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Nutrient loadings from urban catchments under climate change scenarios: Case studies in Stockholm, Sweden

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HIGHLIGHTS

- Climate change effects on nutrient loadings in urban watersheds are investigated.
- A source model is integrated with a watershed model in a substance flow structure.
- Annual nitrogen loadings and the seasonal distribution may be modestly affected.
- Groundwater may potentially be the most sensitive pathway of nitrogen transport.
- Phosphorus loadings by water pathways may be less sensitive to climate change.

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ABSTRACT

Anthropogenic nutrient emissions and associated eutrophication of urban lakes are a global problem. Future changes in temperature and precipitation may influence nutrient loadings in lake catchments. A coupling method, where the Generalized Watershed Loading Functions method was tested in combination with source quantification in a Substance Flow Analysis structure, was suggested to investigate diffuse nutrient sources and pathways and climate change effects on the loadings to streamflow in urban catchments. This method may, with an acceptable level of uncertainty, be applied to urban catchments for first-hand estimations of nutrient loadings in the projected future and to highlight the need for further study and monitoring. Five lake catchments in Stockholm, Sweden (Råcksta Träsk, Judarn, Trekanten, Långsjön and Laduviken) were employed as case studies and potential climate change effects were explored by comparing loading scenarios in two periods (2000–2009 and 2021–2030). For the selected cases, the dominant diffuse sources of nutrients to urban streamflow were found to be background atmospheric concentration and vehicular traffic. The major pathways of the nitrogen loading were suggested to be from both developed areas and natural areas in the control period, while phosphorus was indicated to be largely transported through surface runoff from natural areas. Furthermore, for nitrogen, a modest redistribution of loadings from surface runoff and stormwater between seasons and an increase in the annual loading were suggested for the projected future climate scenarios as compared to the control period. The model was, due to poor monitoring data availability, only able to set an upper limit to nutrient transport by groundwater both in the control period and the future scenarios. However, for nitrogen, groundwater appeared to be the pathway most sensitive to climate change, with a considerable increase and seasonal redistribution of loadings. For phosphorus, loadings by different pathways were apparently less sensitive to climate change.

1. Introduction

Excessive nutrient loadings to water recipients can cause eutrophication problems, threatening aquatic environments and services provided to humans (e.g., Kaye et al., 2006). Furthermore, climate change has been projected to lead to changes in temperature and precipitation, factors affecting all parts of the hydrological cycle and causing e.g., flooding and changes in rainfall (De Risi et al., 2013; De Paola et al., 2013; Jalayer et al., 2014). These potential changes may influence nutrient loadings from catchments. Therefore, many models have been developed to investigate nutrient loading scenarios in response to climate change in order to combat future eutrophication. For example, the HBV model has been used for the Baltic Sea basin (Bergström and Graham, 1998), the SWAT model for the Vantananjoki watershed (Bouraoui et al., 2004), the Generalized Watershed Loading Functions

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(GWLF) model for the Daugava river basin (Wallin, 2005) and the PolFlow model for the Norrström catchment and Lake Mälaren basin (Mourad and Van der Perk, 2004; Darracq et al., 2005).

However, most previous studies have focused on large-scale catchments in a long-term view. Predictive models for urban catchments, where there are complex interactions between humans and environments, are still largely lacking. Such urban catchments are usually small in size and located in different areas of a city, but they play an important role in urban ecosystems. However, not all urban catchments are monitored sufficiently well to investigate future climate change effects on nutrient loadings. Therefore, studies of urban catchments are needed, particularly in areas characterised by a lack of basic data and previous studies, in order to highlight the need for further studies and to identify implications for monitoring in practice in the context of climate change.

In order to handle future urban eutrophication from a nutrient flow management perspective, a clear understanding of nutrient sources, pathways and loadings in urban areas is also necessary. Coupling nutrient sources with the loadings to urban streamflow can be a useful first step in developing relevant scenarios addressing underlying changes in society in parallel with climate change. When investigating nutrient sources, diffuse sources to receiving waters are generally difficult to quantify and manage (e.g., Carey et al., 2013).

In models dealing with urban drainage, e.g., the StormTac model in Sweden (Larm, 2000) and the SLAMM model in the US (Pitt and Voorhees, 2004), diffuse nutrient sources are often quantified together with other pollutants in stormwater through determining the pollutant concentration in different waters in combination with water flow data. Such models are capable of tracing source areas, but not the real primary sources. They are also rarely used to investigate climate change effects, as the dataset of projected temperature and precipitation in existing climate models cannot be directly plugged in. Although source-based approaches have been proposed for tracing primary sources of heavy metals (e.g., Sörme and Lagerkvist, 2002; Cui et al., 2010), one of the key aspects in these models is the fraction of pollutants delivered to different types of water paths. This is handled by an empirical factor that is unable to handle the consequences of future climate change. Furthermore, nutrient loadings from groundwater are not covered in these models.

Therefore, accurate methods for prediction of urban diffuse nutrient sources, pathways and loadings through different water pathways in response to climate change are urgently needed. In a previous study, we qualitatively analysed climate change effects on nitrogen flows in Råcksta Träsk, an urban catchment in Stockholm, Sweden (Wu et al., 2013). Based on the results, we concluded that biological, hydrological, meteorological and biogeochemical effects and changes in human behaviour in response to climate change may lead to altered nutrient flows through urban catchments. The aim of the present study was to quantify nitrogen and phosphorus flows and their loadings under the future hydrological effects arising from climate change. Specific objectives were to: (1) identify major sources of nitrogen and phosphorus in urban streamflow and couple the sources with the loadings from selected catchments; (2) quantify the loadings of nitrogen and phosphorus contributed by different water pathways and identify the most sensitive pathway under future climate change; and (3) identify potential impacts from future climate scenarios on total loadings of nitrogen and phosphorus to urban streamflow.

2. Case study

Five lake catchments in Stockholm, Sweden (Råcksta Träsk, Judarn, Trekanten, Långsjön and Laduviken), which are regularly monitored for water quality, were used as case studies in this work. These five catchments were selected because they represent different proportions of various land uses and different levels of nutrient concentrations in lake water (Stockholm Vatten, 2006), in order to allow generalization of the results and consider the implications for future catchment management. In addition, they are isolated catchments with no upstream surface water system and are mainly supplied by streamflow from urban areas with various land uses, allowing potential urban nutrient sources and pathways to be investigated. In order to facilitate presentation and discussion of the results, the land uses were categorised into 'developed areas' and 'natural areas'. The characteristics of the five lake catchments are shown in Table 1.

In all five catchments, there is no heat and power production, refuse incineration or relevant industrial emissions that could cause airborne nitrogen (Malmqvist, 1983). The only local source of airborne nitrogen is traffic. Moreover, all five catchments largely comprise woodland and open land except Lake Långsjön, where 60% of the drainage area is composed of residential buildings. The drainage area of Lake Trekanten has the largest vehicular volume in its road area of the cases studied (Table 1). 'Traffic area' in the five cases includes road area, tram area and parking area.

The catchment of Råcksta Träsk, in the western suburbs of Stockholm, includes a larger number of different land uses than the other catchments, with a horse riding area and construction area, categorised as the land uses 'Livestock' and 'Contaminated soil', respectively. These two land uses are not present in the other catchments. In addition, the drainage areas of lakes Råcksta Träsk, Trekanten and Laduviken have quite small areas of 'Cultivated land' that are near residential buildings, with negligible contributions of nutrients to urban runoff, and were thus excluded from the study. Therefore 'Contaminated soil' and 'Cultivated land' were lumped into the 'Other permeable areas' class, while 'Livestock' was taken as a separate land use given the particular source of horse droppings in the Råcksta Träsk area (Table 1). Moreover, there is a treatment pool and a lamella plant in the drainage area of Råcksta Träsk. They treat collected urban runoff and the treated water is discharged to the lake. Such facilities are not present in the other catchments studied.

'Other permeable areas' was placed under 'Natural areas' rather than 'Developed areas', given that they do not represent a land use dominated by impervious area as in the developed area category. We also quantified the sources using the same approach as for the natural areas, due to data availability. It should be noted that the original land use data were obtained from Stockholm Vatten (2000) with a high resolution of classification of land uses, and only the mentioned areas above are summed for purposes of presentation and discussion. The land use map for the five lake catchments is presented in Fig. 1, where the dedicated horse riding area is also noted.

Despite the northerly location of Stockholm, it has a humid, continental climate and relatively mild weather compared with other locations at similar latitude. According to the Swedish Meteorological and Hydrological Institute (SMHI), the mean daily temperature in Stockholm in 2011 was 8.5 °C and mean annual precipitation was 478.8 mm (SMHI, 2014). SMHI maintains well-structured data series on daily temperature and precipitation for both historical periods and future climate projections for the Stockholm area (Kjellström et al., 2005). Potential climate changes can be expected in both the short and long terms (Stockholms Stad, 2007). Detailed climate data with a 20-year perspective were used in this study.

3. Methods

3.1. Overview of the approach

3.1.1. Nutrient flow analysis

Substance Flow Analysis (SFA) was used to identify nitrogen and phosphorus flows within the five study catchments, which were generalized as shown in Fig. 2. The system boundary for each case was defined as the drainage area of the lake and the focus was on nutrient source identification, nutrient distribution for each land use type and loadings to streamflow. Streamflow in this work refer to water flows caused by rainfall and snowmelt that can potentially transport nutrients into water