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The INtegrated CAtchment model of phosphorus dynamics (INCA-P): Description and demonstration of new model structure and equations

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ABSTRACT

INCA-P is a dynamic, catchment-scale phosphorus model which has been widely applied during the last decade. Since its original release in 2002, the model structure and equations have been significantly altered during several development phases. Here, we provide the first full model description since 2002 and then test the latest version of the model (v1.4.4) in a small rural catchment in northeast Scotland. The particulate phosphorus simulation was much improved compared to previous model versions, whilst the latest sorption equations allowed us to explore the potential time lags between reductions in terrestrial inputs and improvements in surface water quality, an issue of key policy relevance. The model is particularly suitable for use as a research tool, but should only be used to inform policy and land management in data-rich areas, where parameters and processes can be well-constrained. More long-term data is needed to parameterise dynamic models and test their predictions.

1. Introduction

Eutrophication of freshwaters due to excessive anthropogenic inputs of nitrogen and phosphorus (P) is a global problem (e.g. Elser et al., 2007), and reducing P concentrations in surface waters has become a top priority in many areas. Across Europe, marked decreases in dissolved P concentrations in rivers have been seen during the last two decades (around 3 μg l^{-1} per year), driven largely by improvements in wastewater treatment and reductions in detergent P content (EEA, 2015). However, many surface waters still suffer from P-related eutrophication due to both sewage effluent and agricultural P inputs. Across Europe, for example, diffuse P inputs from agriculture are a significant pressure in 50% of surface water bodies (EEA, 2012). To achieve further reductions in surface water P concentrations, reductions in both point and diffuse P inputs are therefore needed. Effective management of diffuse P sources is particularly difficult: in-stream P concentration is the result of a variety of input fluxes and processes, many of which are highly variable spatially and temporally, meaning there is often no straightforward link between P inputs on land and in-stream P concentrations. In particular, the long-term accumulation of P in catchment soils, groundwater and stream bed sediments may continue to affect freshwater ecology long after farm or effluent-based remediation has been implemented (Jarvie et al., 2013;

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Meals et al., 2010; Sharpley et al., 2013).

Dynamic, process-based integrated catchment models provide a means of formalising current knowledge of complex catchment systems, and can therefore be useful catchment management tools. Models can be used to highlight knowledge and data gaps and to help design monitoring strategies (e.g. Jackson-Blake and Starrfelt, 2015; McIntyre and Wheater, 2004). Once shown to capture the dominant modes of behaviour in a system, models can provide scientifically-based evidence to support decision-making; for example, to help set appropriate water quality and load reduction goals, to advise on the best means of achieving those goals, to predict time lags and trade-offs in the system, and to explore potential system responses to future environmental change.

Many catchment-scale P models have been developed during the last few decades. Here, we describe the latest version of the INtegrated CAtchment model of Phosphorus dynamics (INCA-P) which, together with SWAT, AGNPS/AnnAGNPS, HSPF and HBV-NP (now superseded by HYPE), is one of the top five catchment water quality models used worldwide (Wellen et al., 2015). INCA-P is a semi-distributed, process-based, mass-balance model that simulates the daily dynamics of P transport in catchments. During the last decade, INCA-P has been applied to catchments throughout Europe (e.g. Couture et al., 2014; Farkas et al., 2013; Martin-Ortega et al., 2015; Starrfelt and Kaste, 2014; Wade et al., 2002b, 2007; Whitehead et al., 2013), Canada (Baulch et al., 2013; Crossman et al., 2013; Jin et al., 2013) and more recently India (Jin et al., 2015), to explore how P dynamics may respond to changes in land use, land management and climate.

The original version of INCA-P (Wade et al., 2002a) used the same conceptual structure as the nitrogen version of the model, INCA-N (Wade et al., 1999; Whitehead et al., 1998), incorporating the in-stream P dynamics of the Kennet model (Wade et al., 2002b). The model was then tested across a range of European catchments as part of the EU Eurolimpacs project (http://www.refresh.ucl.ac.uk/eurolimpacs). These applications highlighted the need for a number of improvements, and major revisions to the model structure were undertaken. Key changes included: (1) the incorporation of physically-based soil erosion, sediment delivery and in-stream transport processes, based on INCA-sed (Jarritt and Lawrence, 2007; Lazar et al., 2010); (2) the separation of total P into particulate and dissolved forms, to better describe P loss and transport mechanisms and potential bioavailability; (3) the adoption of adsorption isotherms to describe the interaction between solid and dissolved P; and (4) removal of the separation of TP into inorganic and organic fractions, primarily motivated by a lack of monitoring data to parameterise the two phases separately. The model was later adapted to allow for the simulation of fully branched river networks (Whitehead et al., 2011). The most recent phase of model development included addressing a number of issues identified by Jackson-Blake et al. (2015). Key improvements included: (1) a reformulation of the equations governing particulate P (PP) delivery to the water course and subsequent in-stream processing, so that PP dynamics are better linked to suspended sediment dynamics, and (2) replacing the constant equilibrium P concentration of zero sorption parameter (EPC_0) with a dynamic variable, calculated as a function of adsorbed P.

In this paper we describe the equations under-pinning INCA-P v1.4.4 (Section 2), providing the first full model description paper since Wade et al. (2002a). We then present a test application to the Tarland Burn catchment, in northeast Scotland (Section 3). This application is used to demonstrate the improved PP simulation and ability to simulate long-term soil P dynamics in the latest version of the model. Finally, we discuss model applicability and limitations (Section 4).

2. Description of INCA-P v1.4.4

2.1. Model overview and conceptual framework

INCA-P operates at a daily time step, tracking the stores and fluxes of water, sediment, dissolved and particulate P in both the land and in-stream phases of a river catchment. The model is spatially ‘semi-distributed’ (Fig. 1): the water course is split into reaches with associated sub-catchments. Two spatial set-ups are possible – the traditional set-up, in which there is a single main stem, or a branched set-up (Whitehead et al., 2011). The branched version allows in-stream processes and effluent inputs in tributaries to be simulated, and can be useful in larger catchments or complex river networks. Each sub-catchment is split into landscape classes, as many as are desired or warranted by the data resolution or needs of the study. Landscape classes are “functional units”: within each class, P inputs, plant uptake, soils and flow pathways should be similar, although for convenience classes are often based on land use and/or soil type. All land-based processes are calculated for a generic 1 km^2 cell for each landscape class within each sub-catchment. Water, sediment, total dissolved P (TDP) and particulate P (PP) outputs from the 1 km^2 cell for each land class are multiplied by the land class area, and summed to provide total inputs from the sub-catchment to the reach. These inputs are assumed to enter the stream reach directly, rather than being routed spatially from one land class to another. Reach inputs are therefore from the land phase and from any upstream reaches.

The main stores, processes and pathways in INCA-P are summarised in Fig. 2. The model has six main modules:

1) *Hydrological module*: calculates the flow of effective rainfall through terrestrial flow paths and the water course. Three terrestrial flow pathways are simulated: quick flow, soil water flow and groundwater flow. Quick flow drives terrestrial erosion and sediment transport to the stream and is primarily conceptualised as being made up of infiltration and saturation excess overland flow; in practice it is also likely to include drain

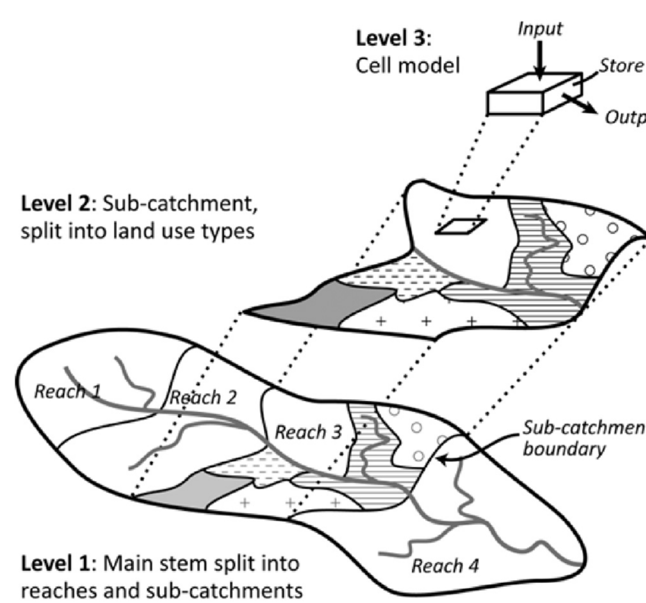

Fig. 1. The three-tiered semi-distributed spatial set-up used by INCA. After (Wade et al., 2002a). When using the branched version of the model, tributaries may also be split into reaches with associated sub-catchments.