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Review and assessment of nitrate reduction in groundwater in the Baltic Sea Basin

Anker Lajer Højberg[a,*], Anne Lausten Hansen[a], Przemysław Wachniew[b], Anna J. Żurek[b], Seija Virtanen[c], Jurga Arustiene[d], Johan Strömqvist[e], Katri Rankinen[f], Jens Christian Refsgaard[a]

[a] Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen K, Denmark
[b] AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Krakow, Poland
[c] Drainage Foundation sr, Simonkatu 12 B 25, 00100 Helsinki, Finland
[d] Lithuanian Geological Survey, S. Konarskio str. 35, LT-03123 Vilnius, Lithuania
[e] Swedish Meteorological and Hydrological Institute, SMHI, 60176 Norrköping, Sweden
[f] Finnish Environment Institute, P.O. Box 140, 00251 Helsinki, Finland

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ABSTRACT

Study region: Six countries within the Baltic Sea Basin: Denmark, Sweden, Finland, Lithuania, Poland and Germany

Study focus: During transport from the field to the sea nitrogen undergoes natural reduction, but with large spatial variations. Mapping this variation would allow more optimal regulation strategies, by imposing most restrictions in areas with low natural reduction. In the present study, a map for spatially variable nitrate reduction in groundwater is developed covering six countries in the Baltic Sea Basin. In contrary to previous studies within the Baltic Sea Basin, the present study provides an independent estimate of the nitrogen reduction in groundwater, based on review of national data and studies. Depending on availability, different approaches were used for the countries ranging from national modelling to expert judgement. Through a joint workshop the assessments were, to the extent possible, harmonised.

New hydrological insights for the region: The review revealed large variations in the hydrogeochemical conditions important for transport and degradation of nitrogen in groundwater. This includes the hydrogeology, the reducing conditions of the subsurface, and the fraction of water transported by drainage systems bypassing the reducing subsurface environments. Significant variations in groundwater reduction between the countries and within most of the countries were thus found, indicating that strategies for nitrogen regulation and mitigation measures may be optimised, if variation in the natural reduction of nitrate is considered.

1. Introduction

Nutrient load, primarily by waterborne riverine transport, has changed the environmental conditions for the Baltic Sea from oligotrophic to eutrophic conditions in most parts (Larsson et al., 1985). To revert the conditions, the Baltic Sea Action Plan (BSAP) was adopted in 2007 (HELCOM, 2007) and revised in 2013 (HELCOM, 2013). In the updated fifth Baltic Sea pollution load compilation (PLC5.5) it is estimated that nitrogen loads has been reduced by 9% from the reference period (1997–2003) to 2013, but

* Corresponding author.
E-mail address: alh@geus.dk (A.L. Højberg).

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it is also found that a further abatement of 14% is required (HELCOM, 2015). Analysing trends in monitoring data from 1970 to 2000, Saaltink et al. (2014) found that the reduced loads in nitrogen is not evenly distributed but display large spatial variation and are related to the socio-economic developments within the Baltic Sea Basin. The estimated required abatement similarly varies significantly with a required reduction of up to 26% in the Baltic Proper (HELCOM, 2015). Furthermore, specific estuaries and coastal waters may require even higher specific abatements in order to protect coastal and transitional water ecosystems and comply with the good status objectives of the Water Framework Directive (e.g. Hinsby et al., 2012).

A significant part of the nutrient reduction to the Baltic Sea can be attributed to major developments in the wastewater treatment, due to technological developments and more people being connected to municipal wastewater treatment plants. In combination with the improvement of fish farms, direct nitrogen input from point sources to the Baltic Sea has been lowered by 43% in the period 1994–2010 and contributes with approximately 4% to the total waterborne nitrogen input (HELCOM, 2015). Although some further decrease in the nutrient load to the Baltic Sea may be realised by improved wastewater treatment, the fifth Baltic Sea pollution load compilation (PLC-5) (HELCOM, 2011) estimates that the diffuse sources with a share of approximately 45% constitutes the largest anthropogenic contribution of riverine nitrogen of which 70–90% is estimated to originate from agriculture.

During transport from the root zone to the discharge into the sea, nitrogen may be removed in either the groundwater or the surface water system. Removal occurs by different natural biogeochemical processes or sedimentation, often referred to as retention or reduction and expressed as a percentage removal. The magnitude of the retention/reduction depends on the actual hydro-biogeochemical conditions and may vary significantly. Applying the statistical model MESAW to the 117 catchments in the Baltic Sea, Stålnacke et al. (2015) estimated a total nitrogen retention of approximately 40% in surface water. As noted by the authors, this estimate is substantially higher than the estimate by Mörth et al. (2007), reporting a mean in-stream nitrogen retention of 15% in the Baltic Sea rivers. Combining a statistical nitrogen leaching model with a fully distributed groundwater/surface water hydrological model and statistical surface water retention models, Højberg et al. (2015) developed a national nitrogen model for Denmark. They estimated mean retentions of 63% and 25% for groundwater and surface water, respectively, but with large spatial variations.

Natural removal of nitrogen is, however, generally not sufficient to reduce the diffuse nitrogen loads to the required levels. Implementing various mitigation measures has successfully lowered the diffuse loads from several of the member countries of the Baltic Marine Environment Protection Commission (HELCOM); Denmark, Estonia, the European Union, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. These measures have typically been implemented in response to a general and uniform regulation, i.e. a regulation imposing the same restriction in all areas without considering the variation in the natural reduction of nitrogen. Reaching a further abatement in nitrogen load calls for new and innovative measures and regulation strategies, where measures are targeted towards areas, where the natural reduction is low and the measures thus most cost-effective (Jacobsen and Hansen, 2016). A wide range of different mitigation measures may be employed to combat the nitrogen load from diffuse sources. These may be located on the agricultural fields, e.g. catch crops, at the edge of the fields, such as constructed wetland (MST, 2015) or in the surface water system upstream the outlet to the Baltic Sea. Efficiency of the mitigation measures varies according to the type of measure and where in the hydrological regime they are located. Studies devoted the estimation of optimal location of measures have primarily studied on-field measures, based on the estimation of nitrogen leaching from the root zone and possible protection areas (Hirt et al., 2012; Andersen et al., 2016; Hiscock et al., 2007; Kunkel et al., 2008; Rode et al., 2009). Most studies only consider either the groundwater or surface water system, but fail to include the entire hydrological system and are thereby not able to evaluate whether the optimal location of measures are on-field or in-stream.

Studies at the Baltic Sea scale (Stålnacke et al., 2015) and for Finnish catchments discharging to the Baltic Sea (Lepistö et al., 2006; Huttunen et al., 2016) found a generic relationship between nitrogen retention and the areal fraction of lakes in the different catchments, indicating that retention in lakes is dominating, when the percentage of the area covered by lakes is high. Groundwater is, however, the linkage between the root zone and the surface water system, and nitrate removal was found to be dominated by subsurface processes in other studies within the Baltic Sea Basin, with a small percentage of lakes (Hansen et al., 2009; Hesse et al., 2013; Windolf et al., 2011). Although reduction in groundwater is an important process, it is most commonly only included in a lumped approach in nutrient modelling studies. In a review of the current state of distributed catchment nutrient water quality modelling Wellen et al. (2015) found that most modelling concepts are based on empirical descriptions of groundwater at sub-catchment level, and of the 275 scientific studies included in the review they reported only one study that includes directly simulations of groundwater flow. Some recent studies emphasizes the need to include the groundwater nitrate transport more explicitly in the models (Hesser et al., 2010; Rode et al., 2010), but such studies have primarily been restricted to detailed small scale studies, with few exceptions such as the Danish national nitrogen model (Højberg et al., 2015).

Knowledge on how much and where nitrogen is degraded in the groundwater is a prerequisite for designing optimal cost-effective mitigation measures utilising the natural nitrogen reduction in the subsurface. Spatially variable nitrate reduction in groundwater has, however, only been considered by few studies, either by detailed geochemical modelling (Wriedt and Rode, 2006; Hesser et al., 2010), or by the estimation of travel times and the association of different first-order decay rates for different geological formations (Kunkel et al., 2008; Wendland et al., 2004; Tetzlaff et al., 2013). Assuming the subsurface to be divided into an upper oxic part with no nitrate transformation and a lower reduced part with instantaneous removal of nitrate, Hansen et al. (2014b) studied the impact of a spatially heterogeneous redox interface on the reduction of nitrate in the groundwater. No previous study has focused on the spatial heterogeneity at the Baltic Sea scale. The objectives of the present study are thus to:

- Provide a review of studies addressing nitrate reduction in groundwater in the Baltic Sea Basin
- Develop a map of nitrate reduction in groundwater in the Baltic Sea Basin with best possible spatial resolution, based on a compilation of exiting knowledge