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How well can we model stream phosphorus concentrations in agricultural catchments?

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ABSTRACT

Mechanistic catchment-scale phosphorus models appear to perform poorly where diffuse sources dominate. We investigate the reasons for this for one model, INCA-P, testing model output against 18 months of daily data in a small Scottish catchment. We examine key model processes and provide recommendations for model improvement and simplification. Improvements to the particulate phosphorus simulation are especially needed. The model evaluation procedure is then generalised to provide a checklist for identifying why model performance may be poor or unreliable, incorporating calibration, data, structural and conceptual challenges. There needs to be greater recognition that current models struggle to produce positive Nash–Sutcliffe statistics in agricultural catchments when evaluated against daily data. Phosphorus modelling is difficult, but models are not as useless as this might suggest. We found a combination of correlation coefficients, bias, a comparison of distributions and a visual assessment of time series a better means of identifying realistic simulations.

1. Introduction

Within the European Union (EU), the Water Framework Directive (WFD) requires all water bodies to be at 'Good' ecological status by 2015. As part of this, decreases in soluble reactive phosphorus (SRP) concentrations are needed in many lakes and rivers across Europe. Improved waste water treatment has led to significant reductions in SRP concentrations, but non-point sources also need addressing. These may include inputs from septic tanks and agricultural activities, and provide a great challenge to water and land managers. Loadings from diffuse inputs are often poorly constrained, measures aimed at reducing them tend to be complicated to implement, and there is great uncertainty around both the timing and magnitude of any in-stream effects of decreasing diffuse loads (Jarvie et al., 2013).

Catchment and reach-scale nutrient models can help us to explore some of these uncertainties. Models are a means of formalising current knowledge, and if shown to adequately capture system behaviour, they can be used to highlight gaps in our understanding of catchment processes, to help set appropriate water quality and load reduction goals, to explore means of achieving those goals, and to look at potential water quality responses to scenarios of changing land use and climate. Nutrient models range in complexity from simple steady state empirical models to highly parameterised, dynamic, process-based models. Models from the latter group are frequently used where response times and lags form part of the research question and for assessing scenarios of future conditions. Results from such modelling exercises may inform catchment management, for example what measures to prioritise spending on within a river basin.

Process-based phosphorus (P) models appear to perform acceptably where point sources provide the dominant P input, but performance is substantially poorer where diffuse sources dominate (e.g. Dean et al., 2009; Wade et al., 2007a). The poor performance of mechanistic P models in rural catchments is not a topic that has received widespread recognition in the literature. This is a major source of concern, particularly when these models are used to inform water management and policy decisions.

In this study, we assess the performance of INCA-P (the INtegrated CAtchment model of Phosphorus dynamics; Wade et al., 2007b, 2002b) in a diffuse pollution dominated catchment. INCA-P is just one of many mechanistic catchment phosphorus models,

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but it is fairly representative and commonly used. It includes the major terrestrial and in-stream processes affecting the transport of water, sediment and phosphorus to and within a waterbody. To date, the model has been applied to investigate waterbody responses to scenarios of future land use and climate and to assess the effectiveness of measures to reduce P inputs (e.g. Couture et al., 2014; Crossman et al., 2013; Farkas et al., 2013; Starrfelt and Kaste, 2014; Wade et al., 2002c; Whitehead et al., 2013).

The specific aims of the study are to: (1) use a daily water chemistry dataset to test INCA-P's ability to simulate in-stream dissolved and particulate P concentrations in a rural catchment, where diffuse agricultural P inputs dominate; (2) investigate which processes the model captures well and identify areas where improvement and simplification could be made. This includes examining the sensitivity of the model to different representations of the system. We then raise the more general question of whether we are expecting too much from the current generation of mechanistic P models, and whether we are using the right metrics to assess model performance. The process of assessing and critiquing model structure and assumptions, underlying data and calibration method is then generalised to provide a checklist for assessing why environmental models may underperform. Finally, the usefulness of mechanistic P models is discussed in relation to these findings. This paper includes the first description of a full INCA-P parameter set since a major model re-write in 2007.

2. Description of the INCA-P model

INCA-P provides a process-based representation of the transport of sediment and P from catchments to streams and down the river channel. The model is ‘semi-distributed’: the main stem of a catchment is split into reaches with associated sub-catchments (Fig. 1). Each sub-catchment is then split into land cover types; these are functional units, which should have similar phosphorus inputs, plant uptake, soils and slopes. In practice, they tend to be based on land use, given the important differences in fertilizer and manure inputs between different land use classes. Within each sub-catchment the flow of water, sediment and nutrients is calculated for each land use type and summed to give the overall input to the associated reach. Inputs from each sub-catchment are then added sequentially down the river network. This spatial set-up makes for relatively fast run times, but the hydrological connectivity of the landscape is not modelled as it is in fully distributed approaches such as PSYCHIC (Davison et al., 2008).

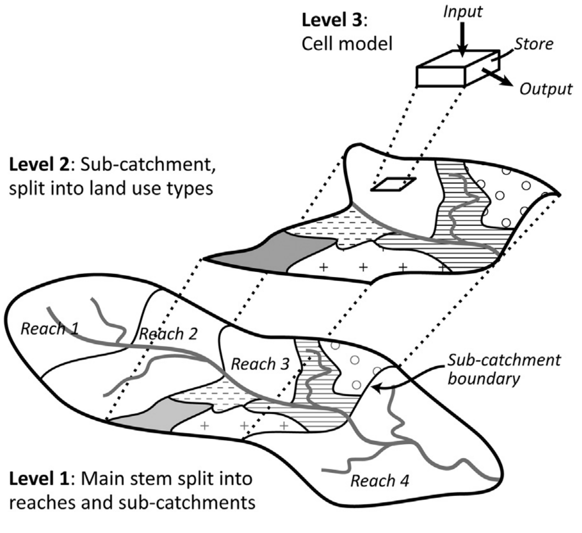

Fig. 1. The three-tiered semi-distributed spatial set-up used by INCA. After Wade et al. (2002a).

The model operates at a daily time step. For each land use class, the model tracks the fluxes of water, sediment, dissolved P and particulate P between the major terrestrial stores and the receiving waterbody (Fig. 2). Briefly, water is delivered to the stream via three flow paths: (1) throughflow from the soil compartment; (2) ‘quick’ flow, or direct runoff, which accounts for overland flow, field drains and flow through macropores; and (3) groundwater flow. Hydrologically effective rainfall (HER; precipitation that contributes to discharge) enters the soil water box, the ‘quick’ flow box is supplied by infiltration and saturation excess flow, whilst groundwater is derived from soil water via percolation (Fig. 2). All flows transport total dissolved P (TDP), whilst particulate P (PP) and suspended sediment (SS) are only transported via quick flow.

Terrestrial P inputs are split into solid forms, which enter the soil box, and liquid forms, which enter soil water; the major terrestrial output is plant uptake (Fig. 2). Rate parameters control the rate of plant uptake, weathering and immobilisation and are a function of temperature and soil moisture deficit. Plant uptake also varies according to the seasonal variations in solar radiation. Sediment and associated particulate P delivery to the waterbody is based on INCA-sed equations (Jarritt and Lawrence, 2007; Lazar et al., 2010). Briefly, sediment is generated by splash detachment and overland flow erosion. Sediment generated by splash detachment is stored on the surface as moveable sediment. The transport capacity of quick flow then determines whether sediment is transported to the waterbody. Within the in-stream component of the model, processes such as sediment settling and re-suspension, bank erosion, P adsorption/desorption and biological uptake may be taken into account, as well as any point source inputs or abstractions (Fig. 2).

Soluble P concentrations in all but the quick flow compartment are affected by adsorption/desorption reactions. The amount of P adsorbed to/released from sediment is calculated using a form of the Freundlich isotherm used by House and Denison (2000, Equation (1)), where Δm is the change in mass of P adsorbed to sediment (mg P/kg sediment), TDP is the concentration in the water (mg P l^{-1}), K is the adsorption coefficient (l kg^{-1}), n is a dimensionless constant (the Freundlich isotherm constant) and EPC_0 is the equilibrium TDP concentration at which no adsorption/desorption occurs (mg P l^{-1}). The latter three are user-input parameters.

$$\Delta m = K\left(\mathrm{TDP}^{\frac{1}{n}} - EPC_0{}^{\frac{1}{n}}\right) \quad (1)$$

The original version of INCA-P (Wade et al., 2002b) underwent major revisions in 2007 (Wade et al., 2007b), including incorporation of the sediment delivery aspects of INCA-sed, separate tracking of particulate and soluble P forms and the adoption of sorption/desorption isotherms. The most recent model development is the facility to simulate fully branched river networks (Whitehead et al., 2011); in this application we used version 1.0.2.

3. Methods and study catchment

3.1. Study catchment

The Tarland Burn lies in the middle reaches of the River Dee catchment, in northeast Scotland. Only the upper catchment is considered here, with a stream length of 9.3 km and a catchment area of 51 km^2. The catchment drops in elevation from 600 m above mean sea level in the northwest to 140 m at the catchment outflow in the southeast. Stream bed sediments are a mixture of patches of finer mud and silt, and coarser sand and gravel beds, the latter providing important habitat for spawning salmon. Land use is a mixture of intensive agriculture, rough grazing, forestry and moorland (Fig. 3). Agriculture in the catchment comprises a mosaic of arable fields, primarily spring barley, and grassland, with beef cattle and sheep. Humus iron podzols and brown forest soils are the dominant soils underlying all but semi-natural land, where peaty podzols are important. The village of Tarland has a small waste water treatment works and septic tanks serve around half the