Addressing Water Quality Problems Through the Integration of Ecological and Economic Modelling

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Abstract: Eutrophication is one of the major water quality problems in Australian coastal waterways. Eutrophication involves chronic enrichment with nutrients from agricultural, domestic and industrial sources that can lead to impaired ecosystem functions and loss of economic and social benefits. A spatially explicit ecological simulation model was developed in conjunction with an extended input-output model to evaluate the potential economic impacts of policy interventions on the water quality of the Bremer River. The ecological model was consistent with the major ecological processes affecting biochemical oxygen demand (BOD) dynamics in the Bremer River, which is a freshwater tidally influenced tributary of the Brisbane River (Southeastern Queensland). The economic model was developed using an input-output data base incorporating a waste stream or effluent discharge sector. Policy interventions evaluated will provide information about the regional economic costs of BOD reduction in the river over a long-term planning horizon.

Keywords: Eutrophication; BOD; Bremer River; causal loop modelling; input-output economic data base

1. INTRODUCTION

Eutrophication is one of the major water quality problems in Australian coastal waterways. Eutrophication involves chronic enrichment with nutrients from agricultural, domestic and industrial sources that results in decreased ecosystem health and impairment of ecosystem services such as clean water and nutrient recycling.

The Bremer River is a tidally influenced freshwater system that flows into the Brisbane River and then into Moreton Bay in southeastern Queensland. Ipswich is a major provincial centre for the Bremer Catchment located at ca 15 km upstream on the Bremer River. The Bremer River has been subject to a long history of chronic nutrient enrichment due to agricultural runoff and discharge from wastewater treatment plants and abattoirs located along the waterway distributed through the catchment. The economy of the Bremer Catchment is growing, putting increasing pressure on the condition of environmental resources in the catchment. Between 1986 and 2000 the estimated resident population in the Bremer Catchment increased by approximately 16.8% to 135,000 people. Between 1986 and 1996, employment in the catchment increased by 11.7% with over 17.5% of the total employment in the catchment in 1996 located in manufacturing industries dominated by a number of abattoirs that discharge effluent into the Bremer River.

The water quality of the Bremer River is monitored each month by the Queensland Environment Protection Agency. Recent statistical analyses of these data have shown that there are serious declines in Bremer River ecosystem health indicated by a decline in dissolved oxygen during the 1990s (Figure 1) and the increased turbidity since the mid-1990s following an anomalous series of droughts (Figure 1). Chlorophyll 'a', which is a simple measure of algal biomass in the river water, increased during the early 1990s (Figure 1) because of the decreased turbidity, which itself was a function of reduced stream flow because of the droughts and also because of the high nutrient availability caused by waste discharges to the river. Clearly, water quality in the Bremer

River is declining and so too are the recreational opportunities of the local community that depend on a clean and safe waterway.

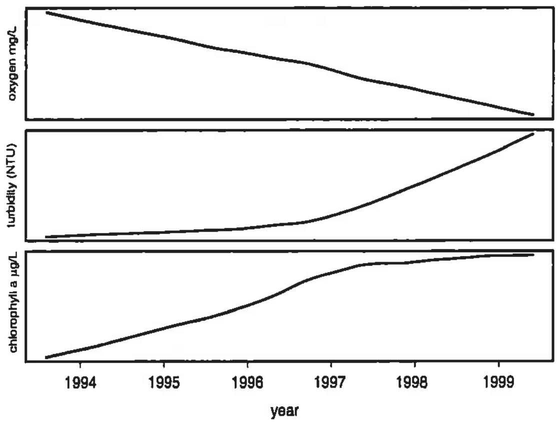

Figure 1. Long term deseasonalised trends in monthly estimates of key water quality parameters in the Bremer River near Ipswich (1993-2000). Solid curve in each panel derived from a robust nonparametric regression time series decomposition procedure known as STL. Top panel shows trend in dissolved oxygen in the river. Middle panel shows trend in river turbidity or water clarity. Bottom panel shows trend in chlorophyll 'a' in the river — chlorophyll 'a' is a proxy measure of algal biomass.

We discuss here the development of an approach to integrating economic and ecological models that can be used to help evaluate the potential economic impacts of policy interventions on the long term water quality of the Bremer River.

2. BREMER RIVER ECOSYSTEM MODEL

A spatially explicit dynamic simulation model accounting for the major environmental processes affecting Bremer River water quality was developed using a system of ordinary differential equations linked by environmental and demographic processes characterised by nonlinear, time-varying and stochastic properties. Environmental forcing functions are based on extensive statistical modelling of historical records of environmental factors such as river flow, solar radiation, rainfall, and river salinity profiles. The model is designed to support risk-based assessment of nutrient loading from various anthropogenic sources on river ecosystem function and health. The model includes microbial, viral and planktivorous fish dynamics and stochastic rainfall-runoff processes. The model is designed to support Monte Carlo based policy experiments and the design and testing of ecosystem health indicators.

A simplified version of this ecological model is constructed to support linkage with an economic model based on an input-output data base applicable to the Bremer Catchment. The simplified model is consistent with the major ecological processes affecting water quality in the Bremer River. Biochemical oxygen demand (BOD) and dissolved oxygen (DO) consumption are the major components of the ecological water quality model. BOD is a measure of microbial productivity and consumption of oxygen in the river due to waste discharge from economic activities such as agriculture, abattoirs, and wastewaste treatment plants.

A simple conceptual model of the Bremer River ecological-economic modelling approach is shown in Figure 2. The conceptual model is based on causal loop modelling principles consistent with the development of simultaneous equations or simulation modelling based on coupled systems of differential equations.

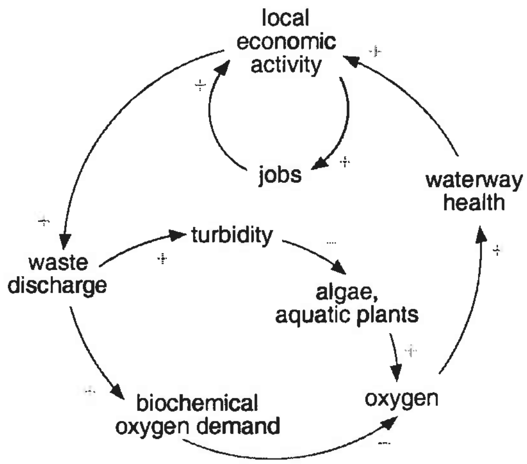

Figure 2. Simple conceptual model of the Bremer River ecosystem dynamics linked to local economic activities. Economic activity is linked to ecosystem health through the waste stream from the household, manufacturing and agricultural sectors and its effect on bacterial productivity and oxygen consumption in the river.

Causal loop modelling is a special class of signed digraph theory. Signed digraphs are read as follows. Arrowed links between variables are signed positive if the 2 variables change in the same direction. For instance as waste discharge from agricultural production increases then so does catchment runoff resulting in increased turbity in the river caused by the increased suspended sediment load. A negative link means that the 2 variables respond in opposite directions. For instance, as turbidity increases in the river then algae and aquatic plants decrease due to the reduce light in the water column caused by the suspended sediments.

Causal loop modelling or signed digraphs are a structured graphical procedure for the development of meaningful conceptual models that are then used in qualitative modelling of complex biological systems [Puccia and Levins 1985] or economic and corporate policies [Morecroft and Sterman 1994].

Overall, the conceptual model comprises the following logic that enables a simple ecological-economic model to be developed that derives the waste stream from economic production and the effect on BOD and hence ecosystem health —

- as economic activity (manufacturing, agriculture) and the population in the Bremer River catchment increases then so too does the waste stream unless new waste minimisation technologies are adopted
- the waste stream comprises dissolved inorganic and organic nutrient discharge from the wastewater treatment plants, dissolved organic carbon from the abattoirs and both sediment and dissolved inorganic nutrient discharge in the catchment runoff from agricultural activity
- as the waste stream increases then so does the river turbidity, which in turns results in decreased algae and aquatic plants due to the reduced underwater light and smothering by sediments
- meanwhile the increased waste stream results in increased microbial production in the river water and sediment due mainly to dissolved organic carbon input that is measured as BOD or increasing biochemical oxygen demand
- both increasing BOD and decreasing algae/plant production result in decreased oxygen production because the bacteria consume the oxygen and there are now fewer and fewer algae and aquatic plants to produce the oxygen
- decreased oxygen results in decreased ecosystem health overall as bacteria dominate the system while oxygen consumers such as zooplankton and fish that depend on the algae and plants as well are in decline
- deceased ecosystem health results in economic activity decreasing due to lost household consumption as recreational opportunities such as fishing, boating and swimming are reduced.
- decreased economic activity results in a local multiplier effect on the local economy in terms of reduced gross output, employment as well as exports from the catchment.

Using this simple but spatially explicit BOD-DO simulation model enables coupling of ecosystem dynamics with waste streams from the local economic industry sectors. This economic-ecological modelling approach can then be used to evaluate the potential economic impacts of policy interventions on the water quality of the Bremer River.

3. INCORPORATING THE ENVIRONMENT INTO AN ECONOMIC MODEL

Traditional neoclassical economic models have tended to ignore the crucial role the environment plays in economic processes. In such models, non-market environmental goods and services such as air and water quality have been treated as 'free' commodities and assigned a zero or near zero price. In this study an environmental sector termed "waste stream" is modelled explicitly and incorporated into the economic model. For the purposes of this study, the waste stream refers to the value of the wastewater discharge (measured as BOD) into the Bremer River or its tributaries. A simple conceptual representation of this extended economic model is shown in Figure 3. The economy is represented as a number of sectors, in this case including a sector modelling the water quality of the Bremer River. All sectors interact with each other, including the Bremer River and with the rest of the world (ROW), which includes the tidal exchange of BOD between the Bremer and the Brisbane River. Within the input-output framework, wastewater discharged into the Bremer River would conventionally be represented as a payment for a license to discharge and/or as a payment to the local council for sewerage treatment. The full cost of discharging waste is not accounted for in the balance sheet of households, producers or the local government.

Currently, the Bremer River is treated as an open access and free resource. It is used for low cost and in some cases, no cost, discharge of wastewater. The economic problem that needs to be addressed is how to regulate waste disposal so that the private costs of an industry equate with the social costs, which include the cost to the environment of waste disposal. In brief there is a need to internalise the negative externalities associated with industry activities along the Bremer. For this study, an extended economic input-output model has been constructed for the economy of the Bremer Catchment. It incorporates a waste stream in a commodity-by-industry model with flow matrices within and between economic activities and the ecological system. Extending the input-output model to measure the impact of environmental impacts is not new [see for example Isard et al., 1968; Leontief, 1970]. These early studies can be described as either generalised input-output models which extended the technical coefficients matrix of the input-output data base to reflect pollution or economic–ecological models that attempted to represent flows between the economy and the environmental in the form of complex interregional models. For the most part early models suffered from lack of data. More recently, a computable general equilibrium (CGE) model, the Monash Multi-Regional Forecasting-Green (MMRF-Green) [Adams et al., 2000] has been developed. It is a dynamic, multi-sectoral, multi-regional model of Australia, with capabilities for analysis of environmental policies. These CGE models are complex, data intensive and are more appropriate for national or state level impact analysis. The water quality problems in the Bremer Catchment do not warrant such complex modelling.

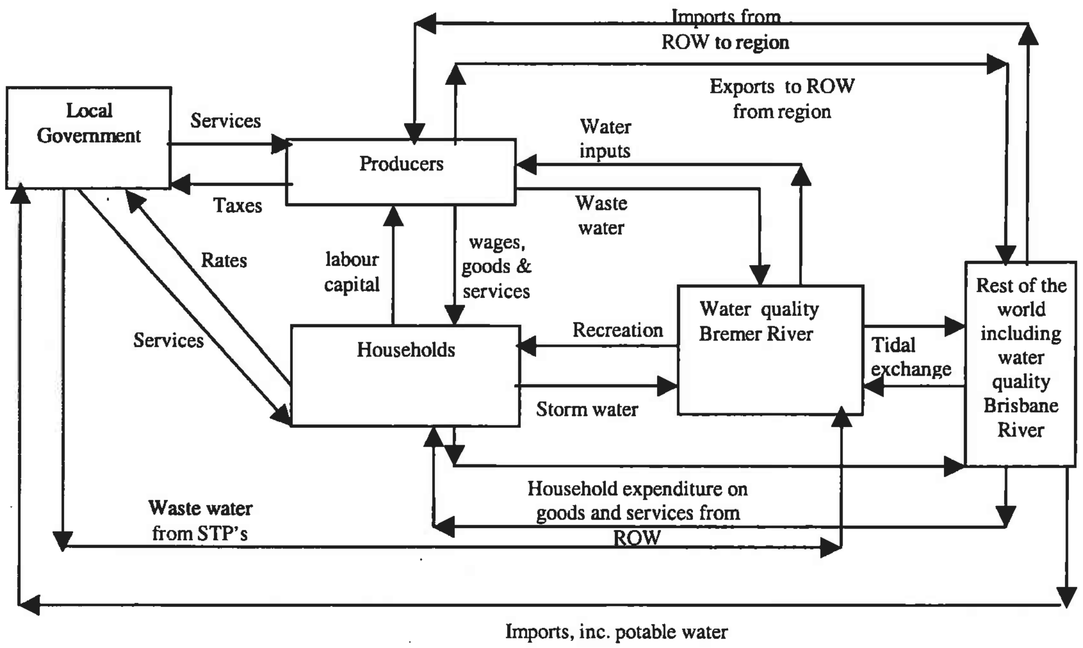

Figure 3. A simplified extended economic model incorporating the flows of wastewater to the Bremer River.

The integration of an ecological system and an economic system into a single model presents a number of difficulties. Firstly, the two systems need to be linked so that outputs of one module become the inputs of the other. Secondly, the units of measurement of the two systems need to be uniform or at least readily converted from one to the other. In particular, economic systems are traditionally modelled in monetary terms whereas ecological modelling usually deals in physical units. A third problem for the integration of models is the spatial scale. An ecological model may well be at the level of a sub catchment for which data are unavailable for a meaningful economic model to be developed. In general, economic systems are larger than ecosystems. Frequently, a number of ecosystems make up an economic system. In choosing an appropriate scale trade-offs may be required between the comprehensiveness of the integrated ecosystem and economic system and the degree of complexity in the model. Finally, the temporal scale can be a problem. For the purposes of ecological modelling, monthly, or even daily fluctuations in the variables of a model are important information. For the purposes of economic modelling, these relatively short-run time scales are aggregated to show changes in economic variables over a longer time period, usually one year.

For the Bremer study, choice of temporal and spatial scales for both the ecological model as well as the economic model has been largely determined by the type of information required by decision makers to manage resource use in the catchment. In particular, information is required about the possible reduction in gross output and employment in the area if initiatives were taken to reduce wastewater disposal into the Bremer. In relation to this, and equally important, is information about the extent to which restrictions on industry wastewater discharge would provide a measurable reduction in the degree of eutrophication of the river.

4. CONCLUDING COMMENTS

Information about the impact of eutrophication or measures to address the problem on an economy is important information for decision makers. The issues associated with eutrophication are particularly relevant at a catchment scale. This paper has described the integration of ecological and economic system modelling at a catchment scale. The research has gone someway towards addressing a number of problems associated with the integration of these two systems, including, identification of a link between the two systems, identification of a spatial scale that is meaningful from an economic and an ecological perspective as well as temporal issues that could minimalise important ecological detail.

5. REFERENCES

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