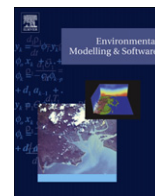




Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Using models to bridge the gap between land use and algal blooms: An example from the Loweswater catchment, UK

Lisa Norton^{a,*}, J. Alex Elliott^a, Stephen C. Maberly^a, Linda May^b

^a Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

^b Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK

ARTICLE INFO

Article history:

Received 30 September 2010

Received in revised form

12 July 2011

Accepted 16 July 2011

Available online xxx

Keywords:

Catchment

Modelling

Water quality

Farming

Expert opinion

ABSTRACT

The goods and services that lakes provide result from complex interactions between meteorology, hydrology, nutrient loads and in-lake processes. Hydrology and nutrient loads are, in turn, influenced by socio-economic factors such as human habitation, water abstraction and land-management, within their catchments. Models provide a means of linking these different domains and also of forecasting and evaluating the effects of different management scenarios on lakes. This paper describes the application of such models to Loweswater, a well-studied lake with water quality problems in the English Lake District, where a community-based approach to catchment management is being undertaken.

Three models were linked. Firstly, PLANET (Planning Land Applications of Nutrients for Efficiency and the environment), an ‘off the shelf’ farm nutrient budgeting model, was supplemented by local information on septic tanks and used to produce an annual nutrient load to the lake. Secondly, GWLF (Generalized Watershed Loading Function), a generic nutrient runoff model, was used to generate daily nutrient runoff values using input from PLANET plus additional information on land-cover, air temperature and rainfall within the catchment. Thirdly PROTECH (Phytoplankton Responses To Environmental CHange), driven by input from GWLF and locally measured meteorology, was used to forecast the abundance of different algal types within the lake. The linked models were used to describe the current impact of catchment management on lake water quality, validated by *in situ* measurements, and to explore the potential impact of a number of alternative catchment management scenarios. Issues surrounding the use of generic modelling applications for catchment management and relevance for stakeholders living in and/or managing land within the catchment are discussed.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

An understanding of the impacts that land managers and occupiers have on their environment is key to achieving sustainable use of natural capital and the ecosystem services that flow from it (Daily and Matson, 2008; Swinton et al., 2007). All ecosystems, including those that are managed, have an important role in supporting human well-being (Assessment, 2005). The challenge for scientists is how to address the inherent complexities of socio-ecological systems (Carpenter et al., 2009; de Lange et al., 2010) when providing advice on sustainable resource management.

Despite concerns surrounding the use of hydrologically-defined surface water catchments for understanding complex socio-ecological systems (de Lange et al., 2010; Herr and Kuhnert,

2007), catchments have received international recognition as potentially suitable units for the integration of land and water management issues, including stakeholder involvement, within the concepts of Integrated River Basin Management (IRBM) and Integrated Catchment Management (ICM) (Hooper, 2005; Mitchell, 1990). The UNESCO ‘Hydrology for the Environment, Life and Policy’ (HELP) initiative, launched in 2001, is centred on a number of catchments of varying scales. Within the UK, the Rural Economy and Land Use programme (RELU) (Lowe and Phillipson, 2006) further recognised the potential importance of catchment based approaches to rural, land and water management by funding research aimed at exploring options for catchment management with a strong emphasis on stakeholder engagement (Lane et al., 2006; Macleod et al., 2007; Smith and Porter, in press). These studies, alongside other catchment approaches (see Everard (2004)), have strongly advocated the importance of integration across different areas of scientific expertise, and of engagement with stakeholders, to provide effective solutions to management problems (see Andersson et al., 2008; Voinov and Bousquet, 2010).

* Corresponding author. Tel.: +44 (0)1524 595825; fax: +44 (0)1524 61536.
E-mail address: lrn@ceh.ac.uk (L. Norton).

Whether scientific tradition, or the problem being studied, should dictate the approaches taken towards ecosystem management is an important question (see Liu and Costanza (2010)); (Jakeman and Letcher, 2003). If science is going to play an important role in the provision of management advice, the scale of study needs to be relevant to the provision of that advice (Jakeman and Letcher, 2003; de Lange et al., 2010). Catchments vary enormously in size, and the issue of scale is particularly important when looking at the level of detail at which investigations can be conducted from water, land and socio-economic perspectives. Natural sciences that cover land and water, using field-based studies, tend to focus either on the micro-scale and study a reduced set of variables with relatively high control, or focus on the landscape scale using large amounts of data collected over a wide range of sites to identify effects/trends (Bilotta et al., 2010; Boix-Fayos et al., 2009; Collins et al., 2007). However, for catchment management the most relevant scale is the scale at which it is possible to understand and affect human impacts which may be intermediate between the micro- and macro-scales.

Policy instruments such as the EU Water Framework Directive (WFD) (European Union, 2000) recognise the importance of catchment management for meeting water quality targets. In the UK, where approximately 75% of land is farmed¹, farmers play a key role in land management in rural catchments. Farming activities that have the potential to impact negatively upon water quality include field applications of nutrients (fertilisers, manures, animal feed, etc), pesticide usage, or the inappropriate storage of animal feed or waste (Haygarth, 2005; Heathwaite and Johnes, 1996). Farmers and other householders in rural areas are also heavily dependent upon septic tanks to deal with human waste and these are increasingly being recognised as having potentially serious impacts on water quality (May et al., 2010). Influencing farmers and other sectors of rural populations, either as individuals or groups, to reduce their impact on water quality will benefit the catchments that they occupy and also wider society. However, there are significant challenges associated with affecting attitudes, particularly those of farmers, when they have little confidence in the evidence used to inform policy decisions (Barnes et al., 2009). For the natural sciences, major challenges include identifying appropriate scales at which to work, integrating land and water perspectives, and understanding how scientists can use the expertise of stakeholders to help facilitate effective catchment management. The SLIM (Social Learning for the Integrated Management) Project (Blackmore et al., 2007) has highlighted the need for science to become part of a more integrated approach to the management of water catchments.

The work described here focuses on understanding the causes of algal blooms, and ways of reducing them, using appropriate data and expertise, including data from farmers and householders alongside that collected by scientific experts. The study focuses on Loweswater, a small lake in the English Lake District (Fig. 1). The lake experiences regular blooms of cyanobacteria (i.e. blue-green algae) (Maberly et al., 2006) and has been the subject of a RELU action research project investigating the potential for improving water quality through community catchment management. These potentially-toxic algal blooms are a major water quality issue for Loweswater affecting the use of this amenity by visitors and local residents. The approach uses detailed catchment-level information on land use, including farm nutrient budgets and losses from septic tanks, alongside meteorological and hydrological data, to model nutrient inputs to the lake from its catchment. These nutrient inputs are then used to model algal abundance within the lake. A

range of catchment management scenarios have been used to test the impacts of altering land use on lake water quality with the intention of providing useful management advice to land managers aimed at reducing the incidence of water quality problems. Ultimately, the project seeks to identify general approaches and principles for the management of the rural environment that are transferable to other catchments (Blackmore et al., 2007; Steyaert and Jiggins, 2007).

2. Methods

2.1. Loweswater catchment

Loweswater is a small lake within a partly upland rural catchment in the Northwest of England (Fig. 1). The catchment forms a bowl around the lake with steep slopes to the north-east and south-west of the lake and shallower more productive land at either end. A number of streams flow into the lake from different parts of the catchment. The catchment's sparse population is supplemented with modest numbers of visitors to the area with residential, visitor accommodation and farm buildings occupying approximately 1% of the catchment, while over 85% of catchment land is farmed.

Previous work on Loweswater has indicated that phosphorus (P) is probably the main nutrient controlling phytoplankton production in Loweswater (i.e. the 'limiting' nutrient). The concentration of soluble reactive (biologically available) phosphorus (SRP) in the water column is extremely low throughout the growing season (Maberly et al., 2006), suggesting that any P entering the lake is rapidly incorporated into algal biomass. Evidence from a lake sediment core taken in 2000, indicates that raised P levels in the lake result from anthropogenic sources and have been in evidence since the 1970s (Bennion et al., 2000). This study focuses on P input but also models N input in order to make the models realistic.

2.1.1. Role of expert opinion

As the focus of a RELU project experimenting with local-level, community catchment management that integrates both natural (land and water) and social sciences (see Tsouvalis and Waterton, submitted for publication) the Loweswater catchment has provided the opportunity to try out modelling approaches which incorporate a wide range of expertise from land management to scientific measurement. The rationale is that increasing local engagement with an issue can help to improve the potential for understanding the causes of the problem through provision of more accurate site-based information. Additionally, the potential for resolving the problem is increased by understanding the causes, and engagement with those who can effect change. The expertise associated with data collection is outlined in Section 2.4 below.

2.2. Factors impacting on water quality

The primary land uses in the catchment, apart from residential buildings, are farming and tourism. Land is mainly used for beef cattle and lamb production, with eight farms managing land that falls within the Loweswater catchment boundary. Only two of these farms are completely within the catchment (although 5 have their buildings within the catchment); the remaining farms are situated partly within and partly outside of the catchment. Several farms include residential accommodation for visitors and the catchment also includes a small hotel. As well as farm residences there are a number of individual houses. In total an average of 59 people are resident in the catchment each night on an annual basis (Webb, 2010).

As phosphorus (P) is the main nutrient controlling phytoplankton production in Loweswater (see introduction), the key processes and structures potentially affecting water quality are those associated with P loss to water, i.e. water movement through the catchment, the production of animals, including waste management, and human waste management facilities.

2.3. Models

A series of linked models were used to assess P runoff from the catchment to the lake and its impact on water quality (Fig. 2). Models were linked in the sense that the outputs from one fed into the next, so that farm nutrient budget information fed into the runoff model and nutrient outputs from the runoff model fed into the algal production model. The data required to run the models are described in detail in Section 2.4 (below). Modelling methodology is described in detail in Section 2.5. The following three models were used:

2.3.1. PLANET – farm nutrients

As P loss from agricultural land is potentially a key reason for water quality problems in Loweswater, a model focussing explicitly on nutrient loss from managed land, as opposed to all other land cover types, was included in the methodology. The farm gate nutrient budgeting module of PLANET (Planning Land Applications of Nutrients for Efficiency and the environment) was used in combination with the

¹ (http://www.ukagriculture.com/uk_farming.cfm).

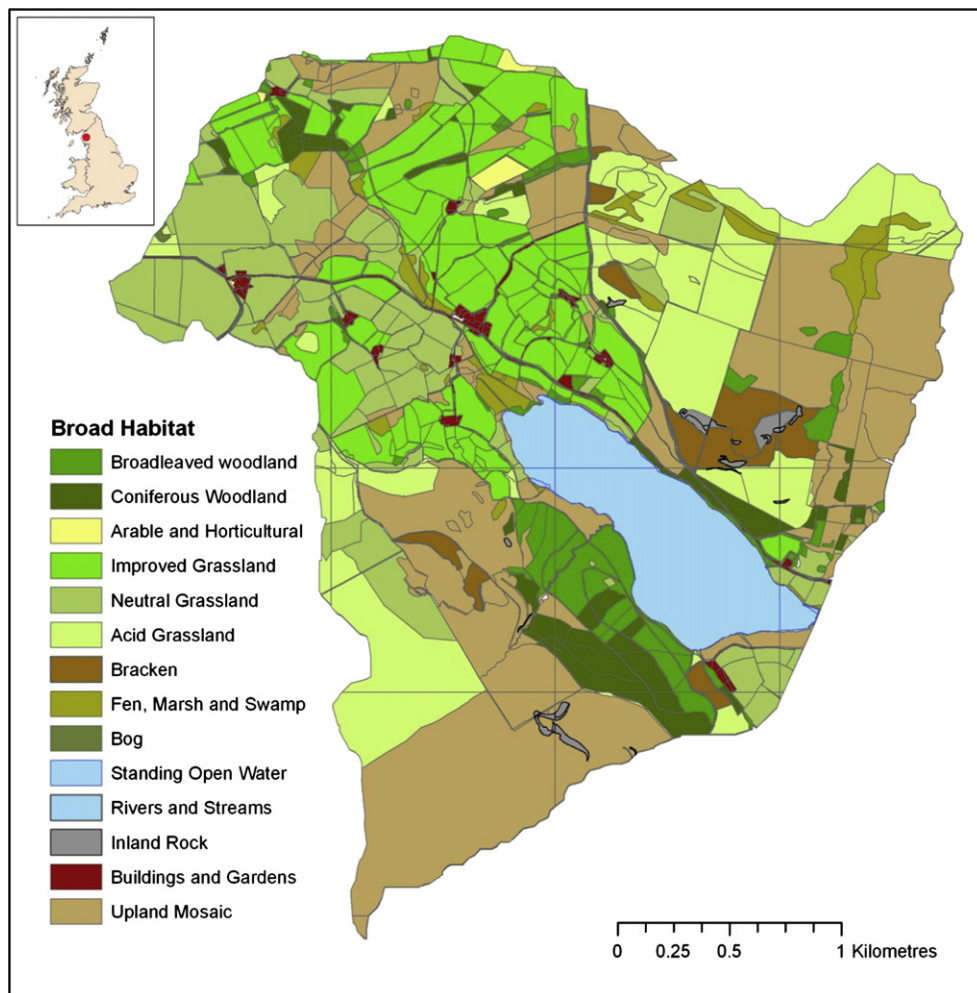


Fig. 1. Map of Loweswater catchment showing UK Broad Habitats and location of Loweswater in the UK.

estimated soil P deficit (see below) to determine the overall nutrient surplus or deficit on each farm within the catchment. The ADAS software PLANET² is a generic, computer-based nutrient management tool that is used by farmers and agronomists to optimise on-farm nutrient management. PLANET was selected on the advice of the agricultural consultant (see 2.4.1) and because of its wide availability.

2.3.2. Generalized Watershed Loading Function (GWLF) – nutrient runoff

A calibrated nutrient runoff model GWLF was used to estimate average daily flows and nutrient concentrations in the streams draining from the catchment to the lake. GWLF is a lumped, non-point source nutrient loading model in which the loading functions provide a practical compromise between simple empirical export coefficients that predict annual losses of nutrients to water and complex chemical simulation models that require unrealistically large amounts of detailed data for most practical applications at the catchment scale. GWLF was originally developed by Haith and Tubbs (1981) and validated by Haith and Shoemaker (1987) to simulate dissolved and total P and nitrogen (N) loads in streamflow. There are several versions of the original GWLF model currently in use; this study used a version provided by the New York City Department of Environmental Protection and described by Schneidermann et al. (2002). The parameterisation of the model for application to Loweswater is as described by Schneiderman et al. (2010), Pierson et al. (2010) and Moore et al. (2010) in relation to its application to the nearby Esthwaite Water catchment, with some minor modifications as outlined below.

2.3.3. PROTECH – algal growth

A lake phytoplankton model PROTECH (Phytoplankton RespOnses To Environmental CHange) was used to predict the effect of nutrient laden runoff on lake water quality and algal species composition and abundance (Fig. 2). PROTECH is a process based deterministic model that operates on a daily time step and simulates the

physical structure within a lake (e.g. temperature profile) and the growth of functional algal types in response to changing environmental conditions (see Reynolds et al., 2001 for full details). It has been successfully applied to nearly a dozen different water bodies around the world and has been used in more than 30 peer reviewed studies (Elliott et al., 2010).

2.4. Data

The following data were collected/used as input to the models;

2.4.1. Catchment land cover and land-use and export coefficients

For the purposes of this study the Loweswater catchment area was initially defined using Ordnance Survey (OS) data and expert judgement as to likely direction of water flow from land surrounding Loweswater. The catchment boundary (watershed) was further ground-truthed during survey work in the catchment and following discussion with catchment residents with expert local knowledge on the direction of drainage from particular land parcels at the margins of the catchment.

Total catchment area was measured at 7.6 km² with the lake comprising 0.64 km². Data on land cover and associated land uses were collected to parameterise both GWLF and PLANET (see below). The Loweswater catchment was digitally mapped using a geo-referenced, hand-held, geographical information system (GIS) that had been developed for the UK Countryside Survey 2007 (Carey et al., 2008). Mapping was based on underlying Ordnance Survey MasterMap, and data, collected as disaggregated vegetation categories, were aggregated into categories relevant for the models used. Catchment mapping was carried out by an expert in habitat mapping which resulted in high quality data on the extent of different land cover types for model input. Without such expertise, use of generic land cover data such as Land Cover Map (2000) would have resulted in far coarser data resolution creating greater uncertainty about model inputs.

PLANET requires detailed information on land management at the farm level to calculate a farm nutrient budget. To collect these data, each of the farmers managing

² <http://www.planet4farmers.co.uk>.

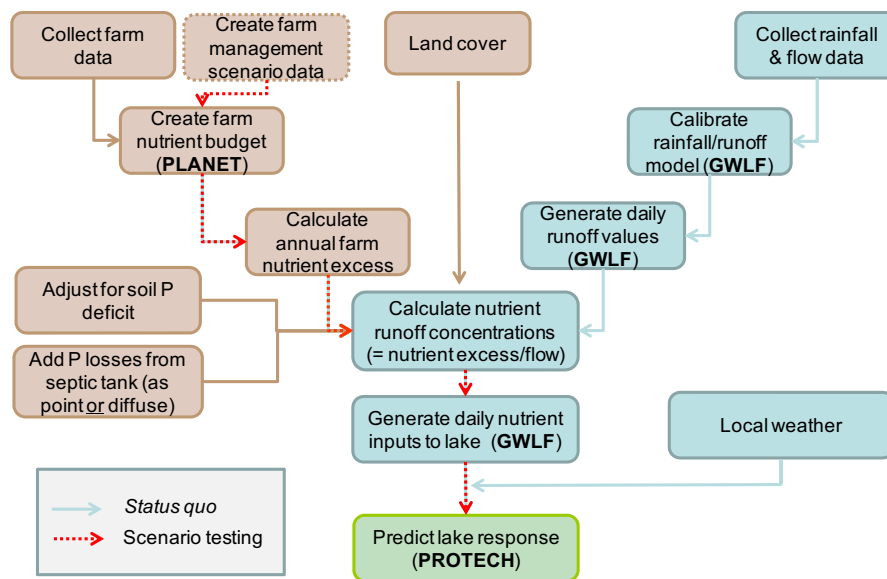


Fig. 2. Schematic of linked models and driving data used to forecast the impacts of land management and septic tank use on lake water quality.

land in the catchment was interviewed by an agricultural consultant. Farmers were questioned on all aspects of their farming activities, including land area and usage, livestock management, and import or export of nutrients in the form of fertilisers, manure/slurry, silage and bought in feedstuffs. The use of an agricultural expert to interview farmers considerably enhanced the quality and depth of data obtained. Additionally, because the farmers were offered anonymity in terms of how the results would be reported, this enabled them to be more open about their management practices.

Export coefficients are a practical and widely used approach to derive P losses from different land cover types. Inevitably, there are site-specific variations in rates of P loss from any given land cover type which will introduce uncertainties. This is particularly the case in managed landscapes and since the impacts of farming practices on lake water quality are the focus of this study, particular effort was placed on deriving Loweswater-specific nutrient export coefficients for high production grass that reflected the actual management of that land in the catchment. Export coefficients, expressed as in-stream nutrient concentrations (mg m^{-3}), for land cover types other than the heavily-managed land, were gleaned from the literature (see Maberly et al., 2006 and Table 1). Export coefficients for high production grass (which is the dominant land cover type within this catchment) were calculated from the nutrient budget information provided by farmers.

2.4.2. Soil phosphorus

The extent to which a soil is likely to lose P to water bodies will depend on nutrient inputs and outputs (farm nutrient budget) as well as current soil P status. Hence, soil samples from similarly managed groups of high production grassland fields across all farms were taken, by the consultant agronomist, and analysed for phosphorus content using standard agricultural soil analysis techniques (Defra, 2010). The phosphorus requirement (P deficit) of each group of fields was then calculated from this information, taking into account the corresponding land use (Rockliffe, 2009). A total farm soil P deficit was calculated by summing values for each group of fields across the farm. Inevitably, the sampling process involves some degree of uncertainty resulting from spatial variability across the fields. This was minimised by following a standard protocol (Defra, 2010) involving taking up to 25 replicate samples along a 'W' shaped walk across the sampled area.

Table 1

Area of different land cover types within the Loweswater catchment and estimated average concentration of total phosphorus (TP) in runoff draining each land cover type.

Land cover type	Area (km ²)	TP (mg P m^{-3})
High production grass	2.79	32
Broadleaved woodland	0.65	10
Coniferous woodland	0.35	10
Natural grass	1.39	5
Urban	0.12	56
Arable	0.03	17
Moors and heathland	2.29	7

2.4.3. Septic tank data

Phosphorus load from septic tanks was calculated from information on their number and location within the catchment as well as their condition, number of users, detergent usage and level of management. This information, gathered by an expert on waste management who lived locally, was obtained by interviewing householders, where applicable, or derived from average annual occupancy figures provided by the owners for visitor accommodation (Webb, 2010). Calculating the P losses from these systems involved the use of published data on average P levels in human waste and actual information on P levels in the detergents used by specific households. The opinion of the expert on waste management was used to estimate the level of P retention within each type of septic tank. A total of 20 septic systems were identified within the catchment serving a population equivalent of 59 people. Webb (2010) estimated that, of the 37.1 kg P y^{-1} that entered these systems as raw domestic waste, 31.4 kg P y^{-1} was discharged to soil-based soak-away in the form of treated effluent, 0.6 kg P y^{-1} was spread as sludge on land within the catchment and a further 5.1 kg P y^{-1} was exported from the catchment as sludge for disposal elsewhere. There are two potential fates for this phosphorus output, each included as a scenario. In a 'worst case' scenario phosphorus removal by the soil is assumed to be minimal and hence the septic tanks are acting as a point source. In an alternative scenario, diffuse phosphorus loss to water depends on the soil P-deficit (see 2.5.1).

Webb (2010) also suggests a 'most likely case' scenario, whereby the soil would retain about 35% of the P in the effluent. This would result in a likely P load to water from this source of approximately 26.4 kg P y^{-1} but this load was not included in the modelling.

2.4.4. Hydrological data

Daily hydraulic discharge data from Loweswater was required to validate the hydrological aspect of GWLF. Measured discharge values were not available for the period 2008–2009. They were, therefore, derived from the relationships between available discharge data from Loweswater (across the period 13 September 1999 to 5 July 2001) and contemporary flows measured at nearby Park Beck and Scale Hill (Fig. 3; R^2 values greater than 0.83, $P < 0.001$). Park Beck (National Grid Reference NY1513 2048) is the inflow to Crummock Water from the catchment that includes Loweswater. Scale Hill (National Grid Reference NY1490 2143) is the outflow from Crummock Water. Discharge from Loweswater for 2009 was estimated by averaging the discharge values simulated for the outflow from the Park Beck data and those simulated from the Scale Hill data.

2.4.5. Weather data

Other data required to parameterise GWLF included continuous daily rainfall data for the catchment for the period 1/1/2008 to 31/12/2009. These were compiled from records kept by a local resident and an automatic rain gauge at the southern end of the lake. Maximum and minimum air temperature data used in GWLF was collected at a weather station located on a water quality monitoring station situated over one of the deepest parts of the lake between December 2007 and February 2010. The water quality monitoring station also provided daily data on wind speed, air temperature and relative humidity used to drive the algal model PROTECH. Daily cloud cover from a met station 30 km to the south-east (Ambleside, the closest available) was also used to drive PROTECH.

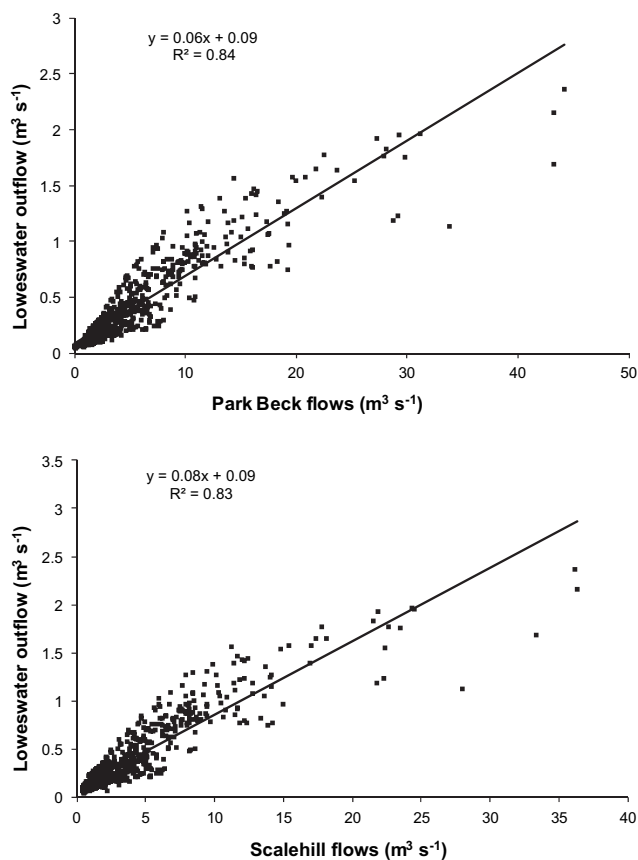


Fig. 3. The relationship between flows measured at Park Beck (upper panel) and Scale Hill (lower panel) and the outflow from Loweswater between September 1999 and July 2001.

2.4.6. Lake water quality data to validate the models

The automatic water quality monitoring station provided data on variation in water temperature with depth. Monthly samples collected during limnological surveys provided data on phytoplankton abundance expressed as chlorophyll *a* concentration (the main photosynthetic pigment), concentrations of key nutrients (i.e. soluble reactive phosphorus, nitrate and silicate) and phytoplankton composition and abundance. Water samples were based on an integrated sample collected from the upper 5 m of the water column.

2.5. Modelling

2.5.1. Scenarios

The models outlined in 2.3 were run as described below. The aim was to assess P-runoff from the catchment to the lake and its impact on water quality. It was decided that if the model was able to provide a good fit to water quality measures under current conditions, it could be used to test other land management scenarios in the catchment. The test for fit to 'current conditions' was labelled scenario 1 (S1). A further four scenarios were selected to reflect alternative land management options for the catchment. The scenarios were chosen in an attempt to provide the Loweswater community with an understanding of the extent to which farming *per se* impacts on water quality and to provide some information on how changing farming options may affect water quality. The non-farming scenarios represent two significant landscape changes, one to a wooded (deciduous) catchment in non-upland areas, i.e. the 'woodland' scenario (S2), and the other to a catchment in which all grassland received no inputs and supported no livestock, i.e. 'natural grassland' (S3). The latter scenario is a somewhat artificial one given the likelihood of long-term vegetation succession to eventual woodland, but provides an indication of nutrient inputs from a catchment that looks similar to current conditions (although without livestock). Scenarios 4, i.e. 'no cattle', double sheep (S4), and 5, i.e. 'double cattle', half sheep (S5), represent potential, though extreme, changes in the livestock composition of the catchment. These scenarios were less moderate than likely shifts in livestock composition would be, as it was considered that the models were unlikely to be sensitive to less significant shifts in stocking. Essentially, the scenarios influenced nutrient runoff values from catchment land cover entering GWLF.

As a result of uncertainty about how much phosphorus enters the watercourses from septic tanks, P from these sources was input to the GWLF model in two different ways; (1) as diffuse sources of nutrients with nutrient laden runoff generated by rainfall (i.e. with more runoff in wetter periods) (this is the default option) and (2) as point sources of nutrients with nutrient laden waste discharged into drainage channels at a constant rate (for this option scenarios are labelled with an addition A). In (1), P discharge from septic tanks was incorporated into the farm nutrient budget in the same way as other sources of nutrients such as animal waste and inorganic fertiliser and so output was controlled by the net P-balance for that land cover type (all septic tanks in the catchment are located on high production grassland). In (2), effluent was added as a direct and constant discharge to the watercourse. In the latter case, the worst case scenario was assumed, i.e. that all of the P in septic tank effluent would eventually make its way into a watercourse.

2.5.2. PLANET

Detailed data on imports or exports of animals, inorganic fertilisers, slurry and animal feedstuffs *per farm* were input to the 'farm gate' nutrient budgeting module of the PLANET software. From this information, PLANET derived an overall annual nutrient balance for each farm by calculating the differences between the amounts of P and N that entered the farm and the amounts that left the farm *via* an imaginary farm gate. A positive result from these calculations indicated a nutrient surplus on the farm, with imports of nutrients exceeding exports, while a negative value indicated a nutrient deficit. P surplus values were then further modified by subtracting the farm soil P deficit, as estimated from soil P measures (2.4.2, above) on each farm from the estimated 'farm gate' P surplus.

For the purposes of this project, the traditional measure of phosphorus used by agriculturalists (kg of P₂O₅), was converted to elemental P as commonly used by water managers by multiplying the value for kg of P₂O₅ by a factor of 0.44. This enabled direct conversion of the agricultural P surplus/deficit data to the units required to calculate driving data for GWLF. Once these calculations were complete, it was then assumed that any net surplus in the farm scale nutrient budget was potentially available to generate nutrient laden runoff to the lake; in contrast, any deficit in the farm level nutrient budget was taken to suggest that the amount of nutrient laden runoff would be negligible. Finally, it was also assumed that the farm nutrient surpluses and deficits could not be balanced across farms, because the majority of farms drained directly towards the lake shore or bordering streams rather than into neighbouring land. This approach reflects the best case scenario in relation to potential nutrient losses from farming activities within the catchment in that it assumes that best management practices are in place on each farm to reduce runoff from fertiliser applications and animal husbandry to a minimum. Nutrient losses from the catchment to the lake would be higher if this assumption is incorrect.

The model was originally run using the data collected by the agronomist (2.4.1 and 2.4.2) to reflect 'current conditions' in the catchment (S1) along with the two alternative septic tank scenarios described above (2.5.4). Nutrient runoff values for the 'no cattle' (S4) and 'double cattle' (S5) scenarios were generated by changing the number of animals within the PLANET management software and using the revised nutrient balances to create new nutrient export coefficients for farmland using the method of calculation outlined above.

2.5.3. GWLF

The hydrological part of the model had been calibrated in a previous lake modelling exercise using daily rainfall data, minimum and maximum air temperatures, and daily lake outflow data for a period between 1999 and 2001 (Maberly et al., 2006). Although the flow calibration in this modelling exercise was good ($r^2 = 0.8$), the P calibration was less good ($r^2 = 0.12$), with one particularly large data peak not predicted by the model. However, excluding this point, the average modelled daily load, 0.10 kg SRP d⁻¹ was only slightly more than the measured load, 0.07 kg SRP d⁻¹. The optimised hydrological parameters for the catchment were: precipitation correction factor = 1.01; snowmelt coefficient 0.4 cm °C d⁻¹; runoff recession coefficient 0.21 d⁻¹; soil water capacity = 10 cm; recession coefficient = 0.081 d⁻¹; slow recession coefficient = 0.015 d⁻¹; baseflow capacity = 2.24 cm. Outflow data for 2009 were generated from the calibrated version of GWLF using daily rainfall and air temperature data for the same period (Fig. 4b). In the absence of any measured outflow data, the modelled values for 2009 were validated against closely matched lake discharge data which were derived from flow records from the two adjacent monitoring sites, as described in 2.4.4 (Fig. 3). When all of the data were compared, the modelled data had a relatively low level of fit to the 'measured' data ($R^2 = 0.39$; $P < 0.01$, Fig. 4a). However, this was mainly due to two very high 'measured' values (i.e. those above 2 m³ s⁻¹). When these high flow events were excluded from the comparison, the level of fit for the remaining points improved ($R^2 = 0.63$; $P < 0.01$). The average discharge in 2009 was the third highest at Park Beck and the highest at Scale Hill compared to the ten-year period from 2000 to 2009.

The nutrient delivery part of the GWLF model was initially calibrated using monthly data on flows and nutrient concentrations obtained for the inflows compiled during a previous modelling exercise carried out between September 2004 and September 2005 (Maberly et al., 2006). These data took into account nutrient sources within the sub-catchments upstream of the sampling sites, which were situated very close to the lake. For the modelling exercise described here, the

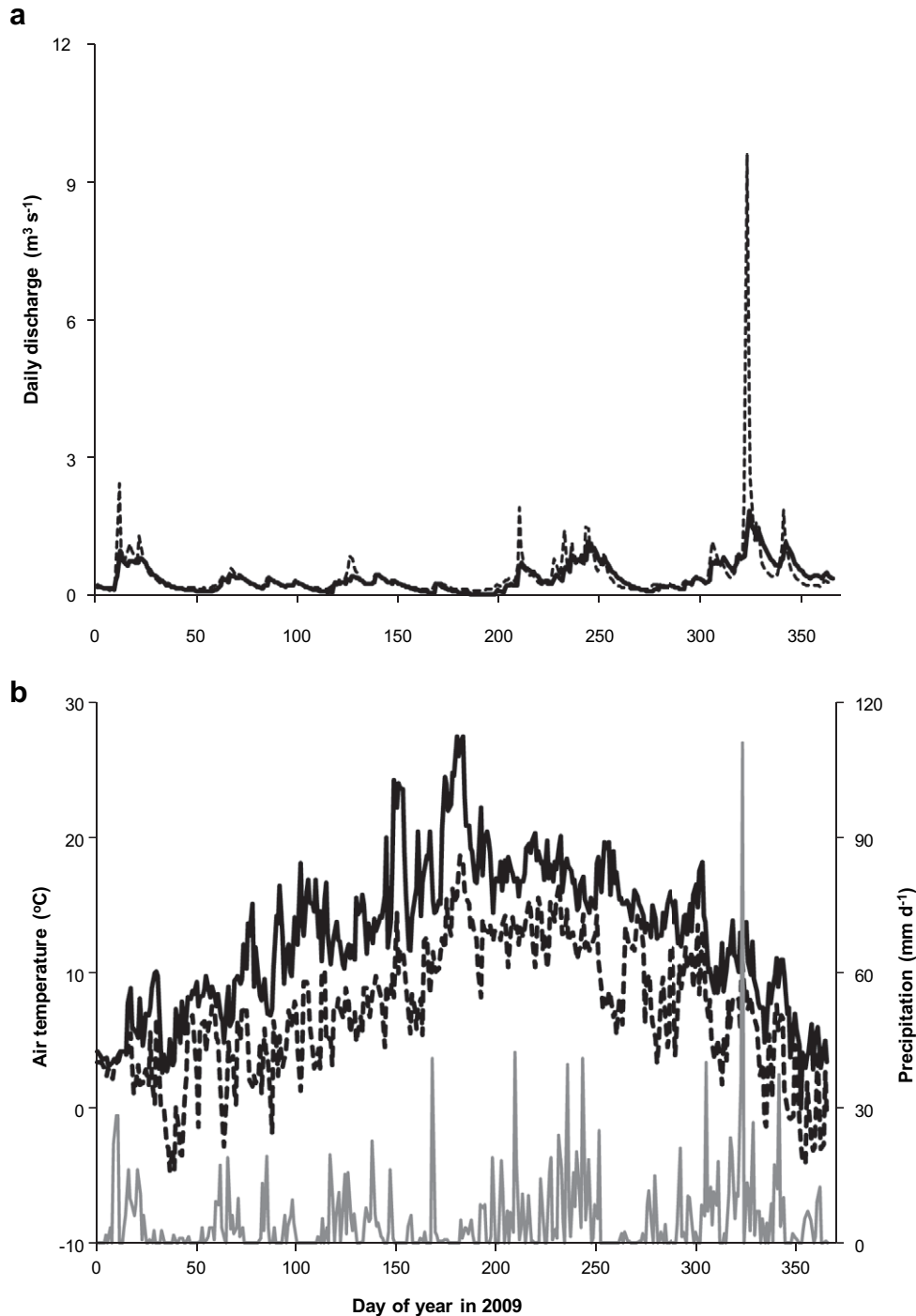


Fig. 4. a) Modelled (GWLF) (solid line), and measured (dashed line) discharge from Loweswater for 2009, b) Driving meteorological data used by GWLF for the same period. Maximum (solid line) and minimum (dashed line) air temperature and daily precipitation (grey line).

model was re-run for 2009 using relevant rainfall and air temperature data and information on potential nutrient sources within the catchment, including export coefficients for the total area of each land cover type (see 2.4.1, Table 1) (but excluding high production grass – covered by the PLANET outputs, 2.5.2) and the number and locations of septic tanks. Export coefficients for the managed land in the catchment (i.e. 32 mg P m^{-3}) were calculated by dividing the overall nutrient surplus for the farms within the catchment (as derived from PLANET) by the average annual runoff volume over the catchment in 2009 (i.e. about $18.2 \times 10^3 \text{ m}^3 \text{ ha}^{-1}$), after addition of the P loads from septic tanks (see 2.4.3).

The GWLF model was initially run for conditions in 2009 using nutrient runoff values generated by PLANET for the 'current conditions' scenario and the two different septic tank scenarios outlined above (scenarios S1 and S1A). Subsequent

model runs were carried out for each of the 4 land cover/use scenarios coupled with the two different septic tank scenarios. While the study was, primarily, focused on levels of P entering the lake (due to its previous identification as the 'limiting' nutrient for algal growth), daily nitrate and silica concentrations and lake discharge values were also simulated by GWLF for input into PROTECH.

2.5.4. PROTECH

PROTECH was used to simulate the development of the phytoplankton population in Loweswater in 2009. The simulations were driven by daily meteorological measurements (see 2.4.5) and daily nutrient concentrations and discharge values generated by the GWLF (above). Eight algal types were selected for the simulation representing the most common genera in the algal count data from the limnological

surveys during 2009 (see 2.4.6 above). These were the diatoms *Asterionella*, and *Aulacoseira*, the green alga *Chlorella*, the cryptophyte *Plagioselmis*, the chrysophyte *Dinobryon*, and the cyanobacteria; *Anabaena*, *Planktothrix* and *Aphanizomenon*. As monthly measurements of algal biomass (expressed as chlorophyll *a* concentration) and species level count data were available for 2009, a simulation was run for this period using the nutrient concentration and flow data generated by GWLF for conditions in 2009 under the 'current conditions' (S1) scenario (see 2.5.1). The PROTECH output was validated against these observations (see 3.4).

Using this validation as a baseline, the model was re-run using GWLF output for each of the other nutrient loading scenarios (see 2.5.1). For all scenarios, including 'current conditions', PROTECH was run for two consecutive years by simply repeating the driving data for the second year. The rationale for doing this was that the baseline simulation for 2009 had been initialised to reproduce the actual starting conditions for that year (i.e. those for early January) in terms of nutrient concentrations in the lake. By running the model for two years for each scenario, PROTECH was able to run down this initial nutrient supply and generate a new and more realistic baseline starting value for the beginning of the second year. For example, the 'woodland' (S2) and 'natural grassland' (S3) scenarios had greatly reduced loads compared to the 'current conditions' scenario (S1), which would not be correctly reflected in the model output at the start of the year if the starting values had been those for the current situation, i.e. S1.

3. Results

3.1. Catchment land use

Improved grassland comprised about 37% of the catchment area with moorland, heathland and natural grassland making up a further 48% (Table 1). Woodland comprised 13% of the catchment area and less than 1% was arable. The survey of the eight farms showed variation in farm size, areas of high production grass and rough grazing, and total livestock units on farmland within the catchment (Table 2). High production grass comprised between 38% and 100% of farm area, with livestock density varying between 0.2 and 1.4 livestock units per hectare.

3.2. Farm nutrient balance from PLANET

For the majority of the farms, P was in limited supply and most farms were found to be running a small P deficit in terms of maximising their productivity (Table 2). The exception was Farm 4, which generated a P surplus of about 197 kg P y⁻¹. Overall the total loss of P from all improved grassland in the catchment was equivalent to 0.56 kg ha⁻¹ y⁻¹. This situation is reflected in the 'current conditions' scenario S1 of the catchment management options evaluated.

3.3. Nutrient loads

Annual P runoff values predicted by GWLF for the various scenarios ranged from 22 to 378 kg P y⁻¹, or 0.029–0.5 kg ha⁻¹ y⁻¹ (Fig. 5). Seasonal variation in the pattern of P delivery to the lake for scenarios S1 to S5 is shown in Fig. 6. If P from septic tank discharges were included as point sources, and therefore not susceptible to

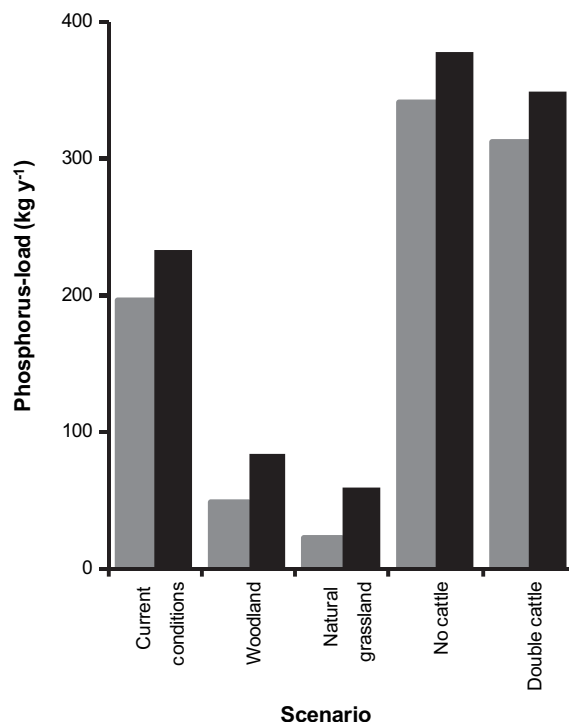


Fig. 5. Annual phosphorus runoff values predicted by GWLF for the scenarios tested, grey bars represent septic tanks as diffuse sources, black bars represent septic tanks as point sources.

uptake in the soil of farms with a net P-deficit, the daily loads shown in Fig. 6 would increase by 0.09 kg d⁻¹ (33 kg y⁻¹) for each scenario.

3.4. PROTECH validation

Using the GWLF nutrient input data from the current conditions scenario (S1) as a driver, PROTECH was used to simulate the development of the phytoplankton population in 2009. This simulation was compared to the observed phytoplankton data to test whether PROTECH was capturing the key changes in algal biomass over the year. The overall pattern of change in total chlorophyll *a* concentration was reproduced reasonably well (Fig. 7; R² = 0.53, P < 0.01), although biomass in the late summer tended to be overestimated. The algal count data were used to estimate the proportion of the observed total chlorophyll *a* that was made up of cyanobacteria and this estimate was compared to that produced by the cyanobacteria in PROTECH. Again, the model captured the seasonal dynamics and produced a good fit to the observed values

Table 2

Summary of farm level land use and animal stocks, annual phosphorus (P) budget based on output from PLANET, soil P deficit values, estimated P losses from septic tanks situated on farms and net P surplus.

Farm no.	High production grass (ha)	Rough grazing (ha)	Total livestock units	Surplus P (kg y ⁻¹)	Soil P deficit (kg y ⁻¹)	P from septic tanks (kg y ⁻¹)	Net P surplus (kg y ⁻¹)
1	32	30	56	134	375	3.1	0
2	121	85	187	177	1652	5.3	0
3	12	20	14.5	-1	183	7.1	0
4	27	53	64	356	161	2.0	197
5	43	26	13	63	101	3.6	0
6	32	0	32	147	447	1.2	0
7	38	59	55	290	416	3.4	0
8	46	20	91	138	552	0.0	0
Total	350	293	512.5	1306	3887	25.7	197

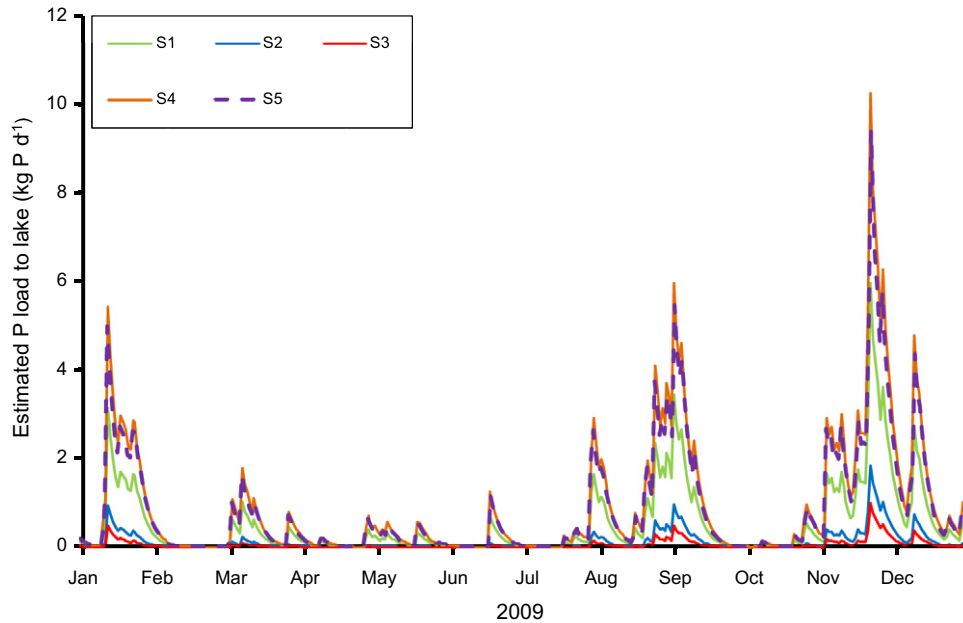


Fig. 6. Seasonal variation on phosphorus (P) delivery to the lake resulting from the different scenarios tested.

(Fig. 7; $R^2 = 0.64$, $P < 0.01$). The predicted annual mean in-lake chlorophyll *a* concentration of 8.9 mg m^{-3} accorded well with the observed annual means for 2008 and 2009, i.e. $9.0 \text{ mg chlorophyll } a \text{ m}^{-3}$ and $9.6 \text{ mg chlorophyll } a \text{ m}^{-3}$, respectively.

3.5. PROTECH scenario results

The results of running PROTECH for the different catchment management scenarios are presented as simple metrics from the second year outputs, namely annual mean concentrations of total chlorophyll *a* and of cyanobacterial chlorophyll *a*. Comparing these annual mean chlorophyll *a* metrics across the scenarios, it was clear that some scenarios produced markedly different results to those generated by the 'current conditions' scenario (S1; Fig. 8). Scenarios 'woodland' (S2) and 'natural grassland' (S3) show very low levels of both P and N input to the lake predicting a sharp decline in both total chlorophyll *a* and cyanobacterial chlorophyll *a* concentrations which results in a greater than 66% decrease in the former metric and a reduction of over 80% in the latter. At these low nutrient levels, and for 'natural grassland' (S3) in particular, chlorophyll

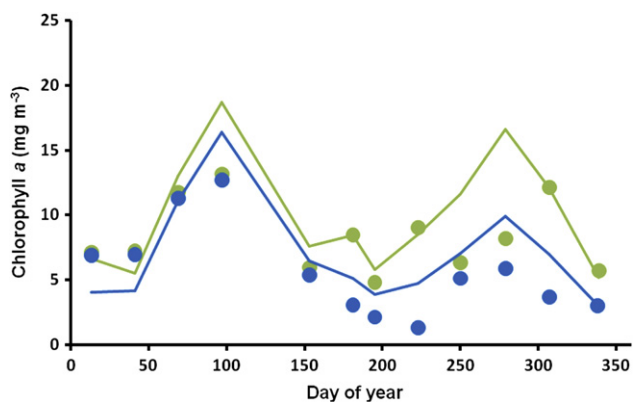


Fig. 7. Measured (filled circles) and modelled (solid line) total (light grey) and cyanobacterial (dark grey) chlorophyll *a* concentrations for 2009. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

a production in the lake is particularly sensitive to the inputs from septic tanks as point sources, where P reaches the lake directly. The 'no cattle' (S4) and 'double cattle' (S5) scenarios produced a much smaller change in these annual means, particularly for total chlorophyll *a* compared to the 'current conditions' scenario (S1) because P-loads are already high. This suggested that other factors than P load (e.g. light, non-phosphorus nutrients) were restraining the total phytoplankton carrying capacity of the lake under these conditions.

The relationship between annual mean total algal chlorophyll and cyanobacterial chlorophyll *a* and total annual mean load of SRP followed a regular pattern and so can be used to estimate the response of the lake to other SRP loads. In the case of mean total chlorophyll *a*, this response was best described by a logarithmic curve described by Eq. (1) with standard errors in parentheses:

$$y = 3.67(0.29)\ln(x) - 10.20(1.49) \quad (R^2 = 0.95, P < 0.001) \quad (1)$$

where y = chlorophyll *a* concentration (mg m^{-3}) and x = SRP load (kg P y^{-1}). The response for cyanobacterial chlorophyll *a* increased linearly with SRP load over the range of loads used here, as described by Eq. (2):

$$y = 0.028(0.002)x + 0.029(0.37) \quad (R^2 = 0.98, P < 0.001) \quad (2)$$

These relationships make it possible to assess the differential responses of the lake algae to altering nutrient loads. Hence, if the 'best case' scenario in relation to potential nutrient losses from farming activities within the catchment referred to above (2.5.2) is inaccurate and nutrient losses from the catchment are greater than estimated, the resultant algal growth can be predicted from the relationship in Fig. 8. The empirical logarithmic response curve used here suggests a negative concentration of chlorophyll *a* at a zero phosphorus load. A power curve, that fitted the data slightly less-well, gave a small positive concentration of chlorophyll *a* at a zero load. This suggests that the response of phytoplankton chlorophyll *a* to low phosphorus loads is not well-defined and more simulations at this range of the load range would be needed to reduce the uncertainty.

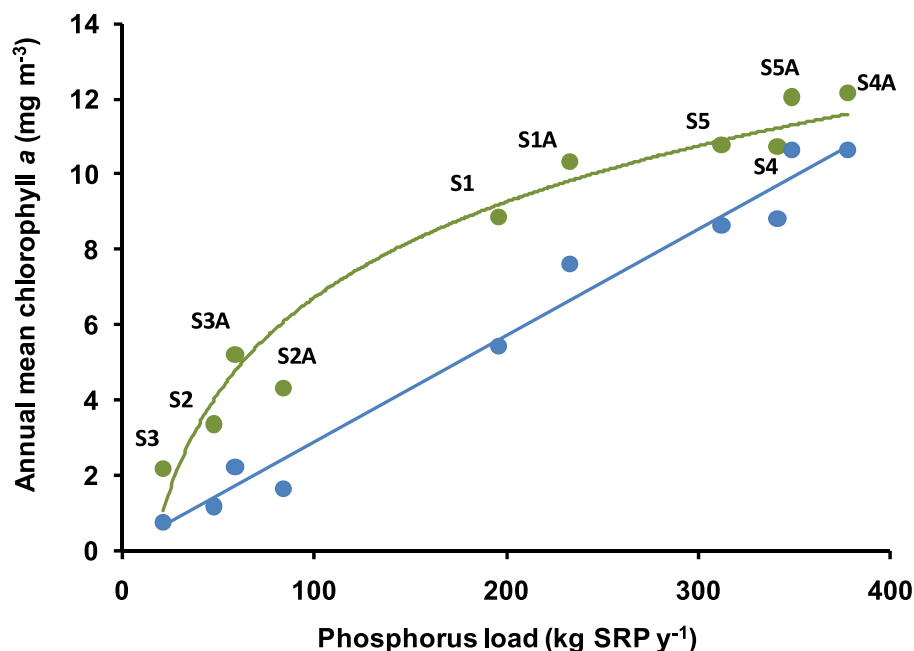


Fig. 8. Annual mean in-lake total (green circles) and cyanobacterial (blue circles) chlorophyll *a* concentrations resulting from changes in the soluble reactive (bioavailable) phosphorus (P) load to the lake under the various catchment management scenarios. The scenario for each blue circle is the same as that for the green circle vertically above it. S1 – ‘current conditions’, S2 – ‘woodland’, S3 – ‘natural grassland’, S4 – ‘no cattle’, S5 – ‘double cattle’. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The measurements and modelled ‘current condition’ scenario place Loweswater within the ‘moderate’ category (Carvalho et al., 2006) under the EU Water Framework Directive (European Union, 2000), requiring a programme of measures to be introduced to improve water quality. Fig. 8 suggests that the current load of SRP would need to be halved to achieve ‘Good’ ecological status, while removing high intensity farming altogether (as in scenarios S2 ‘woodland’ and S3 ‘natural grassland’) would enable the lake to reach the ‘High’ category. In contrast, significant changes in livestock densities (‘no cattle’ (S4) and ‘double cattle’ (S5)) could push the lake towards ‘Poor’ ecological status.

A final metric extracted from the PROTECH simulations was the number of days per year when the concentration of cyanobacteria exceeded a particular threshold. A value of 10 mg m⁻³ chlorophyll *a* is relevant, as this has been defined by the World Health Organisation (Chorus and Bartram, 1999) as the threshold above which there is a risk to health. Under ‘current conditions’ (S1), cyanobacterial chlorophyll *a* exceeded this threshold on 28 days a year but under the ‘woodland’ (S2) and ‘natural grassland’ (S3) (and both septic tank scenarios) this threshold was not exceeded. In contrast, the scenarios in which SRP load was increased caused a dramatic increase in the numbers of days of exceedance to about 150 and 190 days for ‘no cattle’ (S4) and ‘double cattle’ (S5), (and both septic tank scenarios), respectively. This would have serious consequences not only for the ecology of the lake but also for the local economy due to its negative impact in terms of tourism and amenity value.

4. Discussion

4.1. Model results

This work was undertaken in an attempt to inform farmers and landowners in the Loweswater catchment (the Loweswater community) about the possible impacts of nutrients from farming

activities and household waste on lake water quality. As the work was part of an integrated approach to catchment management the aim was to involve local expertise alongside scientific expertise to maximise the accuracy of the data and make the modelling directly relevant to the Loweswater community. Similar modelling approaches elsewhere have been recognised as important tools for facilitating collaborative learning (Metcalf et al., 2010). At Loweswater, the modelling approach succeeded in both engaging with local expertise and demonstrating the connection between land use in the catchment, and the occurrence of cyanobacterial blooms in the lake. The finding that potentially only one farm was the cause of P loss to the lake is discussed further below.

The use of scenarios provided the Loweswater community with information about how different land use options are likely to affect lake water quality. Of key importance in the English Lake District, is farming, which while economically marginal, has important cultural implications for landscape structure and accessibility, as well as its aesthetic qualities. The ‘woodland’ and ‘natural grassland’ scenarios were included in the study to indicate the ‘cost’ (social, economic, aesthetic, etc.) of achieving good water quality in a P-limited lake such as Loweswater. These scenarios provide a contrast with the water quality cost of current farming management as seen in S1. The no cattle’ (S4) and ‘double cattle’ (S5) scenarios represented potential management scenarios for the catchment that could arise as a result of, for example, shifts in global market prices for animal production. Both of these scenarios indicated a further deterioration in water quality from the current status, with an associated distinct increase in the relative importance of cyanobacteria within the algal community.

Exposure of the community to the modelling work formed part of the approach towards community-led integrated catchment management. Awareness of pollution issues was already relatively high among the Loweswater community as a result of 1) a previous farmer-led initiative to address lake pollution (which included limiting access of livestock to water bodies and improvements in

slurry tanks, yard water management and septic tanks) and 2) exposure to scientists and institutions concerned with pollution through this project and the previous one associated with the farmer led initiative in the catchment. However all residents (including farmers and non-farmers) had a stake in the modelling by virtue of the inclusion of septic tank information alongside farm management inputs and there was general enthusiasm to see the results. Having already seen the raw data collected by the agricultural consultant, which indicated that most farmers in the catchment were managing land with a P deficit, the community were not surprised to find that land management practices on only one farm in the catchment were resulting in P loss. Losses from septic tanks were clearly less important than agricultural losses overall but the community felt that they provided some scope for improvement without major effects on livelihoods.

Since farmers were promised anonymity when interviewed about their farm management practices (helping to ensure that accurate data were provided reflecting real practices) the identity of the farm/farmer losing P was not disclosed publicly. However, the farmer in question was alerted to the issue and immediately responded by decreasing inputs of P via fertiliser application. Interestingly, as the project has proceeded, and the community project (see Tsouvalis and Waterton, submitted for publication) has matured, farmers have become increasingly confident about the public airing of management information. This is most likely the result of increased understanding within the community about how farmers manage their farms and the constraints under which they operate. Having been exposed to the modelling results, farmers have expressed interest in the impact of a conversion to organic farming in the catchment as a potential scenario which may be explored in future work. It should be noted that presentations of the modelling results to the community always included references to potential uncertainties in the results (as discussed below). It was stressed that although the PLANET outputs fitted well to P levels in the lake, the finding that P loss were entirely due to practices on just one farm was subject to error as a result of those uncertainties.

4.2. Modelling approach

This study is unique in attempting to link algal growth in a lake to farm and septic tank management data at a catchment scale. However, a large body of work exists that attempts to link land management practices to P losses from diffuse sources and their ecological effects on water bodies (e.g. Kronvang et al., 2009). Linking field scale models to catchment scale outcomes is the holy-grail of nutrient research (McDowell and Nash, 2007) because of the uncertainties that surround the quality, appropriateness and scale of the data available and the lack of mechanistic understanding of the processes involved (Heathwaite et al., 2007). This study uses a conceptually simple approach of 1) measuring nutrient surplus in the catchment, 2) using a hydrological model to estimate the flow of nutrients to the lake in the catchment, and 3) predicting algal growth in response to nutrient levels. Despite the linking of different models which themselves simplify reality, the results of the modelling exercise are plausible. The validation data for modelled algal populations compared to measurements give R^2 values at the higher end of the range of algal models (Arhonditsis and Breet, 2004).

This is not the only study to link models (including GWLF and a similar algal model) to investigate algal production in lakes. A recent study investigated the impacts of climate scenarios on lakes (Markenden et al., 2010). However, in general catchment level studies are carried out by hydrologists focused on the water environment, at the expense of ecological and social aspects of catchments (Jakeman and Letcher, 2003). Increasingly the need for

studies which address the wider aspects of catchment management and involve local communities in understanding and managing their catchments is being advocated. This has resulted in the recognition of the need for making the complex simple (White et al., 2010) and finding ways of engaging successfully with land managers in order to affect behaviour (Roberts et al., 2009). The use of the PLANET model in this study sought to address the issue of widespread applicability and ease of use. Similarly in Australia, (Roberts et al., 2009) trialled software to aid farmers with catchment management which incorporated a tool called the Farm Nutrient Loss Index (FNLI) designed to help farmers assess the risk of nutrient loss. In Oklahoma, USA, modellers used Pasture Phosphorus Management Plus as a simple user-friendly P-loss prediction tool (White et al., 2010). Use of PLANET is widespread among farmers and training readily available in the UK, although for reasons of expediency in this study an agricultural consultant provided an intermediary between farmers and the researchers.

We believe that the use of the agricultural consultant (previously known to farmers in the catchment) helped both to improve data quality as well as to increase confidence in the modelling process among land-owners. The same process carried out by a non-expert would have required far greater input from farmers (in terms of explaining agricultural terms) and may well have left farmers with concerns about the extent to which their data would be correctly interpreted. The agricultural consultant, with years of soil sampling experience, was also responsible for soil sampling on managed land. It was important that data collection on farms was generic, practicable and meaningful for the farmers as the use of expertise readily available to farmers was integral to the modelling approach taken. Land management decisions by farmers are based on information and expertise which they can readily access and have to be in an appropriate format. Further development of this approach would ensure that the raw data could be provided directly by farmers as well as minimising the uncertainties described below.

4.3. Uncertainty

Uncertainties in the linked models are balanced by high levels of expertise, both local and scientific, used to acquire detailed data at the catchment scale, including everything from local weather data (buoy and in-catchment rainfall gauges) to detailed land cover and farm management information. However, as is almost always the case, not all data required by the models were available at the necessary temporal and spatial scales. For example, it would have been better if actual outflow discharge data for Loweswater had been available minimising errors introduced by simulating the discharge from adjacent sites. Ideally, stream nutrient data would have been collected at a higher frequency than the calibration points used here as well as during the period of the project to provide a better comparison for modelled loads from GWLF. The uncertainty of flow and nutrient data make it difficult to assess goodness of fit due to the difficulty in quantifying that uncertainty. However, where data for comparison are available, (i.e. discharge simulated from meteorology and modelled and simulated phytoplankton) goodness of fit measures indicate significant ($P < 0.01$, $P < 0.001$) fits between model and observations. In part, this may result from the scale of interest. While we used daily data for the hydrology and nutrient loads, the final desired output was an annual average concentration of chlorophyll *a* and chlorophyll *a* produced by cyanobacteria. As a result, errors in timing of events are averaged out and do not affect the overall amount of phytoplankton produced. Furthermore, Loweswater has an unusually long average retention time for a small lake (about 200 days), so

day-to-day variation in hydraulic discharge and nutrient load will be 'buffered' by the water and nutrients already in the lake.

It is acknowledged that the use of three separate, linked, models to apportion spatially the impacts of different nutrient sources on lake water quality, introduces the potential for propagating errors at each step, particularly given restrictions in available observed data. A limitation of taking a simplistic off-the-shelf model like PLANET, designed to aid farm management is that it is not designed to provide uncertainty as part of its' output or take into account the importance of factors such as connectivity between potential P sources on land and water bodies. In order to improve the approach it may be necessary to consider the use of a model with an explicit connectivity component. Nutrient budgeting models are designed to provide an output which enables the farmer to make decisions about management options, as in Roberts et al. (2009), except in the case of PLANET, the model is designed to optimise nutrient levels from an agricultural productivity perspective (although see below). In reality it is likely that there are uncertainties around the loss of P from the land, as estimated by the PLANET model, including the assumptions that 1) best management practices are in place on each farm to reduce runoff from fertiliser applications and animal husbandry to a minimum and 2) soils are in P-equilibrium and will lose P immediately they reach saturation and, conversely, retain P when in deficit. The former (1) is unlikely to be the case but would require detailed evaluation beyond the scope of this study. Inadequate slurry storage facilities, inappropriate timing or location of slurry/fertiliser spreading and extreme rainfall events are all likely to play a role in P-loss. The latter (2) reflects a mis-match between levels of P that are appropriate agriculturally and levels of P that lead to a loss to water bodies.

PLANET recently underwent a development that included new calculation modules to help farmers comply with the Nitrate Vulnerable Zone action Programme Regulations; that came into force within the UK on 1st January 2009, recognising the importance of land management impacts on water quality as well as farm economy. It may be that this needs to be extended further to capture P issues, although relatively little is known about the relationship between P-indices related to agricultural productivity (in the UK) and P-loss to soil. The relationship between agricultural P index and P indices describing the risk of diffuse P loss (Sharpley et al., 2003; White et al., 2010) may be critical for understanding the links between good agricultural and ecological management of fields and the ecosystem services/dis-services that they provide. For farmers, a simple index describing optimal P levels for maximised productivity and minimised P-loss is required.

Despite its recognised importance in rural areas (Withers et al., 2009) the inclusion of septic tank information in nutrient delivery models is not widely supported in catchment models. An exception to this is the SWAT model (Arnold et al., 1998) which includes data on septic tank condition alongside environmental information affecting the performance of septic tanks. The SWAT model is designed to work on large complex watersheds where the provision of such information would either require estimation or sub-sampling. Due to the small scale of Loweswater and the existence of the wider catchment management project far greater engagement and data access was possible than would be the case in a large catchment. The process of elicitation by a trusted expert in the field, who was also resident in the catchment, engaged individuals in the work, highlighted the relevance of it to their practices and may itself have been a motivation for changing practices. For example, the waste management expert was able to advise locals on appropriate P-free dishwasher detergents. Although the modelling does not include the 'most-likely case' septic tank scenario suggested by Webb (2010) (see Section 2.4.3) the use of two extreme scenarios indicate the range within which this case is most likely to

lie.. In general, lack of work in this area results in uncertainty surrounding the loss of P from septic tanks to water bodies, but factors such as location, including connectivity to water bodies, soil type and water-table depth are likely to have an impact. Further work in this area is required as there are little data available, either on the effectiveness of septic tank functioning (for different types) or the movement of nutrients from them into water bodies.

5. Conclusion

The development of this modelling approach formed part of a project seeking to identify the potential for bottom-up community catchment management and to promote the engagement of scientists with local and institutional stakeholders. As a result, the approach has used detailed scientific and local expertise on social, ecological and hydrological aspects of the catchment to develop a unique tool that links land management activities to algal growth in Loweswater. While it is important to stress the limitations of the models used and the potential importance of unquantified issues, such as extreme events, this approach provides an accessible way of demonstrating links between land management and water quality in small rural catchments. In this catchment, as elsewhere, understanding the human dimension is key to understanding and managing harmful algal blooms (Bauer et al., 2010).

Acknowledgements

This study was funded by the Joint Research Councils UK through its RELU programme as part of the 'Testing a Community Approach to Catchment Management' project. We thank the Environment Agency for granting us access to their hydrological data and to CEH staff (Jack Kelly, Mitzi De Ville, Ben James, Janice Fletcher and Heidrun Feuchtmayr) for monitoring data and to Martin Rouen (Lakeland Instrumentation) for invaluable help with data telemetry from the automatic monitoring station. We thank John Rockcliffe from Mitchell's Farm and Environment Consultancy and all of the landowners and farmers in the Loweswater catchment for providing information on land management and septic tanks. Particular thanks to Ken Bell (farmer and local researcher on the RELU project) for providing us with rainfall records for the catchment. We are also grateful to the New York City Department of Environmental Protection for allowing us to use their version of the GWLF model on the Loweswater catchment and to ADAS for the use of the PLANET software.

References

- Andersson, L., Olsson, J.A., Arheimer, B., Jonsson, A., 2008. Use of participatory scenario modelling as platforms in stakeholder dialogues. *Water SA* 34, 439–447.
- Arhonditsis, G.B., Breet, M.D., 2004. Evaluation of the current state of mechanistic aquatic biogeochemical modelling. *Marine Ecology-Progress Series* 271, 13–26.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment: Part I. Model development. *Journal of the American Water Resources Association* 34 (1), 73–89.
- Barnes, A.P., Willock, J., Hall, C., Toma, L., 2009. Farmer perspectives and practices regarding water pollution control programmes in Scotland. *Agricultural Water Management* 96, 1715–1722.
- Bauer, M., Hoagland, P., Leschine, T.M., Blount, B.G., Pomeroy, C.M., Lampl, L.L., Scherer, C.W., Ayres, D.L., Tester, P.A., Sengco, M.R., Sellner, K.G., Schumacker, J., 2010. The importance of human dimensions research in managing harmful algal blooms. *Frontiers in Ecology and the Environment* 8 (2), 75–83.
- Bennion, H., Appleby, P., Boyle, J., Carvalho, L., Luckes, S., Henderson, A., 2000. *Water Quality Investigations of Loweswater, Cumbria*. Final report to the Environment Agency by University College London. 80pp.
- Blackmore, C., Ison, R., Jiggins, J., 2007. Social learning: an alternative policy instrument for managing in the context of Europe's water. *Environmental Science & Policy* 10, 493–498.

- Boix-Fayos, C., de Vente, J., Albaladejo, J., Martinez-Mena, M., 2009. Soil carbon erosion and stock as affected by land use changes at the catchment scale in Mediterranean ecosystems. *Agriculture Ecosystems & Environment* 133, 75–85.
- Bilotta, G.S., Krueger, T., Brazier, R.E., Butler, P., Freer, J., Hawkins, J.M.B., Haygarth, P.M., Macleod, C.J.A., Quinton, J.N., 2010. Assessing catchment-scale erosion and yields of suspended solids from improved temperate grassland. *Journal of Environmental Monitoring* 12, 731–739.
- Carey, P.D.W.S., Chamberlain, P.M., Cooper, A., Emmett, B.A., Maskell, L.C., McCann, T., Murphy, J., Norton, L.R., Reynolds, B., Scott, W.A., Simpson, I.C., Smart, S.M., Ulyett, J.M., 2008. Countryside Survey: UK Results from 2007.
- Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Diaz, S., Dietz, T., Duraiappah, A.K., Oteng-Yeboah, A., Pereira, H.M., Perring, C., Reid, W.V., Sarukhan, J., Scholes, R.J., Whyte, A., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. In: *Proceedings of the National Academy of Sciences of the United States of America*, vol. 106, pp. 1305–1312.
- Carvalho, L., Phillips, G., Maberly, S.C., Clarke, R., 2006. Chlorophyll and Phosphorus Classifications for UK Lakes, P. 81. Final report to SNIFFER (Project WFD 38).
- Chorus, I.B., Bartram, J., 1999. *Cyanobacteria in Water: a Guide to their Public Health Consequences, Monitoring and Management*.
- Collins, K., Blackmore, C., Morris, D., Watson, D., 2007. A systemic approach to managing multiple perspectives and stakeholding in water catchments: some findings from three UK case studies. *Environmental Science & Policy* 10, 564–574.
- Daily, G.C., Matson, P.A., 2008. Ecosystem services: from theory to implementation. In: *Proceedings of the National Academy of Sciences of the United States of America*, vol. 105, pp. 9455–9456.
- Defra, 2010. Fertiliser Manual (RB209), eighth ed. TSO (The Stationery Office). <http://www.defra.gov.uk/foodfarm/landmanage/land-soil/nutrient/documents/rb209-rev-100609.pdf>.
- de Lange, W.J., Wise, R.M., Forsyth, G.G., Nahman, A., 2010. Integrating socio-economic and biophysical data to support water allocations within river basins: an example from the Inkomati Water Management Area in South Africa. *Environmental Modelling and Software* 25, 43–50.
- Elliott, J.A., Irish, A.E., Reynolds, C.S., 2010. Modelling phytoplankton dynamics in fresh waters: affirmation of the PROTECH approach to simulation. *Freshwater Reviews* 3, 75–96.
- European Union, 2000. The European Water Framework Directive (2000/60/EC).
- Everard, M., 2004. Investing in sustainable catchments. *Science of the Total Environment* 324, 1–24.
- Haith, D.A., Shoemaker, L.L., 1987. Generalized watershed loading functions for stream flow nutrients. *Water Resources Bulletin* 23, 471–478.
- Haith, D.A., Tubbs, L.J., 1981. Watershed loading functions for Nonpoint sources. *ASCE Journal of Environmental Engineering* 107 (EE1), 121–137.
- Haygarth, P.M., 2005. Linking landscape sources of phosphorus and sediment to ecological impacts in surface waters. *Science of the Total Environment* 344, 1–3.
- Heathwaite, A.L., Johnes, P.J., 1996. Contribution of nitrogen species and phosphorus fractions to stream water quality in agricultural catchments. *Hydrological Processes* 10, 971–983.
- Heathwaite, A.L., Reaney, S., Lane, S., 2007. Understanding spatial signals in catchments: linking critical areas, identifying connection and evaluating responses. In: *Diffuse Phosphorus Loss: Risk Assessment, Mitigation Options and Ecological effects in River Basins. The 5th International Phosphorus Workshop (IPW5)*. Faculty of Agricultural Sciences, Silkeborg, Denmark.
- Herr, A., Kuhnert, P.M., 2007. Assessment of uncertainty in Great Barrier Reef catchment models. *Water Science and Technology* 56, 181–188.
- Hooper, B. (Ed.), 2005. *Integrated River Basin Governance*. IWA Publishing, London.
- Jakeman, A.J., Letcher, R.A., 2003. *Integrated assessment and modelling: features, principles and examples for catchment management*. *Environmental Modelling & Software* 18, 491–501.
- Kronvang, B., Rubaek, G.H., Heckrath, G., 2009. International phosphorus workshop: diffuse phosphorus loss to surface water bodies—risk assessment, mitigation options, and ecological effects in River basins. *Journal of Environmental Quality* 38, 1924–1929.
- Lane, S.N., Brookes, C.J., Heathwaite, A.L., Reaney, S., 2006. Surveillance science: challenges for the management of rural environments emerging from the new generation diffuse pollution models. *Journal of Agricultural Economics* 57, 239–257.
- Lowe, P., Phillipson, J., 2006. Reflexive interdisciplinary research: the making of a research programme on the rural economy and land use. *Journal of Agricultural Economics* 57, 165–184.
- Liu, S.A., Costanza, R., 2010. Ecosystem services valuation in China. *Ecological Economics* 69, 1387–1388.
- Maberly, S.C., Norton, L., May, L., De Ville, M., Elliott, A., Thackeray, S., Groben, R., Carse, F., 2006. An Investigation into the Potential Impacts of Farming Practices on Loweswater. http://www.lancs.ac.uk/fass/projects/loweswater/docs/Final_RDS_Report.pdf Report to the Rural Development Service and the National Trust. Report No. LA/C02707/4.
- Macleod, C.J.A., Scholefield, D., Haygarth, P.M., 2007. Integration for sustainable catchment management. *Science of the Total Environment* 373, 591–602.
- Markenden, H., Moore, K., Persson, I., 2010. Simulated lake phytoplankton composition shifts towards cyanobacteria dominance in a future warmer climate. *Ecological Applications* 20 (3), 752–767.
- May, L., Place, C.J., O'Malley, M., Spears, B., 2010. The Impact of Phosphorus Inputs from Small Discharges on Designated Freshwater Sites, Final report to Natural England and Broads Authority, 142 pp.
- McDowell, R.W., Nash, D., 2007. Quantifying diffuse phosphorus (P) losses to the farm/subcatchment scale: targeting methods and uncertainties for P loss mitigation. In: *Diffuse Phosphorus Loss: Risk Assessment, Mitigation Options and Ecological Effects in River Basins. The 5th International Phosphorus Workshop (IPW5)*. Faculty of Agricultural Sciences, Silkeborg, Denmark.
- MEA, 2005. *Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis*. <http://www.MAweb.org>.
- Metcalfe, S.S., Wheeler, E., BenDor, T.K., Lubinski, K.S., Hannon, B.M., 2010. Sharing the floodplain: mediated modeling for environmental management. *Environmental Modelling & Software* 25 (11), 1282–1290.
- Mitchell, B. (Ed.), 1990. *Integrated Water Management: International Experiences and Perspectives*. Belhaven Press, London and New York.
- Moore, K., Jennings, E., Allott, N., May, L., Jarvinen, M., Arvola, L., Tamm, T., Jarvet, A., Noges, T., Pierson, D., Schneiderman, E., 2010. Modeling the effects of climate change on the supply of inorganic nitrogen. In: George, Glen (Ed.), *The Impact of Climate Change on European Lakes*. Springer, London, pp. 179–198. 507p. (Aquatic Ecology Series, 4).
- Pierson, D., Arvola, L., Allott, N., Jarvinen, M., Jennings, E., May, L., Moore, K., Schneiderman, E., 2010. Modelling the effects of climate change on the supply of phosphate-phosphorus. In: George, Glen (Ed.), *The Impact of Climate Change on European Lakes*. Aquatic Ecology Series, vol. 4. Springer, pp. 139–159.
- Reynolds, C.S., Irish, A.E., Elliott, J.A., 2001. The ecological basis for simulating phytoplankton responses to environmental change (PROTECH). *Ecological Modelling* 140, 271–291.
- Roberts, A.M., Park, G., Melland, A.R., Miller, I., 2009. Trialling a web-based spatial information management tool with land managers in Victoria, Australia. *Journal of Environmental Management* 91, 523–531.
- Rockliffe, J., 2009. *Loweswater Catchment Management Project - Summary Agricultural Report For The Catchment*. University of Lancaster.
- Schneiderman, E., Jarvinen, M., Jennings, E., May, L., Moore, K., Naden, P.S., Pierson, D., 2010. Modelling the effects of climate change on catchment hydrology with the GWLF model. In: George, Glen (Ed.), *The Impact of Climate Change on European Lakes*. Aquatic Ecology Series, vol. 4. Springer, pp. 33–50.
- Schneidermann, E.M., Pierson, D.C., Lounsbury, D.G., Zion, M.S., 2002. Modeling of hydro-chemistry of the cannonville watershed with Genealized Watershed Loading Functions (GWLF). *Journal of the American Water Resources Association* 38, 1323–1347.
- Sharpley, A.N., Weld, J.L., Beegle, D.B., Kleinman, P.J.A., Gburek, W.J., Moore, P.A., Mullins, G., 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. *Journal of Soil and Water Conservation* 58, 137–152.
- Smith, L.P. and Porter, K., Management of catchments for the protection of water resources: drawing on the New York City watershed experience. *Regional Environmental Change*, in press.
- Steyaert, P., Jiggins, J., 2007. Governance of complex environmental situations through social learning: a synthesis of SLIM's lessons for research, policy and practice. *Environmental Science & Policy* 10, 575–586.
- Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K., 2007. Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecological Economics* 64, 245–252.
- Tsouvalis, J., Waterton, C. Framing the world another way: 'participation', 'experts', and 'expertise' in the Loweswater Care Project (LCP), Cumbria, UK. *Environmental Modelling and Software*, submitted for publication.
- Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. *Environmental Modelling and Software* 25, 1268–1281.
- Webb, L., 2010. *Survey of Local Washing Practices and Septic Tank Operation in relation to Domestic Phosphorus Inputs to Loweswater*, Report to the Loweswater Care Project, 17 pp.
- White, M.J., Storm, D.E., Busted, P.R., Smolen, M.D., Zhang, H.L., Fox, G.A., 2010. A quantitative phosphorus loss assessment tool for agricultural fields. *Environmental Modelling & Software* 25, 1121–1129.
- Withers, P.J.A., Jarvie, H.P., Hodgkinson, R.A., et al., 2009. Characterization of phosphorus sources in rural watersheds. *Journal of Environmental Quality* 38 (5), 1998–2011.