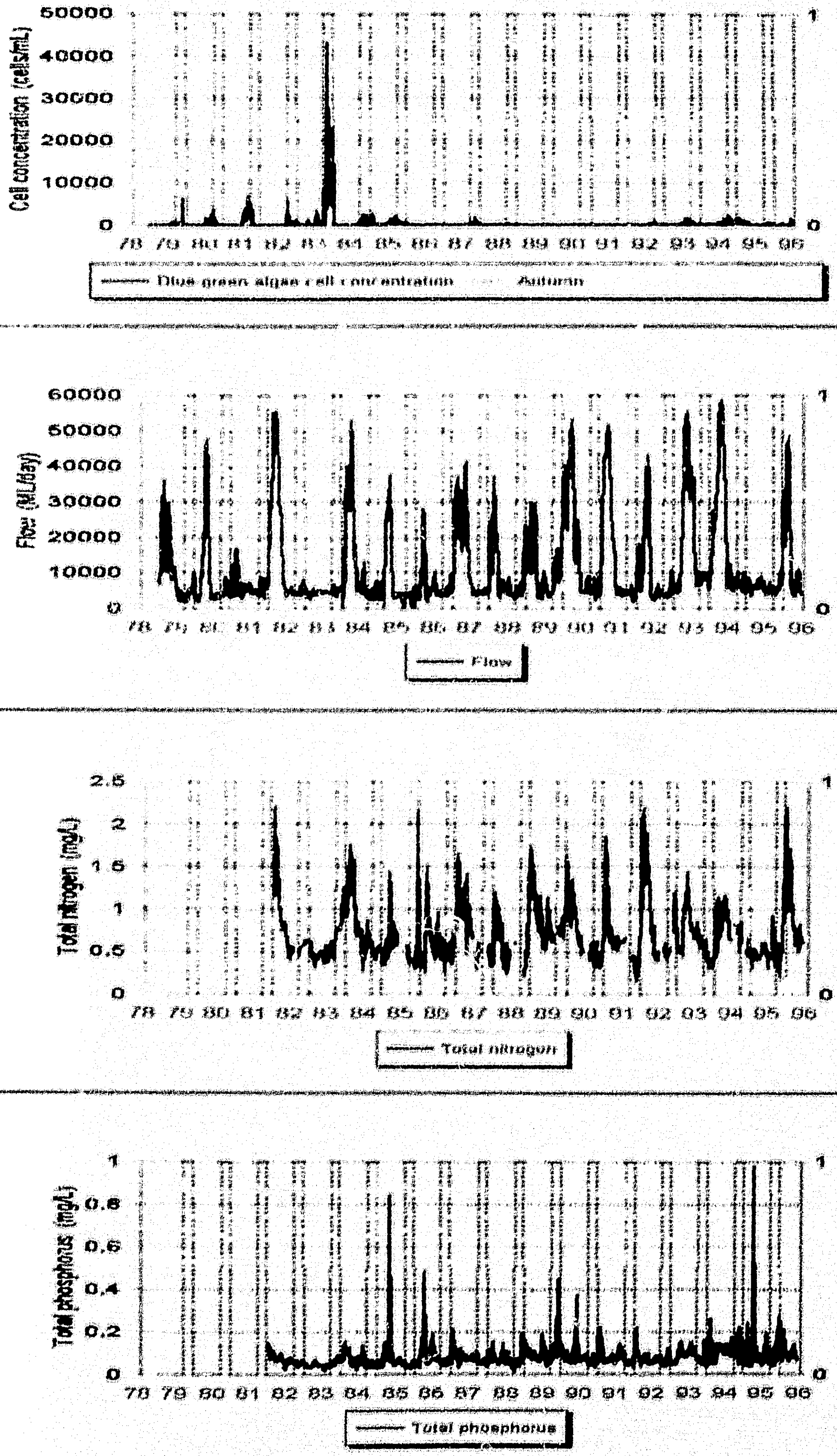
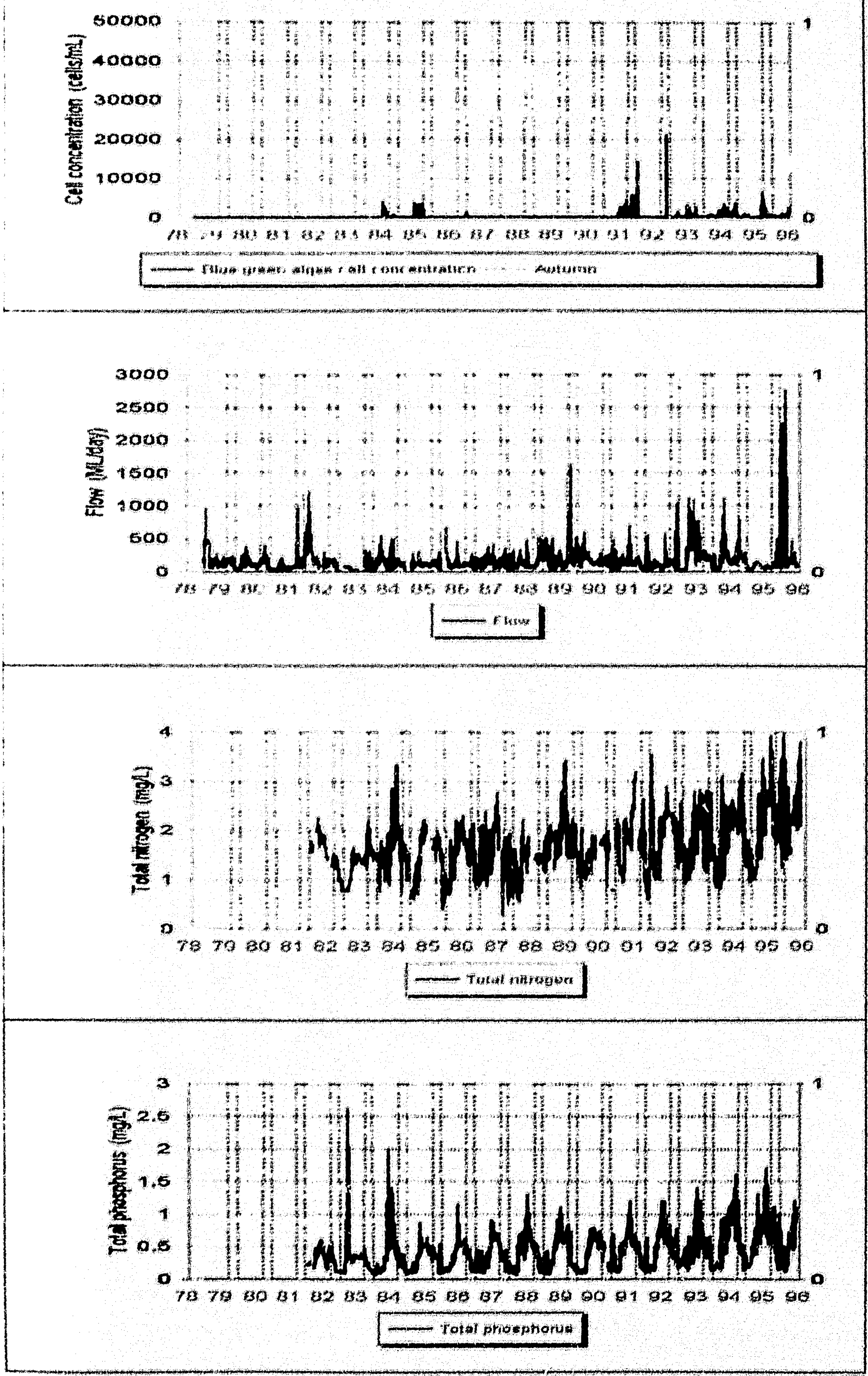
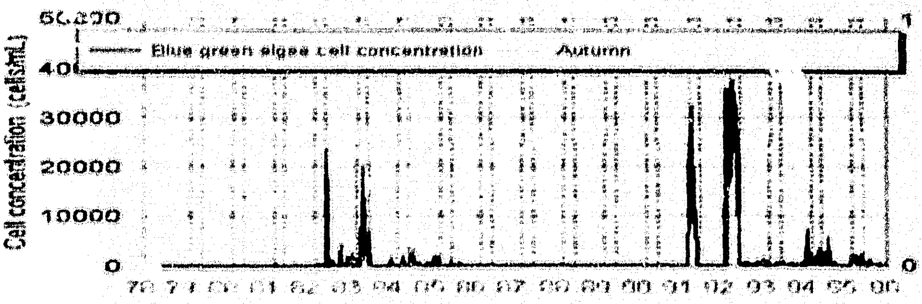
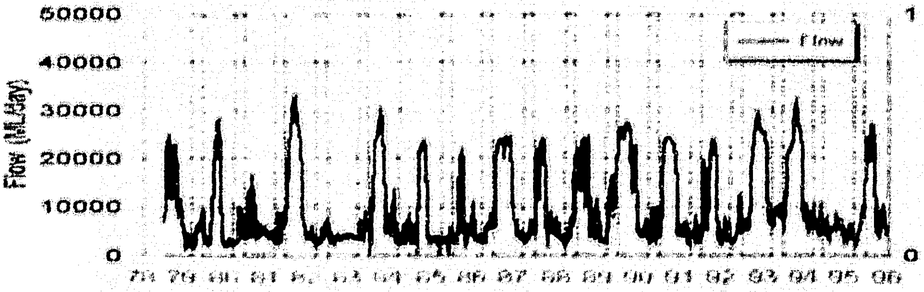
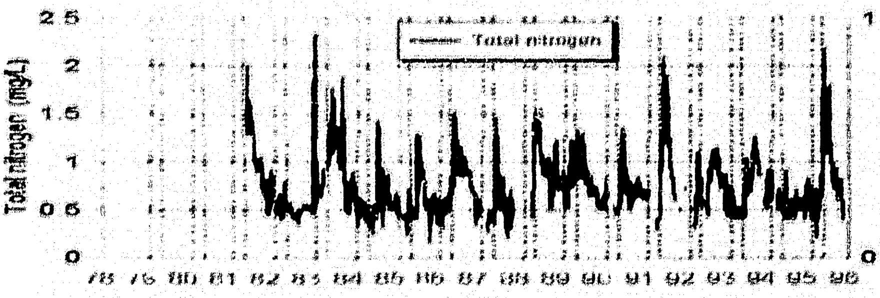


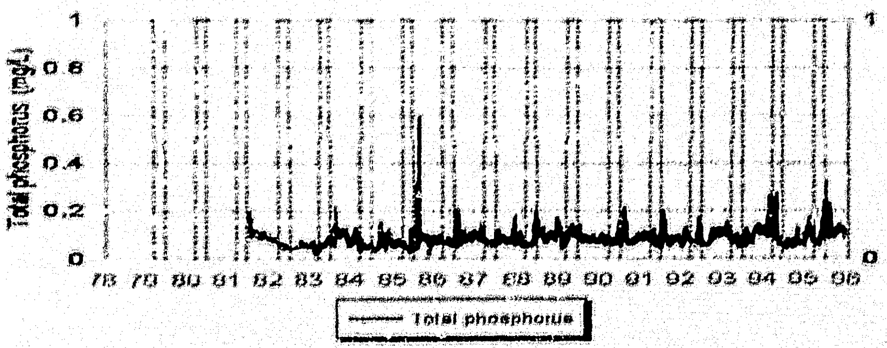
Figure 2: Capel's Crossing weekly profiles
Cell count, flow and nutrient concentrations




50000
40000
30000
20000
10000
0
Cell concentration (cells/mL)
Blue green algae cell concentration
Autumn
1
0
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96


50000
40000
30000
20000
10000
0
Flow (ML/day)
Flow
1
0
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96


2.5
2
1.5
1
0.5
0
Total nitrogen (mg/L)
Total nitrogen
1
0
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96


1
0.8
0.6
0.4
0.2
0
Total phosphorus (mg/L)
1
0
78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96
Total phosphorus

There are no discernible increasing trends in flow or nutrient levels for the two Murray sites from Figures 1 and 3. There is an indication of increasing nutrient concentrations for the tributary through Capel's crossing from Figure 2.

The significant outbreak in Autumn 1983 can perhaps be correlated with the lack of any high peak flows in the preceding winter. However, a similar lack of high peak flows in winter of 1994 did not result in a similar algal outbreak.

Peak algal concentrations tend to be captured by the autumn period. To the untrained eye, there appears to be little explanation of algal outbreaks from the figures. It does appear however that there is a tendency for nitrogen to be high and phosphorus low when algal concentration is high, suggesting a positive correlation between cell concentration and N:P.

Table 3. Blue-green algae alert levels for drinking water supplies[a]

Alert level	Cell concentration (Cells/mL)	Indications
1	500 - 2000	Offensive odours and tastes
2	2000 - 15000	Potentially toxic
3	15000 -	Widespread bloom; Users to be notified of toxic status

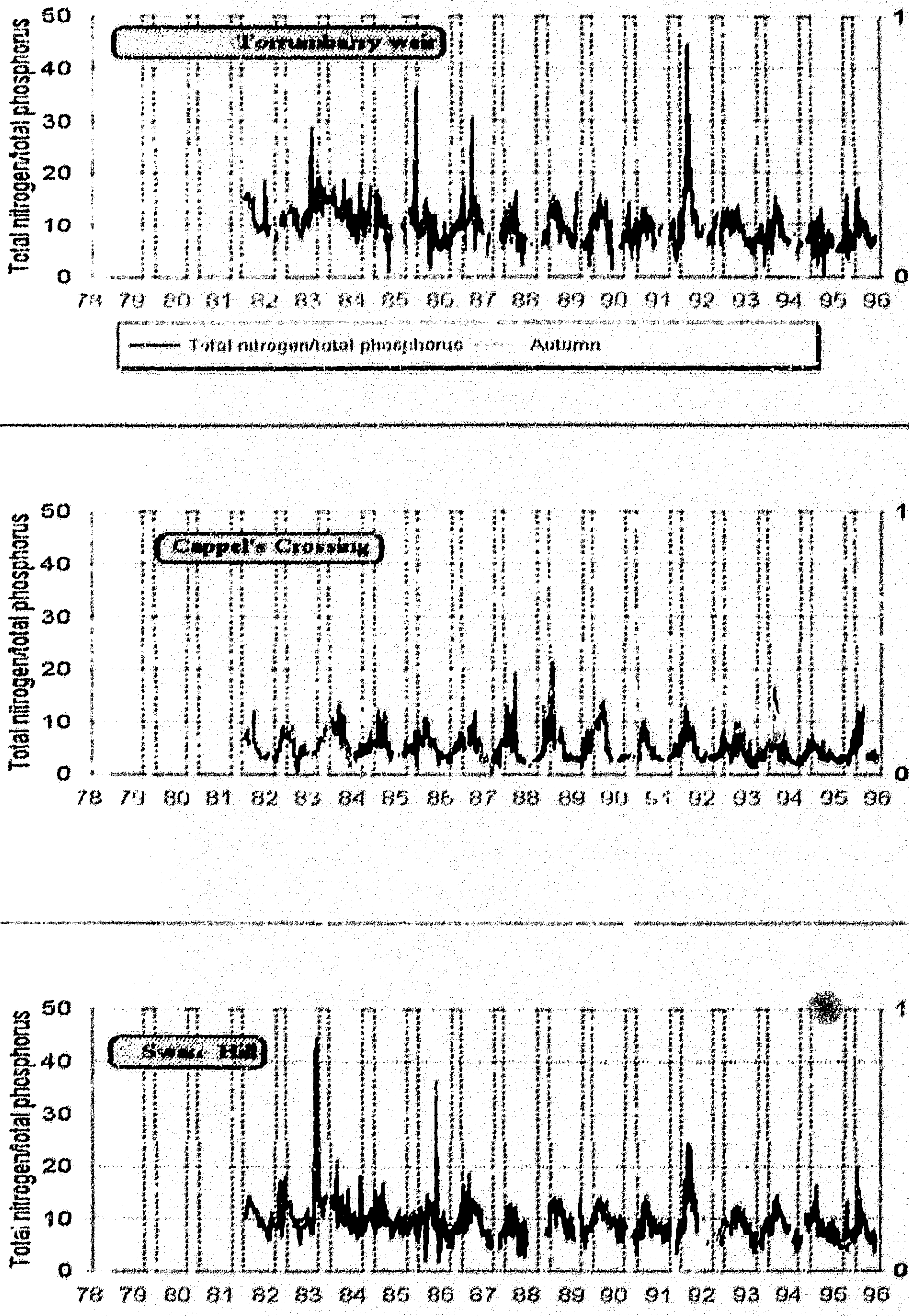
[a] Based on Department of Conservation and Natural Resources, *Blue-Green Algae*, (undated)

Figure 4 shows the time profile of N:P for the three sites. Peak values tend to be outside the autumn period. The ratios for the two sites on the Murray hover around the 'neither N nor P limiting value' of 7.2 referred to above, with occasional spikes when the ratio is relatively very high. The ratios for Capel's crossing are on average less than 7.2, indicating perhaps that nitrogen is limiting, and possible situations conducive to outbreaks of blue-green algae.

The graphical analysis gives a useful picture of simultaneous developments, but interpretations are obviously best made by ecologists and those familiar with the water systems at the sites. For example, just because phosphorus is low when algal cell concentration is high does not necessarily mean that phosphorus does not promote the algal population. It may mean that algae have consumed phosphorus. Interpretation is further complicated by the fact that there are populations of different species of algae, each reacting to the environment in different ways. This suggests that finding significant relationships based on linear least-squares regression is likely to be difficult.

Regression results should be prefaced with some reference to modelling philosophy in this area. Harris (1994) refers to developments of modelling algal blooms progressing from loading models (of the type referred to above in the UNESCO study), to statistical empirical models (which is the type described here) to models of complex dynamics. In the latter type of model, populations of successive algal species within the food chain are modelled. Models at this level of detail are non-linear and may be chaotic in the sense of projections being very sensitive to initial values. Models at the higher level of annual averages such as the loading models are more likely to be successful, particularly if the waterbodies are lakes and reservoirs. For this reason, regressions using annual and seasonal average values were carried out in addition to the regressions based on weekly observations.

Figure 4: Nitrogen/Phosphorus ratio profiles



An example of regression results for the three sites based on weekly data is shown in Table 4. Of major interest is whether the logarithm of blue-green algae cell concentration can be explained by current and two-week lagged flow, water temperature, and the nitrogen to phosphorus ratio. Not surprisingly the most significant explanatory variable in all regressions is the dependent variable lagged one period. Flow lagged two periods is significant in the results for Capel's crossing, but otherwise the flow variables are not significant. The N:P variable lagged two periods is significant in the results for Torrumbarry weir but otherwise N:P is not significant. Although results for statistical empirical models can be expected to be site specific, these results do not suggest any underlying pattern has been captured

Results for the logarithm of cell concentration regressed on the logarithm of total phosphorus, flow and water temperature based on average annual data for Torrumbarry weir and Capel's crossing are shown in Table 5. Results are not shown for Swan Hill which showed no explanatory power. Although the phosphorus and temperature variables may be judged significant, the signs of the coefficients are reversed between the two sites.

It must be concluded that so far it has not been possible to find consistent relationships in the compiled data which could used to determine optimal nutrient or flow strategies However, the results are not really out of line with the findings of others working in this area (e.g. Sullivan et al.). In anticipation that further work or the work of others may still make this possible, the scope for economic control models is considered in the final section.

4.0 Alternative control models

The predominant approach taken by economists to the problem of control of algal blooms has been to assume the problem is nutrient driven, and that the surrogate problem is one of reducing phosphorus and nitrogen concentrations by controlling the inflow of nutrients to water systems (e.g. Alaouze, 1995, Herath, 1995 and DPIE, 1995). The reduction of nutrient inflows may be desirable on grounds other than the control of algal blooms, but as a measure for controlling blooms it may take many years before benefits become apparent. Depending on the rate of discount, measures with a more immediate impact, such as flow regulation and water mixing, may be desirable. Ideally an optimal combined approach should be taken, as advocated by Young et al. (1993) and the New South Wales Department of Water Resources (1992). Combinations should be found such that the marginal cost of reducing the expected cost of an algal bloom outbreak by one dollar is the same across all measures, and approaches one dollar.

There appear to have been few dynamic models developed for optimal control of algal blooms or of eutrophication of waterbodies. An exception is the study of Somlyody and Wets (1988). Some components of a dynamic control model are presented in Table 6. In many ways, the key variable is the state variable, describing the state of the system at any decision stage. Three possibilities are listed in Table 6. The first, cell concentration of different algal species, can probably be dismissed because of the dynamic complexity referred to earlier. The second, phosphate content of waterbody sediments, is problematic because there are no observations of this variable. This would not matter too much if scientific knowledge were such that it could be inferred, say from mass balance equations. After all, fish numbers are unobservable, but optimal control models are developed because stock numbers can be inferred from past catches and using estimated natural mortality rates. A third possibility is to use the volume and quality of water in storage. This seems to be a reasonable prospect, given observability and its strategic importance.

Table 4. Regression results for three sites on the Murray, for log of weekly blue-green algae cell count the dependent variable

	Torrumbarry Weir		Capel's Crossing		Swan Hill	
R^2	0.56		0.58		0.49	
Adjusted R^2	0.55		0.57		0.48	
Standard Error	1.83		2.03		2.03	
Observations	393		364		425	
	Coefficients	***t Statistic***	***Coefficients***	***t Statistic***	***Coefficients***	***t Statistic***
Intercept	-0.1349	-0.07	1.2752	0.56	1.9409	0.64
lncell1	0.6906	18.54	0.6885	17.89	0.6651	18.55
flow	0.0000	0.32	-0.0000	-0.08	0.0000	0.54
flow2	0.0000	0.95	0.0011	2.44	-0.0000	-0.06
temp	-0.0154	-0.28	-0.0172	-0.39	-0.0565	-1.00
temp2	0.0659	1.14	0.0037	0.09	0.0891	1.52
tn/tp	-0.0235	-0.92	-0.0273	-0.50	0.0194	0.80
tn/tp2	0.0516	2.02	-0.0628	-1.23	-0.1580	-0.44
pH	-0.0817	-0.30	-0.1748	-0.62	-0.1099	-1.00
turb	0.0031	0.43	0.0016	0.21	-0.0064	-0.74
ec	0.0037	1.04	0.0001	1.88	0.0008	0.81
col	-0.0134	-2.88	0.0074	1.25	-0.0008	-0.14
autumn	0.3154	1.13	0.5343	1.80	-0.1035	-0.35

Table 5: Regression results for two sites on the Murray, for average annual log blue-green algae cell count regressed on average annual dependent variables

	Torrumbarry Weir		Capel's Crossing	
R^2	0.45		0.52	
Adjusted R^2	0.30		0.39	
Standard Error	1.35		2.07	
Observations	15		15	
	Coefficients	***t Statistic***	***Coefficients***	***t Statistic***
Intercept	37.23	1.75	-32.06	-1.27
lntp	-4.71	-2.36	11.00	3.14
lnflow	-0.39	-0.44	1.71	1.32
lntemp	-14.45	-2.23	12.89	1.60

Table 6 Example model components

Variable or function	Example application
Objective function	Maximise the present value of net returns over infinite periods
Decision interval	Four weeks
Decisions variables	Preventative Release of water in storage, for flushing cells, or diluting nutrient concentrations Aeriation of water in storage Timing of nutrient rich waste water from sewage treatment plants Nitrogen and phosphorus taxes on detergents and fertilisers Land use controls Biological control through the introduction of predator fish Treatment of water contaminated with blooms Chemicals, algicides, e g - Copper sulphate Reactive carbon for purifying water contaminated with toxins Chlorine Procuring pure water to replace contaminated water
State variables	Cell concentration - of different algal species Phosphate content of waterbody sediments Volume and quality of water in storage
Stochastic variables	Weather Rainfall - flushing of nutrients in water system after flood events, particularly in winter - low water velocity in summer and autumn after low rainfall or drought Temperature - warm, sunny weather conducive for occurrence of blooms
Return functions	If take no action when a bloom does occur Cost of ill-health for humans, livestock and fish Costs of taking action if a bloom is imminent or has occurred Cost of lost water usage Cost of treatment to prevent loss of water usage Opportunity cost of storage water used for flushing or dilution

A dynamic optimisation problem based on a model with volume and quantity of water as the state variable is formally formulated in Table 7. As observed by Harris (1994, p. 5), "It is possible to argue that Australia, for very good reasons, concentrated more on the management of water quantity risks than on water quality risks over the last twenty years. Only recently has the issue of water quality risk become a major issue". Harris also notes that releases of water from storage help to determine not just water flows, but also the transport of nutrients, dependent on the nutrient content of the water in storage. This is reflected in the water quality transition function, s_w.

Another important model feature carried over from Table 6 to Table 7 is volume of rainfall captured in the catchment, treated as a stochastic variable. Flood events can flush considerable nutrients into water systems, with significant carryover effects.

5.0 Conclusions

The problem of optimal control of algal blooms is a rich interdisciplinary one, reliant on expertise in ecology, chemistry, agriculture, hydrology, economics and modelling. It is also very challenging because of the complexity of the systems involved. Economists have already made headway in estimating some of the costs and benefits of algal bloom control, and in suggesting principles and policies. However, more interaction between economists and others involved in the research and development process would help to achieve socially desirable measures for ameliorating the incidence of toxic blooms.

Table 7 Formulation of the algal bloom control problem

The following problem

$$\max \sum_{t=1} \alpha^t (i_{\mathrm{mod}(t,12)}\{d_t, r_t\} + h_{\mathrm{mod}(t,12)}\{f_t, y_t, r_t\}) \quad (1)$$

with respect to d_t, f_t $(t = 1, \ldots, \infty)$, subject to constraints, could be solved with the following functional recurrence equation of dynamic programming

$$V_m\{x_m, y_m\} = \max_{d_m, f_m} [i_m\{d_m, r_m\} + h_m\{f_m, y_m, r_m\} + \alpha E V_{\mathrm{mod}(m+1)}\{x_{\mathrm{mod}(m+1)}, y_{\mathrm{mod}(m+1)}\}] \quad (2)$$

subject to $d_m, f_m \geq 0, \quad d_m + f_m \leq r_m + x_m,$

$$x_{\mathrm{mod}(m+1)} = \min [C, x_m + r_m - d_m - f_m], \text{ and} \quad (3)$$

$$y_{\mathrm{mod}(m+1)} = s_m\{x_m, y_m, d_m + f_m, r_m\} \qquad (m = 1, \ldots, 12) \quad (4)$$

Variable or function	Description
m	Month index $(m = 1, \ldots, 12)$
$V_m\{x_m, y_m\}$	Present value of states x_m and y_m from pursuing an optimal policy across infinite months
x_m	Volume of water in storage, month m
y_m	Quality of water in storage, month m
d_m	Diversion of storage water for irrigation, month m
f_m	Diversion of storage water for flushing and dilution, month m
r_m	Volume of rainfall collected in catchment in month m (stochastic)
$i_m\{d_m, r_m\}$	Return from irrigation diversion in month m
$h_m\{f_m, y_m, r_m\}$	Net return from algal bloom control in month m
$s_m\{x_m, y_m, d_m, f_m, r_m\}$	Water quality transition function
α	Monthly discount factor
E	Expectation operator
C	Capacity of storage

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