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Over-parameterised, uncertain 'mathematical marionettes' — How can we best use catchment water quality models? An example of an 80-year catchment-scale nutrient balance

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ABSTRACT

The Integrated Catchment Model of Nitrogen (INCA-N) was applied to the River Lambourn, a Chalk river-system in southern England. The model's abilities to simulate the long-term trend and seasonal patterns in observed stream water nitrate concentrations from 1920 to 2003 were tested. This is the first time a semi-distributed, daily time-step model has been applied to simulate such a long time period and then used to calculate detailed catchment nutrient budgets which span the conversion of pasture to arable during the late 1930s and 1940s. Thus, this work goes beyond source apportionment and looks to demonstrate how such simulations can be used to assess the state of the catchment and develop an understanding of system behaviour. The mass-balance results from 1921, 1922, 1991, 2001 and 2002 are presented and those for 1991 are compared to other modelled and literature values of loads associated with nitrogen soil processes and export. The variations highlighted the problem of comparing modelled fluxes with point measurements but proved useful for identifying the most poorly understood inputs and processes thereby providing an assessment of input data and model structural uncertainty. The modelled terrestrial and instream mass-balances also highlight the importance of the hydrological conditions in pollutant transport. Between 1922 and 2002, increased inputs of nitrogen from fertiliser, livestock and deposition have altered the nitrogen balance with a shift from possible reduction in soil fertility but little environmental impact in 1922, to a situation of nitrogen accumulation in the soil, groundwater and instream biota in 2002. In 1922 and 2002 it was estimated that approximately 2 and 18 kg N ha^{-1} yr^{-1} respectively were exported from the land to the stream. The utility of the approach and further considerations for the best use of models are discussed.

1. Introduction

Increased computational power and the availability of digitised datasets describing the topography, land cover, flow and water quality of river catchments has led to a new generation of semi-distributed, water quality models capable of daily-time step simulations over a period of 80 years (Jackson et al., 2007). These models are useful as they begin to simulate transient changes in the water quality at a temporal scale commensurate with the long-term projected changes in farming and climate whilst providing an estimate of the seasonal and extreme variations in flow and pollutant concentrations (Whitehead et al., 2006). The ability of these models to reproduce past environmental change has not yet

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been examined in detail nor has the output catchment mass-balance been inspected for a range of hydrological conditions and pollutant inputs. If a model can reproduce the observed response to a known environmental change then confidence (or otherwise) can be gained that the model structure and calibrated parameters are able to represent that, and future, changes. In the lowland UK, such a known change is the increase in cultivated land from 1930 to 1990 and the associated increase in the use of manufactured fertiliser which has led to a general increase in stream water nitrate concentrations (Johnes, 1999). As such, this paper describes the application of the *In*tegrated *Ca*tchment Model of *N*itrogen (INCA-N) to a lowland chalk river-system in southern England to test the model's ability to reproduce the response observed in stream water nitrogen concentrations to land management change. The model is applied at a daily time-step from 1920 to 2003 and used to examine the catchment mass-balance under different nitrogen inputs and hydrological conditions to understand how the mass-balance has evolved. The modelled process-loads are compared with literature values and other modelled results. The results are discussed in the context of the current issues of input data, model structural and parameter uncertainty, and catchment management.

Nitrate, the main form of nitrogen in lowland UK river-systems, is a key plant nutrient but the over-enrichment of river-systems with nitrate can lead to problems of eutrophication and reduced biodiversity (Heathwaite et al., 1993). The Cretaceous Chalk rivers of southern England are a major national resource providing water for drinking and agriculture. In these systems there are concerns regarding the growth of epiphytic algae which may suppress macrophyte growth (Neal et al., 2002). Moreover, they provide key trout fisheries and are species-rich in terms of plants, macro-invertebrates and fish (Department of the Environment, 1995a). Currently, in southern England, there are three main pressures on the quantity and quality of the water resource in rural catchments: abstraction which reduces the dilution capacity and flow velocity; nutrient inputs from sewage effluent disposal; and nutrient inputs from agricultural runoff. Climate change may also further compound the problems through reduced water availability for supply, reduced dilution of pollutant inputs and more intense events potentially flushing nutrients rapidly into the river. As such, there is a need to understand the transport, storage and fate of nitrogen in lowland river-systems which are subject to elevated stream water concentrations due to inputs from effluent, farming and atmospheric deposition. As a step towards this, it is useful to construct models of the different catchment nitrogen stores and pathways since this helps the identification of the key sources and determines when, where and for how long the excess nitrogen might enter the river network. Such information is essential for the effective management of nutrient losses and can refine hypotheses of how the system works posing further questions to be addressed through future experimental work and long-term monitoring (Wade et al., 2006).

INCA-N is a dynamic, process-based model capable of addressing the question of time-varying storage in different components of the catchment system in addition to providing an estimate of the annual instream inorganic-nitrogen load based on daily simulations of flow and stream water nitrate and ammonium concentrations (Whitehead et al., 1998; Wade et al., 2002a). It is possible to extract the estimates of the mass stored and transferred between the soil, groundwater and stream from the model. The model simulates the processes associated with the terrestrial and instream nitrogen cycles. The Lambourn was studied intensively under the LOwland CAtchment Research (LOCAR) initiative (Neal et al., 2004a,b; Wheater and Neal, 2006) and other contemporary studies (Prior and Johnes, 2002; Evans et al., 2004), and this is the reason why it was chosen as the study area. Specifically, this work has the following aims:

1. to calibrate INCA-N for the period 1920 to 2003 using the available long-term monthly measurements of stream chemistry and readily-available input data;
2. to calculate the mass-balances for 1921, 1922, 1991, 2001 and 2002 which cover a range of nitrogen inputs and hydrological conditions, and to compare the 1991 balance with other modelled mass-balances for the same year from the upper Kennet, which is adjacent to the Lambourn, and literature values;
3. to use the calculated mass-balance to understand how the nitrogen stores and pathways of Lambourn catchment have changed as a result of long-term changes in land cover and management;
4. to consider the advantages and problems of testing catchment-scale, dynamic models over long simulation periods covering known environmental changes and use these to propose guidelines for the best use of water quality models.

Organic nitrogen was not explicitly included in the mass-balance. Within the INCA-N model organic nitrogen is modelled as an unlimited store with mineralization and immobilisation rates that are modified by soil temperature and moisture (Whitehead et al., 1998; Wade et al., 2002a). Given the predominance of nitrate in the Lambourn and the uncertainty regarding the key factors and processes controlling organic nitrogen, this study focused on inorganic nitrogen.

2. Background

A water quality model is a set of equations used to describe the factors and processes that determine the instream concentrations or loads, or leaching rates if the model is applicable at the plot, field or sub-catchment scale (James, 1993; Chapra, 1997). Typically these models are coded as computer programs or spreadsheets and vary in complexity depending on the degree of process representation included (Lacroix et al., 2006). In this paper, for sake of brevity and clarity, only catchment scale models are considered though many water quality models exist that consider forest plots, fields, regions or instream systems only (Addiscott and Whitmore, 1987; Tietema, 2004; Cox, 2003). Catchment-scale models are required to test hypotheses regarding the complex interaction of all the factors and processes that control water quality. Such models are also required to provide assessments of the likely water quality response to environmental change and the costs of