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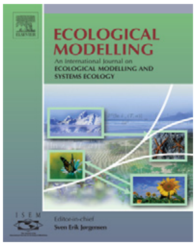

A framework to identify appropriate spatial and temporal scales for modeling N flows from watersheds

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ABSTRACT

We describe a framework (FAMOS) to identify the appropriate spatial and temporal scales for nitrogen (N) flow models. FAMOS has been developed for models of N export from large watersheds. With FAMOS, modelers can identify the appropriate scale for model predictions and for independently scalable model parts.

FAMOS is based upon four criteria to check the appropriateness of modeling scales. Modeling scales thus have to correspond with (A) data and scenarios, (B) model assumptions, (C) available resources for modeling, and (D) appropriately scaled predictions. We present 12 indicators to test these criteria. A user of FAMOS may use all or a selection of these, to identify the appropriateness of a modeling scale for his purpose. The indicators vary between 0 and 1 as a function of scale, and are to be quantified and weighted by the user.

A successful application of FAMOS is illustrated for a global model of dissolved inorganic nitrogen (DIN) export from watersheds to coastal waters. Ranges of appropriate scales are determined for model predictions and five independently scalable model parts, which model the (1) surface N balance, (2) point sources, (3) N flow in sediments and small streams, (4) retention in dammed reservoirs, and (5) riverine DIN retention.

We conclude that FAMOS can contribute substantially to a well-balanced and comprehensive identification of appropriate modeling scales.

1. Introduction

Many different large-scale watershed nitrogen (N) flow models exist (Andersen et al., 2003), which describe processes related to the horizontal movement of N through large drainage networks of river basins. Equations of such models can be applied on different scales. This modeling scale is important because it affects the processes that can be well described, the required input data, the scenarios that can be simulated, and usefulness of resulting predictions. Modeling scale can be measured as a combination of support, extent, and stream order of model parts. Spatial model support is the size of the areas represented by single values of input variables used in model calculations (Heuvelink, 1998). Temporal model support is

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duration of the times represented by single values of input variables used in model calculations. If the model is stochastic then model support applies to single input distributions instead of single input values. Model extent is the total range of time or space within which processes are modeled. The spatial extent of N-flow models is typically a watershed or a group of adjacent watersheds. The temporal model extent is usually between a few months and a few decades. Stream order is a measure of the size of river reaches that are modeled (Strahler, 1964).

The reason for selecting a particular modeling scale is usually not explicitly reported, making the appropriateness of a chosen modeling scale difficult to judge. Modelers often have no clear guide for selecting appropriate spatial and temporal model scales for predicting N flows in large river basins.

Models are often used to predict N export for environmental impact assessments in specific river basins. Such models can have different spatial and temporal supports and extents. For example, the Riverstrahler model (Billen et al., 1994) has been applied with various temporal supports to river basin areas ranging from 100 to 100,000 km^2 and with spatial model supports ranging from 1st to 5th order upstream basins ranging in area between 1 and 5000 km^2 (Sferratore et al., 2005). Other models were developed to cover multiple basins up to a global scale coverage with varying temporal scales. Hence, with models ranging from basin-specific to global and with different temporal scales, it is interesting to asses what the appropriate scale is.

The appropriateness of modeling scale depends on factors such as model assumptions, available resources for modeling, the scale of required predictions, and properties of data, mitigation options, and scenarios. There is empirical information on the appropriateness of scales to apply N-flow models and methodological information on the identification of such appropriateness in the literature. We will first review existing empirical literature, followed by existing methodological literature.

The validity of existing models at different supports as been subject of several empirical studies. These provide (i) empirical information from model developers (e.g. Andersen et al., 2003), (ii) reported tests of prediction accuracy of N-flow models when applied at different supports (Mamillapalli et al., 1996; Curmi et al., 1998; FitzHugh and Mackay, 2000; Beaujouan et al., 2001; Bellamy and Loveland, 2001; Johnes and Butterfield, 2002; Caraco et al., 2003; Jha et al., 2004; Sferratore et al., 2005), and (iii) measurements of the minimum proportion of the catchment area on which modeled drivers must change in order to obtain significantly distinct model responses (Joao, 2002; Eckhardt et al., 2003). In addition, empirical information exists on the appropriateness of model scales for applying model parts describing particular processes. In these studies we may distinguish between (i) expert judgment (Wagenet, 1998; Meybeck, 2002), (ii) validation of watershed N-flow models with different process descriptions on the same scale (De Wit, 1999), (iii) radioactive tracers indicating processes affecting exported N from watersheds on different scales (Costanzo et al., 2003), and (iv) results of an approach called minimum information requirement where all processes that do not contribute to prediction accuracy on a scale of interest are removed from a detailed watershed N-flow model developed on a fine scale (Van Herpe et al., 2002; Quinn, 2004). Moreover, empirical literature exists on the scale at which individual N processes emerge. Such literature may be used by modelers to estimate the appropriate scale for applying model parts describing individual processes. Here we distinguish between empirical research on the sizes of patches of N processes (Dent and Grimm, 1999; Jarvie et al., 1999; Wolfert, 2001; Torgersen et al., 2004) and expert judgment (McClain et al., 2003; Seitzinger et al., 2006). Finally some empirical information exists on the scale at which predictions are required from watershed N-flow models (Sherman, 1991; Omernik and Bailey, 1997; Omernik, 2003; Meybeck et al., 2007).

There is methodological literature that supports the identification of appropriate scales of N-flow model types or parts for which the appropriate scales cannot be reliably estimated from empirical literature. Some of this methodological literature supports research on the effects of model scale on model validity, such as methods aiming at identifying scales where the modeled system is deterministic (Wood et al., 1988; Bruneau et al., 1995; Robin et al., 1995; Habeeb et al., 2005) and uncertainty analyses (Beven, 1995; Heuvelink, 1998; Vachaud and Chen, 2002; Lilburne et al., 2004). Other approaches support the identification of the ranges of measurement scale at which different nitrogen processes can be observed, such as wavelet analyses (Platt and Denman, 1975) and variogram analyses (Kotliar and Wiens, 1990; Isaaks and Srivastava, 1998). Alternatively, some studies support the deduction of scales at which different N processes can be observed, such as methods using knowledge of scale-specific feedbacks controlling these processes (Holling, 1992; Levin, 1992; Gibson et al., 2000; Easterling and Kok, 2002) or knowledge of fractal properties making the processes apparent over a range of scales (Burrough, 1981; Schroeder, 1991; Schneider, 1994; Sposito, 1998).

The current literature does not provide a basis to comprehensively and generically identify appropriate modeling scales of N-flow models. Empirical studies tend to focus on only one measure of scale (either support, extent, or stream order, and either spatial or temporal scale) and can therefore not be considered comprehensive. They also tend to focus on either the scale of processes, modeled scenarios, a single model part, or predictions. The proposed methods in the literature require too much time and data for most practical applications. Further, most of these methods focus on only one measure of scale and on either the scale of processes or single model parts.

The purpose of this paper is to present a comprehensive framework to identify the appropriate spatial and temporal scale for N-flow models. Here models are defined as coupled sets of equations that can be applied at any scale. We refer to the framework as FAMOS (Framework for Appropriate MOdeling Scale). FAMOS has been developed for models that can predict N export from large watersheds and the contribution of N sources and sinks to this N export. With FAMOS, modelers can identify appropriate scales for model predictions and for independently scalable model parts. FAMOS may also assist in reporting the rationale behind the scale of a model's application. A preliminary version of FAMOS has been published in Dumont et al. (2006).