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A geospatial framework to support integrated biogeochemical modelling in the United Kingdom

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A B S T R A C T

Anthropogenic impacts on the aquatic environment, especially in the context of nutrients, provide a major challenge for water resource management. The heterogeneous nature of policy relevant management units (e.g. catchments), in terms of environmental controls on nutrient source and transport, leads to the need for holistic management. However, current strategies are limited by current understanding and knowledge that is transferable between spatial scales and landscape typologies. This study presents a spatially-explicit framework to support the modelling of nutrients from land to water, encompassing environmental and spatial complexities. The framework recognises nine homogeneous landscape units, distinct in terms of sensitivity of nutrient losses to waterbodies. The functionality of the framework is demonstrated by supporting an exemplar nutrient model, applied within the Environmental Virtual Observatory pilot (EVOp) cloud cyber-infrastructure. We demonstrate scope for the use of the framework as a management decision support tool and for further development of integrated biogeochemical modelling.

Software availability

Title: Geospatial framework to support integrated biogeochemical modelling in the United Kingdom
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Tel: +44 (0) 1491 692495
Fax: +44 (0) 1491 692424
First available: 2012
Hardware: Any GIS enabled device
Software: GIS software
Format: ESRI shapefile (vector polygon)
Size: 585 MB
Availability: Contact author directly at shgreene@tcd.ie

1. Introduction

Nutrient enrichment of inland and coastal waters and the subsequent decline in their ecological quality present a widespread problem for water resource management (Sutton et al., 2011; McGonigle et al., 2012; Liu et al., 2012). Effective management for preventative and remedial action at the catchment, regional or landscape scale requires explicit consideration of the complexities of the hydrological and biogeochemical controls that act in unity to

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deliver nutrients to waterbodies (Pärn et al., 2012; Greene et al., 2013; Robson, 2014). However, the development of such integrated management strategies is limited by the availability of science understanding and knowledge that is transferable between spatial scales and landscape typologies.

Observational data used for informing process understanding of nutrient transfer is often generated at relatively small experimental scales. Findings from these studies are not necessarily directly transferable for application at the whole catchment scale without the development of a modelling solution, bespoke for the system and the data available to drive that model (Haygarth et al., 2012; Ye et al., 2012). As catchment area increases, considerable variation in the hydrological and biogeochemical controls on nutrients transpire, reflecting variations in upstream catchment characteristics such as geology, soils, land use and topography. A modelling solution is also often based on the determination of partial fractions of the total nutrient load exported from land to water, underestimating the scale and impact of the enrichment problem, and is therefore likely to misinform the direction of environmental management aimed at mitigating the problem (Burt and Johnes, 1997; Johnes, 2007; Yates and Johnes, 2013).

Policy makers and environmental managers seeking to develop management and mitigation options for impacted systems have had to either (1) fund the development of site-specific modelling and monitoring programmes for each catchment of interest, (2) use knowledge acquired from inadequate, low resolution or partial monitoring of a limited range of nutrient fractions in the catchment of interest or neighbouring catchment, or (3) use knowledge acquired from high resolution studies in systems which might not be directly comparable with the catchment of interest. In order to deliver effective comprehension of nutrient cycling and export dynamics under current and potential environmental change conditions there is an urgent need to develop better mechanisms for the transfer of knowledge and science understanding between data-rich and data-poor systems (Beven and Alcock, 2012).

A range of approaches have been developed to tackle the need for better understanding and management of nutrients in the environment. Simpler correlative statistical modelling approaches, such as the Global News model (Seitzinger et al., 2010), can generate visually attractive simulations of catchment behaviour at regional to global scales, but lack a physical basis (or representation of the specific physical conditions controlling functional behaviour in differing environments). Such approaches are often inaccurate and uncertain when reduced to a scale suitable for environmental management, generating high risk when used to support operational management and policy development. Dynamic process-based modelling approaches with a physical basis, such as the Integrated Catchment (INCA) modelling suite for nitrogen (N), phosphorus (P), carbon (C) and sediment (Whitehead et al., 1998; Wade et al., 2002; Futter et al., 2007; Lazar et al., 2010), provide the opportunity to capture the science understanding generated by high resolution research on catchment behaviours at a range of scales. However expert knowledge and high concomitant costs are currently associated with the calibration of the model(s) to local conditions in each application (Dean et al., 2009).

Less data-intensive models that represent intrinsic nutrient retention and release capacity as a function of environmental attributes provide a suitable alternative approach. Such models have been developed in a number of countries, and based on measureable properties of the landscape, they provide optimised parameter ranges for key drivers of catchment function, related to regional landscape typologies. These include an explicit representation of landscape form and function either within optimised parameter ranges, or embedded within a regionalised framework. Examples include the export coefficient model (ECM) applied within the context of a geoclimatic region framework (Johnes et al., 1996, 2007; Johnes and Butterfield, 2002), the integrated models IMAGE and INTEGRATOR, the Indicator Database for European Agriculture (IDEAg) covering the agriculture sector and sewage systems, the Emission Database for Global Atmospheric Research (EDGAR) covering atmospheric emissions from all sectors, and the Unified EMEP model calculating atmospheric transport and deposition models applied across the whole of Europe in the most recent European Nitrogen Assessment (Leip et al., 2011). These models tend to operate at a coarser temporal scale in order to fit the model predictions to the average annual behaviour of a catchment, but are spatially explicit in simulating typical catchment behaviours within similar, quasi-homogenous region types. As these are based on measureable properties of the landscape, they offer opportunities for aggregating data and knowledge from plot to catchment, regional and global scale, and the transfer of knowledge from data-rich to data-poor environments by using local spatially-explicit high resolution data from the environment.

This paper aims to present an improved regionalised framework that explicitly integrates the myriad of environmental attributes controlling nutrient retention and loading exported to waterbodies across the United Kingdom (UK). Two objectives are set. First, an earlier framework by Johnes et al. (2007), used as a foundation, has been extensively refined in an iterative way to improve the region classification methodology, spatial resolution of source datasets and geographic extent. Second, we demonstrate how this framework has been applied at catchment and broader spatial scales by supporting an exemplar nutrient model. Instead of traditional off-line processing, the framework and associated model has been hosted by a novel cloud cyber-infrastructure, developed in the Environmental Virtual Observatory Pilot (EVOp) project, funded by the Natural Environment Research Council (NERC). This setup provides efficient processing time together with a user-friendly geospatial web portal (Elkhatib et al., 2013; Emmett et al., 2014; Vitolo et al., 2015). A discussion of how such a framework and approach will contribute to advancing nutrient modelling and management is also included.

2. Materials and methods

The functionality of the foundation geoclimatic region framework (Johnes et al., 2007) was demonstrated using the ECM developed by Johnes (1996). For context we give a brief description of the ECM and application to the original framework, including evaluation metrics and limitations (section 2.1). The development of the new framework is described, together with details on source datasets, classification rules and evaluation and application metrics (section 2.2). Application of the framework supporting the exemplar ECM within the cloud computing architecture and evaluation of model estimates is also outlined (section 2.3). All development and evaluation metrics are guided by recommendations by Bennett et al. (2013).

2.1. Background

2.1.1. Export coefficient model

The ECM developed by Johnes (1996) is based on the semi-distributed approach that calculates the nutrient load exported to any water body (freshwater, estuarine or marine) as the sum of the total nutrient load exported to that water body from all sources within its catchment. Different coefficients are adopted for individual crops, as well as for types of livestock units and the coefficients for humans are determined based on the discharge and treatment efficiency of domestic sewage in large Wastewater Treatment Works (WwTW), small packet Sewage Treatment Works (STW) and septic tank systems. The model also takes into account nitrogen fixation by plants (varying by crop type) and deposition of both N and P from atmospheric sources. The ECM is outlined as:

$$L = \sum_{i=1}^{n} E_i(A_i(I_i)) + p \tag{1}$$

where L is the load of nutrients (TN or TP), E_i is the export coefficient for nutrient source i, A_i is the area of the catchment occupied by land use type i, or number of livestock type i, or people, I_i is the input of nutrients to source i, and p is the total input of nutrients from atmospheric deposition. Rates of nutrient input and rates of nutrient export are based on spatially explicit monitoring and experimental data for