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Application of an integrated framework for estimating nitrate loads from a coastal watershed in south-east Sweden

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ABSTRACT

Nitrate-nitrogen (NO_3-N) loading from a 734 ha coastal watershed draining into the Baltic Sea off south-east Sweden was simulated using a simple modelling approach in which the nitrogen model DRAINMOD-N II and a temperature-dependent NO_3-N removal equation were incorporated into the Arc Hydro-DRAINMOD framework. Hydrology and water quality data collected during six periods between 2003 and 2007 were used to test Arc Hydro-DRAINMOD and its performance was evaluated by considering uncertainty in model parameters using GLUE methodology. The GLUE estimates (5th and 95th percentiles) and calculated monthly NO_3-N loads were in satisfactory agreement. There are some sources of errors that may affect the performance of the framework, such as NO_3-N load calculations, soil denitrification and in-stream removal of NO_3-N. Although additional measurements may help to improve the understanding of these processes and reduce uncertainty, they cannot completely eliminate the uncertainty in framework predictions. These uncertainties must be evaluated by some methodology, such as the GLUE procedure. Sensitivity analysis showed the framework to be most sensitive to changes in stream baseflow and N removal processes in the stream network. These results show that the Arc Hydro-DRAINMOD framework can be an effective tool to support water stakeholders in managing NO_3-N loading from small tile-drained watersheds at monthly time step.

1. Introduction

In Sweden, N transport in lowland rivers has resulted in serious coastal eutrophication problems (Larsson et al., 1985; Stålnacke et al., 1999). This ongoing eutrophication has been the most pervasive anthropogenic alteration to marine coastal ecosystems, leading to widespread hypoxia and large permanently reducing bottom areas in the Baltic Sea (Vahtera et al., 2007). Special attention is required for coastal areas of southern Sweden including the island of Öland, which have been classified as particularly vulnerable to nitrogen (N) leaching from agriculture and identified as nitrate vulnerable zones according to the EU Nitrate Directive (SJV, 2006, 2007).

To counteract the undesirable consequences of excessive nutrient loads into aquatic systems, the processes controlling nutrient export from drained agricultural lands to downstream surface waters need to be better understood (Fenn et al., 1998). However, field studies have shown that the effects of improved drainage are difficult to quantify, where increasing drainage intensity on agricultural land may have both positive and negative effects on hydrology and water quality (Skaggs et al., 1994). The development of hydrological models has allowed the description of the mechanisms of nutrient retention and release in these drained areas (Thomas et al., 1992). Modelling of the processes and interactions involved may explain how land use and management practices in coastal watersheds affect the recipient marine ecosystem (Valiela et al., 1992). Computer hydrological models have become an integral component of many drainage projects with outputs that may be used for planning, design, or operational decisions about matters in which hydrological information is relevant and useful (Skaggs et al., 2006). A number of models are available to predict the movement and fate of nutrients and pesticides at field-scale: CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), LEACHN (Hutson and Wagenet, 1991), RZWQM (Singh and Kanwar, 1995) and SOILNDB (Johnsson et al., 2002).

However, only a few models can be applied to quantify the effects of drainage system design and management on losses of agricultural chemicals, such as SOILNDB and DRAINMOD-N II. DRAINMOD-N II (Youssef, 2003; Youssef et al., 2005) was developed to simulate N dynamics under different management practices and soil and environmental conditions. It can be used with the water management model DRAINMOD (Skaggs, 1978, 1999) for

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the development and evaluation of methods that reduce N losses from drained agricultural land. DRAINMOD-N II has been tested by Salazar et al. (2009) at field-scale in a coarse-textured soil under cultivation in south-east Sweden, where predicted nitrate-nitrogen (NO_3-N) load values have been found to be in good agreement with field data. The model has also been calibrated and validated for predicting edge-of-field N losses from drained crop and pasture lands in south eastern and Midwestern U.S. (Youssef et al., 2006; David et al., 2009; Thorp et al., 2009; Luo et al., 2010; Ale et al., 2012) and Germany (Bechtold et al., 2007).

The sum of N inputs to the stream network in a watershed usually exceed loads discharged at the outlet, where the stream network acts as a filter retaining and/or removing N by processes such as denitrification, sedimentation and plant and microbial uptake (assimilation) (Billen et al., 1991). Some researchers have reported that denitrification is the dominant nitrate (NO_3^-) loss process in rivers, where NO_3^- is permanently removed through the formation and release of NO (g), N_2O (g) and N_2 (g) into the atmosphere (Seitzinger, 1988; Saunders and Kalff, 2001). Several studies have estimated that a substantial amount of N (10–76% of total N input) can be removed during transport through the network of streams draining watersheds (Saunders and Kalff, 2001; Seitzinger et al., 2002; Birgand et al., 2007). Other studies show N retention values lower than 10%, mainly for coastal watersheds with practically no lakes (Lepistö et al., 2006; Appelboom et al., 2008).

It is important to consider that management of nutrient inputs to coastal ecosystems requires knowledge of both the magnitude of N losses from the watershed and the proportion of N removed during downstream transport in the watershed (Seitzinger et al., 2002). The N removal rate in the stream network has been included in several modelling approaches at the watershed scale, such as AGNPS (Bhuyan et al., 2003; León et al., 2004), a GIS-based model (Skop and Sørensen, 1998) and DRAINMOD-GIS (Fernandez et al., 2006). It has been represented either as a percentage of the total N input (Bhuyan et al., 2003; León et al., 2004) or as an exponential decay model (Skop and Sørensen, 1998; Fernandez et al., 2002, 2006). However, these approaches did not include temperature as a factor affecting N removal rate, whereas temperature has been identified as a key factor in N denitrification experiments (Dawson and Murphy, 1972; Appelboom et al., 2006). In contrast, a recent modelling study by Alexander et al. (2009) included temperature as an explanatory variable to estimate N losses by denitrification in river networks, based on about 300 published measurements from a variety of US streams.

Birgand et al. (2007) noted that the key to nutrient management at the watershed scale is understanding and quantifying the fate of nutrients, both at the field scale and after they enter the aquatic environment. Therefore, a distributed model that treats the watershed as a spatially variable physical system may be more realistic and have significant theoretical advantages that make them more useful (Ward and Robinson, 2000), for instance to estimate nutrient losses from fields within a small watershed.

Process-based nitrogen modelling usually requires a large number of difficult to measure parameters, which are usually estimated through model calibration. Estimated N parameter values have uncertainties that are propagated in each step of the calculations, an issue that should be assessed (Beck, 1987). Beven and Binley (1992) proposed the Generalised Likelihood Uncertainty Estimation (GLUE) methodology for calibration and uncertainty estimation of distributed models at watershed scale. This methodology has been used in several watershed modelling approaches and has been shown to be an applicable and formal basis for appropriate uncertainty estimation (Mo et al., 2006; Arabi et al., 2007; Choi and Beven, 2007; Blasone et al., 2008).

The aim of the present study was to extend the integrated Arc Hydro-DRAINMOD framework (Salazar et al., 2010) to predict NO_3-N loads at the watershed outlet using a relatively simple approach that can be used by local water stakeholders for managing NO_3-N loading. In this modelling approach the nitrogen model DRAINMOD-N II and a temperature-dependent NO_3-N removal equation were included to create an Arc Hydro-DRAINMOD framework for predicting NO_3-N loading. The performance of the framework was evaluated by considering the uncertainties in model parameters using the GLUE methodology. In addition, a sensitivity analysis was carried out using the GLUE results. The Arc Hydro-DRAINMOD framework was tested by comparing simulated results with calculated NO_3-N loads from a 734 ha artificially drained coastal watershed on Öland Island draining into the Baltic Sea off south-east Sweden for six periods between 2003 and 2007.

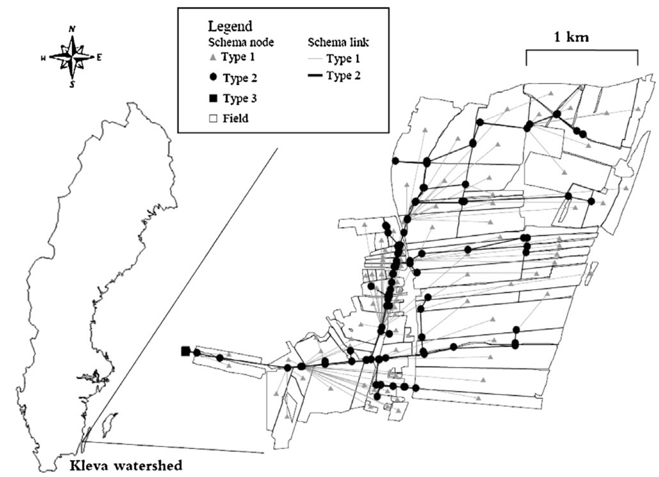

Fig. 1. Diagram of the study area in Kleva watershed with schematic network. Types of links and nodes are explained in Table 2.

2. Materials and methods

2.1. Site description

The 734 ha artificially drained Kleva watershed is located on the coast of the Öland Island in the Baltic Sea, off south-east Sweden (latitude 55°31′N, longitude 16°23′E) (Fig. 1). Land use in the watershed is predominantly agricultural. There are 95 fields in the watershed, ranging in area from 0.2 to 32 ha. A detailed description of area, soil texture and crop rotation for all fields is presented by Salazar et al. (2010).

The watershed soils, which are developed from glacial drifts, are predominantly coarse-textured with low water-holding capacity and high vertical saturated hydraulic conductivity (K_s). There is a small area of peat-derived organic soil close to the outlet. The watershed is underlain by sedimentary rocks such as limestone, alum shale, sandstone and clay shale, which greatly restrict downward movement of water, where the bedrock is covered by Quaternary deposits of varying thickness ranging from 1 to 10 m in the watershed. The watershed drains to coastal waters in the Baltic Sea. It is characterised by flat topography, with average slope lower than 1%. Steep slopes (>10%) only occur on hills located on the eastern watershed boundary, where ground elevation is at its maximum (50 m a.s.l.).

The climate on Öland is Marine West Coast (Cfb) according to the Köppen–Geiger system (Peel et al., 2007). Average monthly temperatures at Mörbylånga, Öland, range from −1.4 °C in February to 16.8 °C in July, with a mean annual temperature of 7.4 °C and long-term average precipitation of 475 mm (Alexandersson et al., 1991).