A Bioeconomic Model for Estimating the Benefits of Acid Rain Abatement to Salmon Fishing: A Case Study in South West Scotland

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ABSTRACT *The United Kingdom, under the Large Combustion Plant Directive of the European Community, is committed to cutting sulphur dioxide (SO_2) emissions by 60% of 1980 levels by the year 2003. In order to justify this action and to support new decisions on further emission reductions, policy makers require knowledge of the economic benefits of abatement. Benefit estimates for the recovery of freshwater fish populations present difficulties since the effect of reduced acid deposition on environmental processes is complex and because fishery records are often inadequate or absent. This paper predicts the economic benefits of acid rain abatement to the rod and line salmon fishery of Galloway, South West Scotland. It achieves this by linking output on long term changes in water chemistry and fish population status from MAGIC, a process based catchment model for acidification, with catch and market value data. Predicted increases in the market value of the fishery are presented and the role of the model in economic analysis of environmental policy discussed.*

Introduction

In northern Europe and North America acid rain is a pervasive environmental pollutant which affects human health (OECD, 1981), agricultural and forest crops (Baker *et al.*, 1986), freshwater ecosystems (Adriano & Johnson, 1989), fish populations (Muniz & Levestad 1980; Wright & Henrikson, 1980; Harvey & Lee, 1982) and building materials (Webb *et al.*, 1990). In the United Kingdom one focus for concern has been damage to the ecology of vulnerable upland areas where some of the most natural and least disturbed sites important for nature conservation occur (Fry & Cooke, 1987) and which are important spawning waters for the Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*).

Although historical information on the abundance and condition of fish populations is sparse, decline in the UK fish stocks as a result of acidification is thought to have begun over 50 years ago (Harriman *et al.*, 1987). Salmonids are most sensitive to acidification during the hatching, fry and smolting stages of development and recruitment failure is thought to be the primary cause of population decline. Lacroix (1987) found, for example, that the production of salmon smolts increased exponentially between pH 4.5 and 6.0[1]. Low pH levels disturb the salt balance within the body tissues with sodium, in particular, being lost from the body faster than it can be taken up (McWilliams, 1982) and inhibit the action of hatching enzymes such as chorionase (Haya & Waiwood, 1981). Elevated concentrations of labile aluminium, leached out of soils by acid water moving through the soil profile, are also believed to impair respiratory processes in salmonids with damage to gill filaments reported (Rosseland, 1980).

The United Kingdom, under the Large Combustion Plant Directive of the EC, is committed to a 60% reduction in sulphur dioxide (SO_2) emissions from 1980 levels by the year 2003 through fuel switching (coal to natural gas) and flue-gas desulphurization. The estimated cost of this programme is likely to be in the region of £6 billion (Department of Environment, 1990). In the European Community (EC) the Single European Act (Article 130R) requires that environmental policy should *take account* of the costs and benefits of action or lack of action. With new decisions on the extent of further reductions in acidic emissions within the EC expected in 1994, it is important to estimate the magnitude of the potential marginal economic benefits of alternative abatement levels.[2]

An important potential benefit of abatement is likely to be recovery in the rod and line (r&l) salmon fishery resource, an important source of income to rural areas, with estimated total gross expenditure by anglers in 1988 in excess of £50 million. The UK r&l salmon fishery is a private resource traded in the market place with an estimated aggregate market value in excess of £300 million (Radford *et al.*, 1991). While the market value of a fishery can be influenced by a wide range of physical fixed features, such as the length of beat and the number of holding pools, the most important variable influencing value is the annual average catch estimated over a five or ten-year period (Radford *et al.*, 1991). *Ceteris paribus*, acid rain abatement would be expected to enhance market values through its effects on water chemistry and fish catch.

Estimating the value of recovery in r&l salmon fisheries presents the economist with several challenges. Firstly, complex modelling of dynamic, environmental processes over very long time periods is required to link reductions in sulphur emissions to improvements in water chemistry. And secondly, although considerable scientific evidence has emerged to suggest that anthropogenic acidification has caused serious denudation of salmon stocks, the complexity of salmon population dynamics and the absence of reliable stock, catch and effort data both in the high seas and in estuaries and rivers have frustrated attempts to quantify the effect of changes in water chemistry, induced by acidic inputs, on fish catch (Waters & Kay, 1987).

This paper describes a bioeconomic model which has been developed to produce estimates of recovery in the economic value of regional r&l salmon fisheries in the UK. Chemical changes in water quality and fish population health due to reduced acid emissions over the next 50 years are modelled using MAGIC (Model of Acidification of Groundwaters In Catchments), a widely applied, process-based, catchment model for acidification and linked to changes in average salmon catch and economic value. The responses of the Galloway r&l fishery in South West Scotland to alternative deposition scenarios are modelled and the marginal economic benefits of alternative abatement scenarios are presented for the period 1988–2038.

Approach

The modelling approach described has three main elements: (1) modelling of changes in water chemistry and fish population status in response to reduced SO_2 emission levels using MAGIC; and links between (2) changes in fish population status and fish catch per unit effort and (3) fish catch and economic value of the fishery. To illustrate its application the Galloway r&l salmon fishery is used as a case study.

The uplands of Galloway is an acid-sensitive environment where slow-weathering, granitic bedrock is overlain by shallow, organic-rich, acidic soils with only a limited capacity for neutralizing acid inputs (Wright *et al.*, 1994) and where decades of anthropogenic acid inputs have damaged salmonid fish populations and other aquatic organisms (Harriman *et al.*, 1987, Flower *et al*, 1987). Acidification in the area has also been exacerbated by the expansion of commercial forestry plantations (Ferrier *et al.*, 1993a) which enhance the process of acidification by increasing the interception of pollutants and by removing base cations from the soil as the crop canopy expands (Miller *et al.*, 1991).

Changes in Water Quality and Fish Population Status in the Galloway Fishery

Changes in water chemistry and predicted fish population status for alternative future deposition scenarios over the next 50 years were determined by MAGIC from a random sample of over 30 individual catchments, located in the upper reaches of six major salmon rivers (Cree & Fleet, Doon, Bladnoch, Dee, Girvan and Stinchar). The headwaters of these rivers regularly fail the EC directive on the quality of freshwater for fish life (78/659/EEC) on the basis of pH, with values falling between 4.3 and 5.0 at certain times (Solway River Purification Board, 1992). The locations of these individual catchments are shown in Figure 1.

MAGIC

MAGIC is a process-oriented, intermediate-complexity model for constructing acidification history and predicting future water chemistry at the catchment level over time periods of decades to centuries (Cosby *et al.*, 1990). It consists of: (1) soil–soil solution equilibria equations in which the chemical composition of soil solution is assumed to be governed by simultaneous reactions involving sulphate adsorption, cation exchange and the dissolution and precipitation of aluminium, inorganic and organic carbon; and (2) mass balance equations in which the fluxes of major ions to and from the soil and surface waters are assumed governed by atmospheric inputs (Ca, Mg, Na, K, NH_4, Cl, SO_4, NO_3), mineral weathering, net uptake in biomass and loss in runoff. The effects of afforestation on net uptake of cations from soil and on dry and occult deposition are also incorporated. Within MAGIC many chemical and biological processes active in the catchment are aggregated into a few readily described processes. The spatial heterogeneity of soil properties, such as depth, bulk density, cation exchange capacity, and amount of exchangeable base cations within the catchment, is lumped into one set of soil parameters (Wright *et al.*, 1993). Uncertainty in the estimation of critical parameters is dealt with using a Monte Carlo technique which selects values within specified ranges for each of these parameters. The optimization procedure is carried out 10 times to produce 10 calibrated

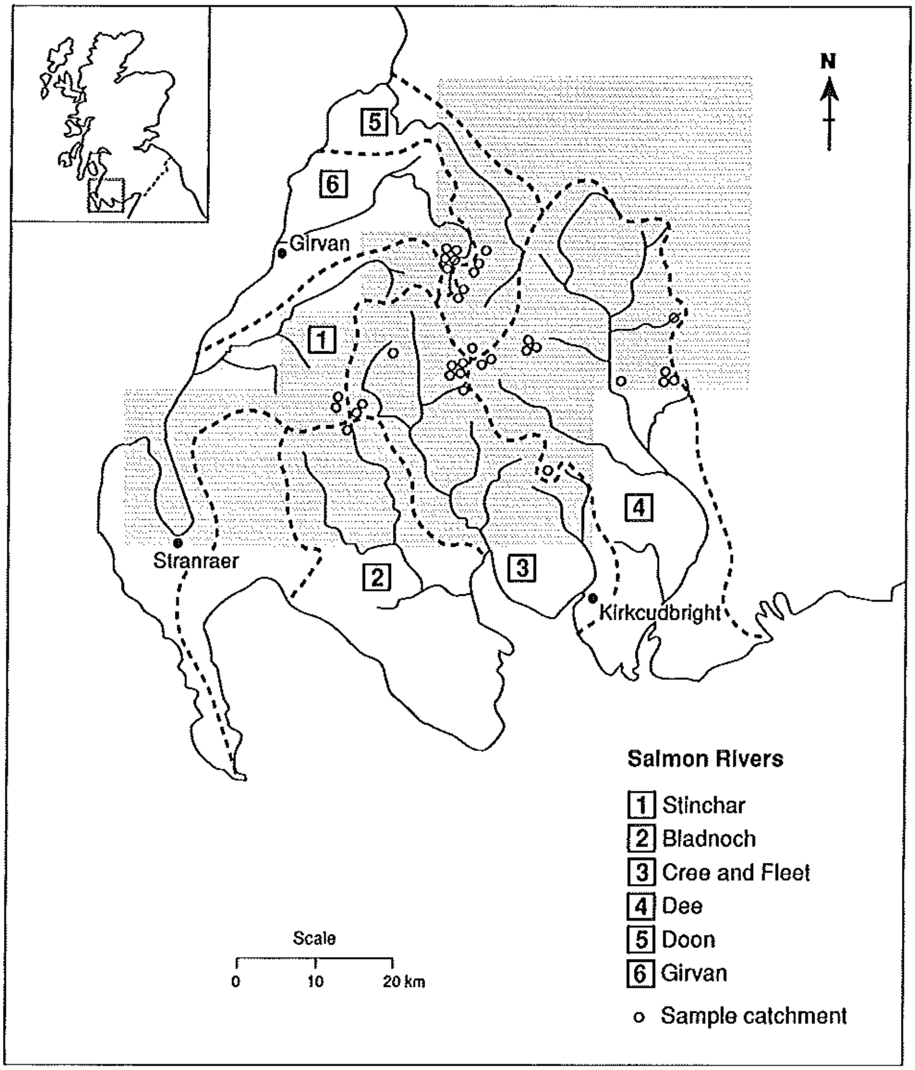

Figure 1. Location of sample catchments in the Galloway fishery. (Shaded area represents acidified area—see note 3).

models for each catchment and provide an indication of the uncertainty in the historical reconstitutions and predictions.

A dynamic fisheries population model has been incorporated into the framework of MAGIC. The model algorithms are based on a statistical evaluation of the salmonid fish population status from the extensive Norwegian thousand lakes survey (Henriksen *et al.*, 1989, Bulger *et al.*, 1992). Fish population status is grouped into three distinct categories: (1) healthy (H), a vigorous population unaffected by acidic deposition; (2) marginal (M), a sparse population, either historically thin or damaged by acidic deposition; and (3) extinct (E), population lost. The probability status of a catchment population falling into each category

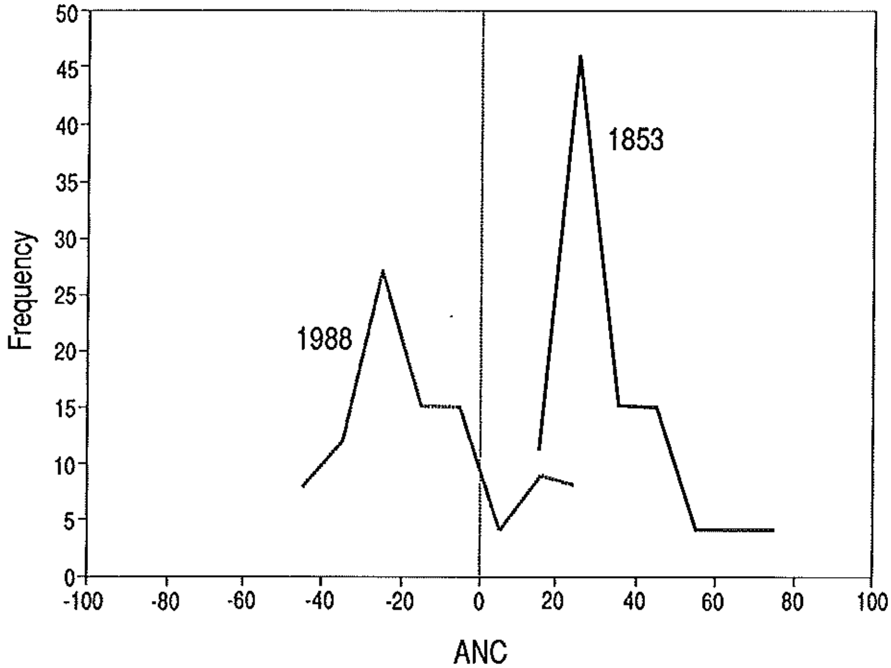

Figure 2. Frequency distribution of acid neutralizing capacity (u egl $^{-1}$) (ANC) for sample catchments in the Galloway area as predicted by MAGIC for the years 1853 and 1988.

is dependent upon water chemistry variables such as pH, alkalinity and acid neutralizing capacity (ANC).

Changes in Water Quality and Fish Population Status in the Galloway Fishery

Predicted values in 1988 for pH, acid neutralizing capacity (ANC), diatom fossil counts and non-marine sulphate concentrations based on 1979 calibration in the Galloway fishery were in close agreement with observed 1988 values (Wright *et al.*, 1994). Figure 2 shows the predicted frequency distribution of regional alkalinity from the model application using the best-fit parameters from the Monte Carlo simulation. The model predicts a large shift in the distribution from pre-acidification times (1853) to recent times (1988). This shift in regional alkalinity is extremely important for aquatic life as an alkalinity of 0 is defined as the value where aquatic systems become damaged. The fisheries status model was also calibrated and applied to the Galloway area. The fish population parameters (*H*, *M* and *E*) agreed well with historical information on the decline in fisheries status of several Galloway lochs and estimated dates of extinction (Wright *et al.*, 1994). Figure 3 presents a comparison of the historical change in fish population status and predicted status reconstructed by MAGIC for Loch Narroch in Galloway with actual extinction coinciding with a predicted percentage probability of 100 around the late 1960s.

In this study, MAGIC was used to predict the mean value for *H* (probability

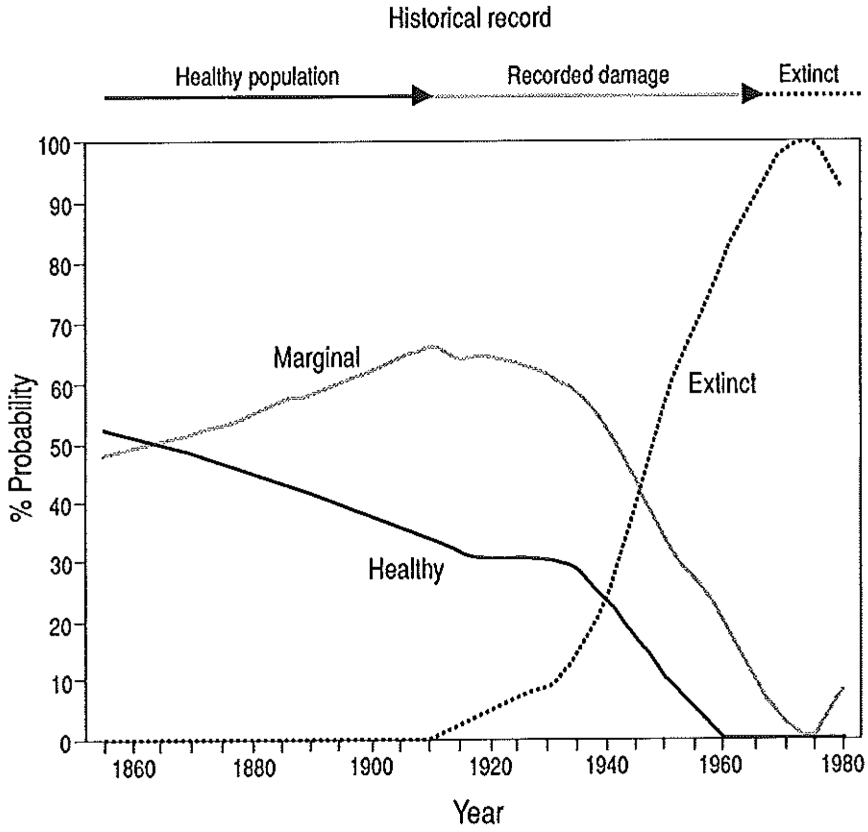

Figure 3. Fish population status in Loch Narroch as reconstructed by MAGIC and from historical information.

of a healthy fish population), weighted by individual sample catchment size, for the acidified area[3] of the combined headwaters of the six salmon rivers. The mean value for *H* was subsequently used to predict the effect on average catch levels in the Galloway fishery.

Estimating the Effect on Catch Levels

The life-cycle of the Atlantic salmon is complex. After hatching in freshwater they migrate seawards to distant ocean feeding grounds before returning, after several years, to their river of origin to spawn. During this cycle the salmon are exposed to a wide variety of biological and environmental stresses and large natural fluctuations in the size, age structure and timing of returning populations are common (Shearer, 1987). During the years 1981 to 1984, for example, the percentage of salmon entering the North Esk, a river in eastern Scotland, during the netting season varied beween 23% and 44% (Dunkley, 1986). While identifying the specific effect of acid rain on salmon abundance would be extemely demanding, in terms of data, due to the presence of many other confounding environmental and biological variables which effect population levels, the task is made impossible by the complete absence of reliable data on

Table 1. Linear regression: analysis of variance of equation (1).

	df	Sum of squares	Mean square
Regression	1	217.654	217.654
Residual	23	81.280	3.534

Notes: F = 61.59. Significant at 1% level.

fishing effort both on the high seas and in estuaries and rivers (Williamson, 1987). Large fluctuations in reported Scottish Office Agriculture and Fisheries Department (SOAFD) catch data for r&l anglers over the past few decades have, for example, been thought to be associated with improved efficiency or closure of unprofitable netting stations downstream (Waters & Kay, 1987).

In order to establish a relationship between improvements in water chemistry and catch per unit effort it is therefore necessary to turn to a more controlled fishing system where many of the external influences on fish status are excluded and for which reliable records of catch per unit of effort are available. In this study the probability of a fish population achieving a healthy status (H), was related to detailed catch per angling day for Loch Reicawr (one of the sample catchments) for the period 1945–1970[4] (Ferrier *et al.*, 1993b). The fitted OLS regression is described below, with the analysis of variance presented in Table 1:

$$C = 97.4\ H - 24.2 \qquad (R^2 = 0.77) \tag{1}$$

(s.e. $B = 11.429$)

where C = average annual fish catch per angling day

H = probability fish population healthy, as predicted by MAGIC

Since no other factor is believed to have affected fish catch in Loch Reicawr and in the absence of other fish catch per unit data from the acidified area of Galloway, it is assumed, for the purposes of this study, that this relationship reflects the wider regional response of catch to changes in H. The percentage increase in the average annual salmon catch for acidified waters of the regional fishery over time can then be estimated from equation (1) by substituting the regional, mean value of H (weighted by catchment area) generated by MAGIC for the period 1988–2038.

The initial catch level (1988) from acidified areas is not known so had to be estimated indirectly from total fishery catch statistics (SOAFD 1986–90) using equation (2):

$$C_a = C_t / ((R_{u:a})^* ((A_u / A_a) + 1) \tag{2}$$

where C_a = estimated five year average r&l salmon catch from acidified waters only

C_t = total five year average r&l salmon catch from the total fishery (obtained from SOAFD statistics 1986–90)

$R_{u:a}$ = ratio of catch between unaffected and acidified waters. Catch values were derived from equation (1) using the 1988 mean value of H, weighted by sample catchment area for acidified waters and an assumed value of $H = 1$ for unaffected waters

A_u = area of fishery unaffected by acidity

A_a = area of fishery acidified

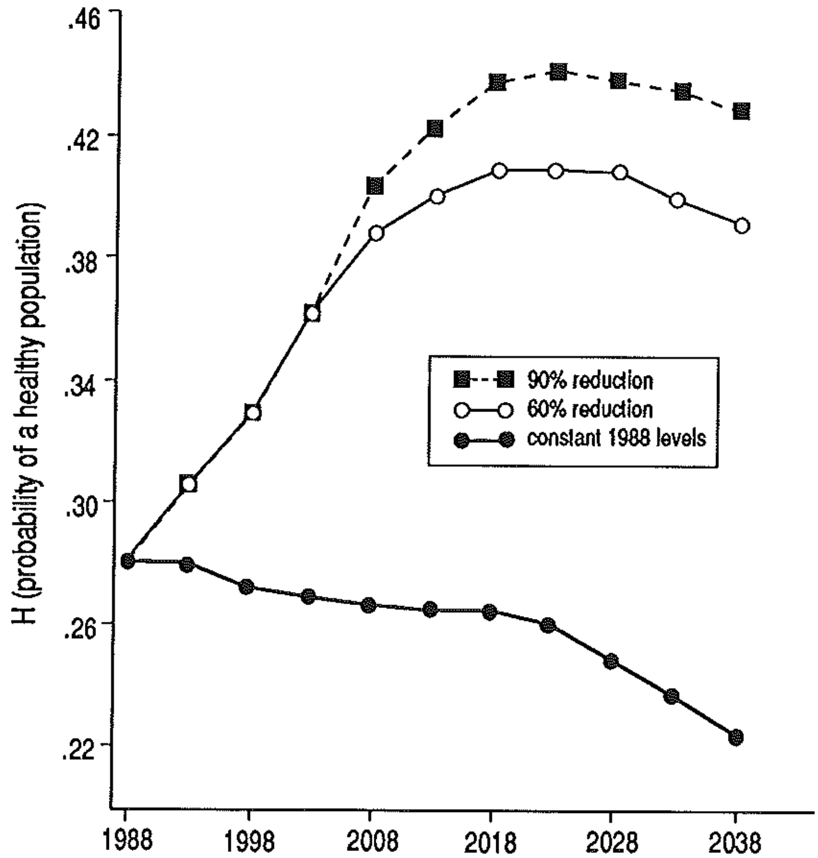

Figure 4. Change in value for H in acidified waters.

Two important assumptions are required for the calculation of the ratio R_{ua} in equation (2). Firstly, the spawning grounds for salmon are assumed to be distributed evenly throughout the entire fishery. Secondly, a value of $H=1$ in the waters of the fishery unaffected by acidification assumes that salmon health is unaffected by acidification or other forms of pollution. For the Galloway fishery, the five-year average annual salmon catch from acidified waters was estimated to be 261 (7%), out of a total of 3676, with the remainder (93%) caught in unaffected waters. Figures 4 and 5 describe the predicted change in H and C for the Galloway fishery.

Economic Value

The appropriate measure for the economic benefits of environmental improvement in salmonid habitat can be defined as the marginal change in net economic value (NEV) where:

$$\text{NEV} = \text{consumer surplus} + \text{resource rent} \tag{3}$$

In this study, since we are concerned with predicting marginal changes in the value of a relatively small regional fishery, we can ignore consumer surplus effects if we adopt the assumption that any increases in the annual fish catch of the Galloway fishery will not affect the market place for r&l salmon (i.e. the demand for r&l salmon is perfectly elastic). Instead, all gains are captured as resource rent, which is measured by the net revenue received from paying anglers by the fishery resource (Copes & Knetsch, 1981). The capitalized potential income flow from rental payments (including income foregone by private fishing by the owner) plus any other private benefits such as status generated by owning a fishery, as represented by the market value of the fishing rights, is therefore a lower bound approximation of the marginal change in total NEV. The capital value of a salmon caught by r&l is equal to the total market value of the fishery divided by the average annual salmon catch. In 1988 this was estimated to be £3420 per salmon caught in Scottish rivers (Mackay Consultants, 1989).

Apart from physical fixed factors, average salmon catch, calculated on a five or ten-year basis, is the most important variable affecting the market value of a salmon fishery. Equation (4) describes a non-linear function, defined by Radford *et al.* (1991), which relates the percentage change in the five-year average salmon catch to the percentage change in market value as a result of (increased demand) i.e. the elasticity of value with respect to catch) for any specified period i:

$$V_t/V_{t+i} = (C_t/C_{t+i})^{0.547} \tag{4}$$

where V_t = estimated market value of salmon fishery in year t (five-year average annual catch of fishery × £3420)
V_{t+i} = estimated future market value in year $t+i$
C_t = estimated five-year average salmon catch of salmon fishery in year t
C_{t+i} = estimated future five-year average salmon catch in year $t+i$

Benefit Estimates

The model was run under three deposition scenarios to generate estimates of the change in the market value of the Galloway fishery: (1) constant 1988 levels; (2) a 60% reduction from 1980 levels by 2003 (the current proposed abatement level under the EC Large Combustion Plant Directive); and (3) a 90% reduction from 1980 levels by 2008 (a possible new target level for reductions).

Under scenario (1) the market value of the fishery declines gradually from £12.6 million in 1988 to £11.7 million in 2033 (Figure 6) in response to declining catch. By contrast, SO_2 emission reductions under both scenarios (2) and (3) initiate a relatively rapid recovery in market value. Under scenario (2) the market value of the fishery peaks at £13.7 million in 2028, after which a slight deterioration takes place. By the end of the period (2038) the market value of the fishery is £13.6 million, an increase of £1.0 million over the 1988 level which is equivalent to a 9% increase over the 50-year period. This is a relatively modest change compared to the five-fold increase in catch from acidified waters but reflects the relatively minor contribution of acidified waters to the total salmon fishery catch (approximately 10%). The present value of the annual increases in

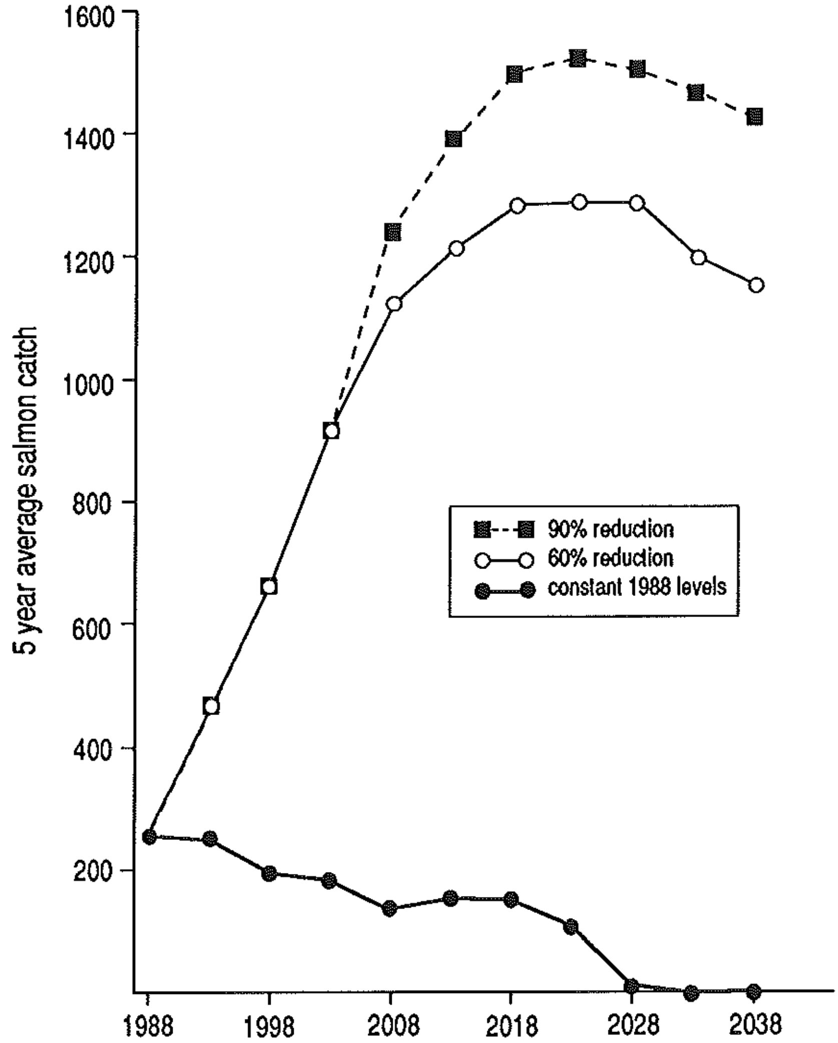

Figure 5. Change in five-year average salmon catch from acidified waters.

the market value of the fishery based on a 6% discount rate, for scenario (2), is £0.88 million.[5] Scenario (3), based on a 90% reduction in SO_2 levels, results in a rate of recovery similar to that predicted for scenario (2) with a final market value of £14.0 million, some £1.4 million higher than in 1988. The present value of the annual increases in the market value of the fishery (at 6%) for scenario (3) is £0.95 million.

The predicted *marginal* increase in the total market value of the fishery and the present value of the *marginal* annual increases in market value for currently planned reductions (scenario 2) over constant 1988 levels (scenario 1) are £2.0 million and £1.08 million respectively. The marginal increases in value predicted under scenario 3 over scenario (2) are considerably smaller (£0.4 and £0.07

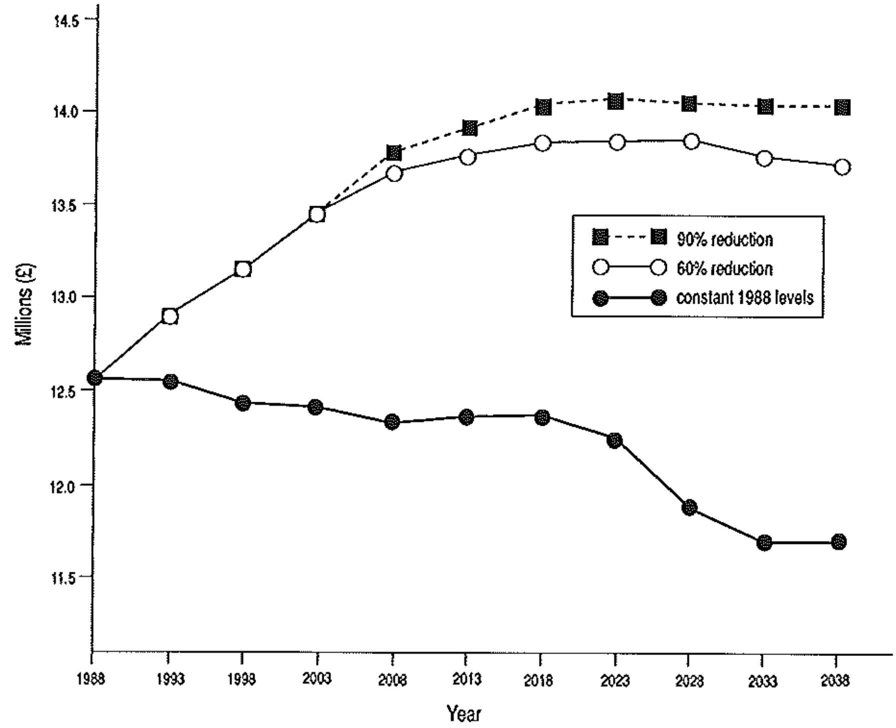

Figure 6. Change in the market value of the rod and line salmon fishery in Galloway under the three sulphur abatement scenarios.

million respectively) and therefore in agreement with theoretical expectations regarding diminishing marginal returns from increasing levels of abatement.

Discussion

The purpose of this paper is to describe a method for estimating the increase in the economic value of regional UK r&l salmon fisheries as a result of SO_2 abatement using the Galloway region as a case study. The primary advantage of this approach is that it permits the introduction of quantifiable monetary benefit estimates for recovery in salmon fisheries directly into the environmental policy process, allowing decision makers to make more informed decisions about appropriate abatement levels. Since recovery from acidification poses substantial problems both with regard to availability and with modelling complex environmental processes over long time periods, benefit estimation by any other approach would be, at best, highly speculative. Clearly this approach relies on a number of important assumptions with respect to catch response at the regional level. Reliable fishery records and historical long term changes in environmental quality are extremely scarce and limit the opportunities to assess the reliability and uncertainty of the predictions. Validation studies based on independent data on water chemistry and diatom records from lake sediments do, however, reveal a high level of consistency with MAGIC output and some confidence can be placed in the long term predictions for recovery (Wright *et al.*, 1994). The link between fish population status and catch is currently weak, relying on a simple empirical correlation for one catchment, and clearly deserves further work. There is a possibility that the catch model is mis-specified, but in the absence of accurate historical data on other environmental variables which might have influenced fish catch during this time period, a closer investigation was not possible. Experimental evidence supports a causal relationship between catch and acidification (*ceteris paribus*) but the approach would be strengthened by incorporating a dynamic, biotic, process-based model of salmon population response to acidification which incorporates survival in different life stages and density dependent regulation (Ormerod *et al.*, 1990).

In order to obtain an estimate of the total economic benefit of acid rain abatement to r&l salmon fisheries it will be necessary to run the model for affected regional fisheries in other areas of the UK (e.g. Wales, Cumbria). Since the approach is catchment based, the model will require recalibration which, given the paucity of historical fisheries records and the requirement for relatively detailed, high resolution data sets to run MAGIC, is not trivial. A wider cost–benefit analysis of acid rain abatement policy in the UK, would also require benefit estimates for recovery in other affected resources including human health, agricultural and forest crops, and the value, motivated by altruistic and passive use concerns, placed by society on improvements to the ecology and biodiversity of the upland environment (Macmillan, 1994).

One significant feature of the recovery path generated by the model is the predicted re-acidification of the region from 2028 onwards under both levels of abatement. This suggests that these catchments are very sensitive even to relatively low levels of anthropogenic SO_2 relative to current emissions. The sustainability of recovery from acidification is therefore in some doubt and deserves further scientific enquiry. Forestry plantations may be critical in this phenomenon and it is intended to run the model using a number of alternative forest cover scenarios over a longer time period (140 years) to quantify the role of forest cover on the recovery process.

Notes

1. Of the main salmonid species, the Atlantic salmon appear to be more sensitive than either sea or brown trout to the effects of acidification (Rosseland & Skoghiem, 1984).
2. In economic theory, the optimum level of abatement can be identified as the point where net benefits are maximized (i.e. where the marginal cost of abatement equals the marginal benefit).
3. In the absence of detailed information on the extent of acidification damage in Galloway, the affected area was estimated from the critical load map for soils which identifies areas where the critical load is exceeded by 1.0keq H^+ ha^{-1} $year^{-1}$ (Department of Environment, 1991).
4. This data was kindly supplied by the Balloch Fishing Club.
5. This discounted value, since it takes account of the speed of recovery as well as the extent, is the appropriate figure for a cost–benefit analysis of alternative abatement levels.

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