Nitrate transport pathways in riparian zones of the Hagens Møllebæk catchment, northern Denmark

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The Water Framework Directive (WFD) of the European Union prescribes “good ecological status” of all waters. In terms of nitrate this means, among other things, to avoid eutrophication and achieve a good ecological balance in surface water systems for the benefit of the groundwater dependent flora and fauna (Hinsby *et al.* 2012). In Denmark, the nitrate load to estuaries has been nearly halved since the first national action plan was implemented in the mid-1980s, but further abatements are required in many areas to fulfil the WFD. New approaches to regulate nitrate use are needed with measures targeted to the areas where most effect is obtained, and this is recognised at political level. Recent legislation allows farmers to increase nitrate application, but should at the same time introduce new mitigation measures and a more targeted approach to regulation. Therefore the physical system, i.e. the geological framework and topography, of the catchment has to be understood (Winter 1999). Previous studies have shown that in hydrological catchments with high geological variability, sampling of groundwater in riparian zones, the stream water itself and water in the stream bed can help to identify near-stream areas with specific nitrate problems. Detailed studies are, however, not feasible in all catchments, and development of representative typologies to guide an optimal location of mitigation measures in the catchment is thus needed. The present study is a detailed characterisation of nitrate transport and reduction in the groundwater–stream system in the river Hagens Møllebæk catchment for this purpose.

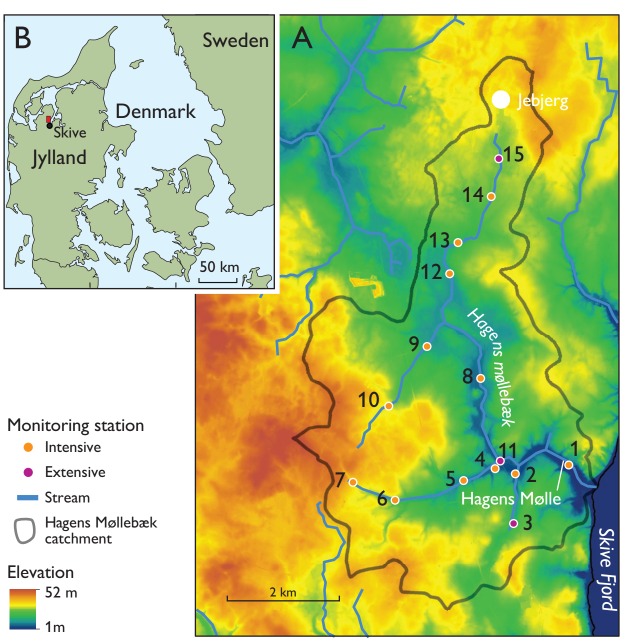

Fig. 1. **A**: Topographical map of the Hagens Møllebæk catchment with locations of nitrate-measuring stations of riparian zones, drain pipe outlets, stream and stream bed. **B**: Index map with position of study area.

Study area and hydrogeological setting

The Hagens Møllebæk catchment is located west of Skive and discharges into Skive Fjord (Fig. 1). The hydrological catchment covers 27.2 km^2. The area is relatively flat with elevations between 1–52 m above sea level (a.s.l.) and slopes near the streams. Quaternary clayey tills dominate in the west and south and glacial meltwater sand and gravel occur in the east. Holocene sand, clay and organic deposits overlie the Quaternary deposits in the stream-valley system and near the outlet of Hagens Møllebæk. In the southern part of the catchment, Oligocene clay with very low permeability is found underneath a few metres of clayey till . The primary land use is agriculture, which covers more than 80% of the area. The soil types are clay (50%), sand (47%) and organic sediments (3%).

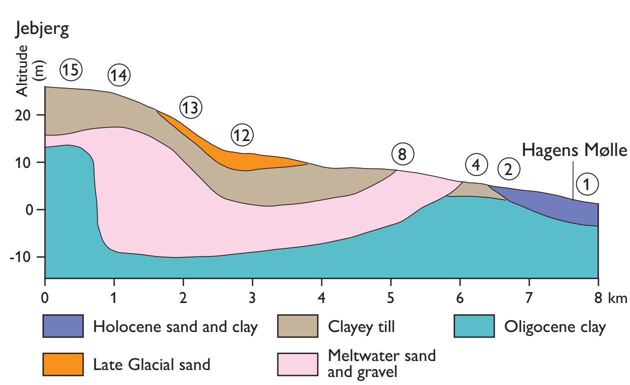

Fig. 2. Conceptual geological profile along Hagens Møllebæk with locations of numbered nitrate-measuring stations along the main stream channel.

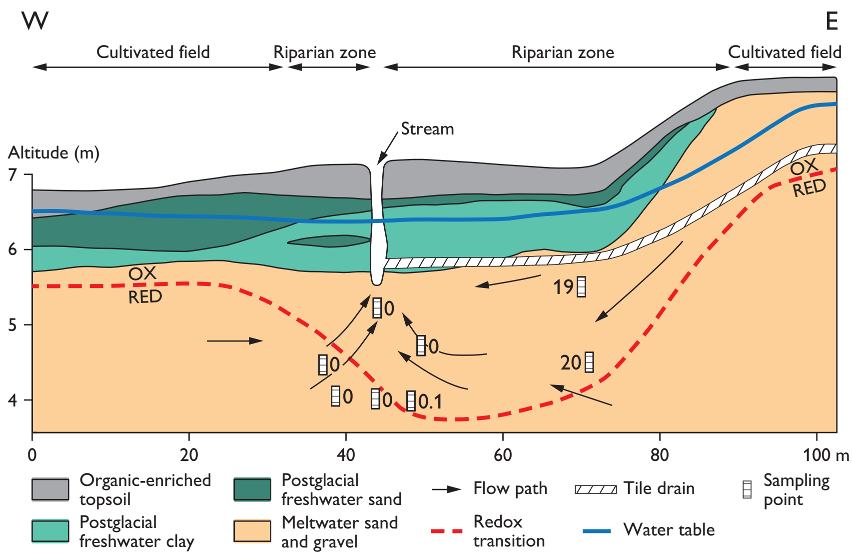

Fig. 3. Example of a cross section along Hagens Møllebæk (10 times vertical exaggeration). The profile represents a riparian hydrological type 6 of Fig. 4A. Nitrate concentrations in NO_3-N mg/l shown in groundwater, stream water and drain water. The water samples were collected in January 2017; the nitrate concentration in the submerged drain pipe outlet was about 15 mg/L, and 5–6 mg/L in the stream water.

Conceptual geological model

A conceptual geological model is presented in Fig. 2 by a profile along the main stream of Hagens Møllebæk from Jebjerg in the north (near station 15, Fig. 1A) to Hagens Mølle (station 1) near the stream outlet into Skive Fjord. The model is based on existing geological data from the Jupiter database and a Quaternary soil map on a scale of 1:200 000 (both found at www.geus.dk). From the conceptual model, a general understanding of the contact and interaction between the stream and the underlying aquifers is established on catchment scale. Between stations 4 and 5 the stream bed overlies poorly permeable clayey tills or Oligocene clay with little or no expected water exchange. Conversely, exchange of water and nitrate between the stream and the underlying aquifer is more likely where the stream bed is located directly on top of sandy aquifers.

Regional contact between aquifers and riparian zones

The local geological and hydrogeological conditions in the riparian zone of the Hagens Møllebæk catchment were characterised at 12 localities by means of geological cross-sections 10–100 m long, from the margin of the riparian zone adjacent to the cultivated field to the margin of the riparian zone on the opposite side of the stream channel (Fig. 3). In each cross-section 8–10 boreholes were hand drilled to depths of 2–4 m and the sediment described at 15 cm intervals. From this geological profiling of the riparian zones, the hydrogeological contact between the stream system and the underlying aquifer was conceptualised according to the typology of groundwater – surface water interaction (GSI; Dahl *et al.* 2007), see Fig. 4A. The hydrogeological settings adjacent to the riparian area aquifer were classified at the twelve cross-sections (Fig. 4B). Combining the regional conceptual model (Fig. 2) and the cross-sections, a preliminary delineation of local or regional sandy aquifers

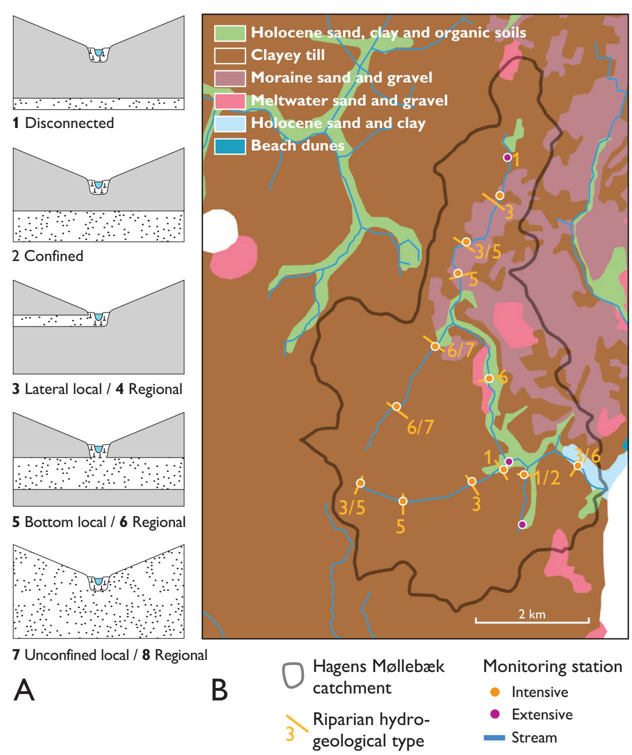

Fig. 4. Riparian zones along Hagens Møllebæk and its tributaries, divided into riparian hydrogeological types. **A**: Eight conceptual hydrogeological models of the riparian zone with different combinations of deposits with high (white-dotted) and low (grey) permeability (from Dahl *et al.* 2007). **B**: Classification of 12 cross-sections in the study area into types of riparian hydrogeological contacts (see also main text).

was obtained (Fig. 5). Further detailed field instigations are still needed at six of the locations to distinguish between local and regional aquifer characteristics. It is evident that stream reaches along the headwater of the stream system have contact to local shallow aquifers, and that the more central and down-gradient parts of the stream system have contact to a regional sand aquifer.

Observed exchange between stream water and groundwater

Stream discharges were measured on the same day in August 2016 at all stations using an OTT acoustic digital current meter (OTT Hydromet GmbH). The groundwater flux to the stream system, quantified as the so-called specific baseflow, was calculated as the change in flow (Q in L/sec) between an upstream and downstream location, divided by their distance along the stream. The specific baseflow for the summer day in August 2016 is shown in Fig. 5B. The first-order streams provide the lowest inflow rates of groundwater to the stream (0–5 L/sec/km) because of limited or no interaction between the stream system and groundwater aquifers. Higher-order (more down-gradient) stream reaches provide 5–25 L/sec/km. Along a shorter reach between stations 4 and 5 the tributary loses water through the stream bed to the underlying shallow aquifer.

At the twelve intensively monitored stations (Fig. 1A), 8–10 piezometers were installed along the cross-sections using metal or polyethylene (PEH) pipes with a screen length of 10 cm (metal) and 30 cm (PEH). The metal piezometers were pushed into the subsurface with a pneumatic hammer. The PEH pipes were manually pushed into the open boreholes for geological characterisation. All piezometers were levelled using the Trimble® R8 GPS system (vertical accuracy ±16 mm). Vertical changes in the hydraulic heads between the water table in the stream (i.e. the water stage) and the intakes of the piezometers about 0.5 m below the stream beds were measured with an accuracy of ±1 cm. Negative, vertical, hydraulic gradients indicate recharge to the groundwater aquifer, whereas positive gradients indicate discharge of groundwater into the stream. This made it possible to identify stream reaches where the exchange and direction between the stream and the aquifer can be assessed. The measurements carried out from August 2016 to January 2017 showed similar spatial distributions. This means that the vertical hydraulic gradients were positive along most stream reaches indicating groundwater discharge to the stream during the period August 2016 – January 2017.

Based on the detailed conceptual understanding of the local hydrogeological setting, the quantitative determination of baseflow and hydraulic gradients, the groundwater–stream interaction at the monitoring stations can be assessed. No or limited groundwater–stream interactions were found at stations 2–4, 6 and 15, while some or significant groundwater–stream interaction is expected to occur at stations 1 and 8–14 between the stream system and an

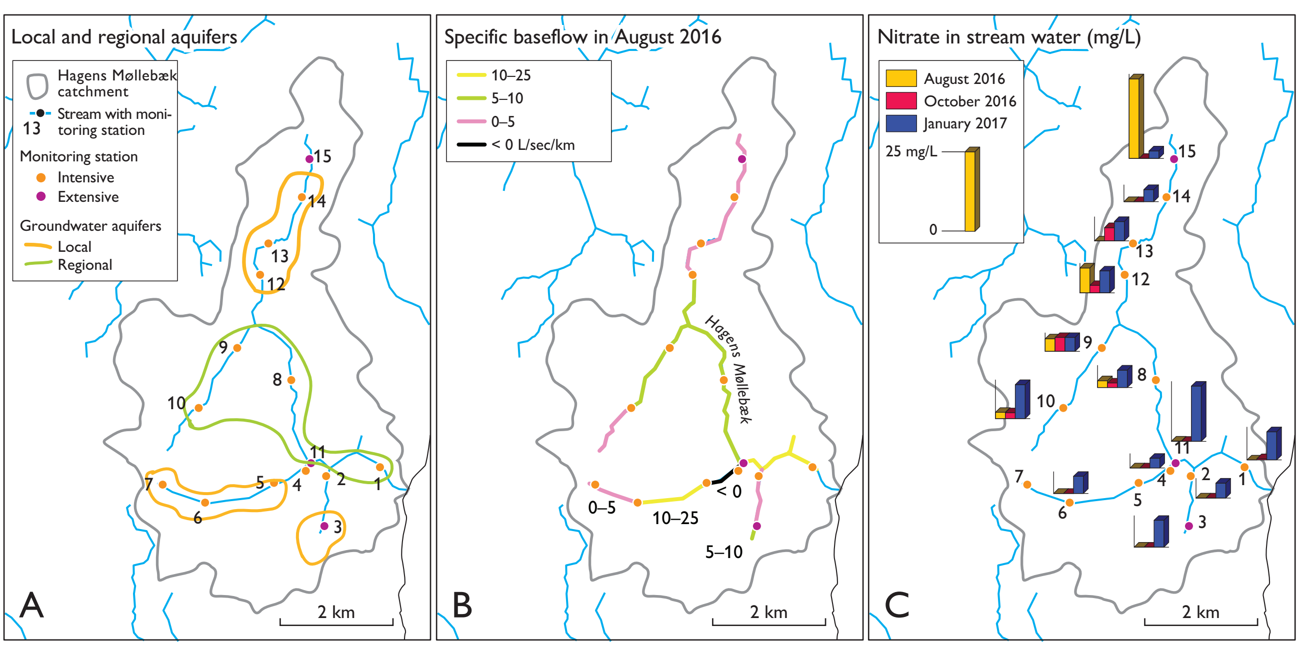

Fig. 5. Aquifers and nitrate in the Hagens Møllebæk catchment. **A**: Delineation of local and regional groundwater aquifers underneath the river system in contact with the river bed at the monitoring stations. **B**: Estimated specific base flow for individual stream reaches in August 2016. **C**: Nitrate concentrations in stream water sampled in August and October 2016 and in January 2017.

underlying sandy aquifer of local or regional extent. Further investigations of the hydraulic conditions are required at stations 5 and 7 before these can be classified.

Exchange of nitrate between groundwater, drains and stream water

The nitrate transport pathways in riparian zones were assessed by collecting water samples from groundwater in the riparian zones, in drain-pipe outlets, in the stream bed and in stream water. Groundwater samples were collected from the piezometers using 100 mL syringes. Drain-pipe outlets to the stream were only observed near five of the cross-sections (stations 4, 5, 8, 10 and 12). Water from drains having outlets above the water stage in the stream was sampled by filling a bottle directly from the outlet. Sampling of drain water from outlets below the water stage was more critical. Here a 2–3 m long, 5 mm tube was pushed into the drain pipe and a sample collected with a 100 mL syringe. The stream water itself was sampled by filling a bottle of water flowing past the monitoring station. All water samples were analysed for nitrate (NO_3-N) few hours after collection using a portable PhotoFLEX STD photometer (WTW GmbH, Weilheim).

In the cross-section of the riparian zone shown in Fig. 3, groundwater samples with nearly 20 mg/L were collected in the oxic zone 25 m east of the stream, decreasing to 0 mg/L underneath the stream bed. Normally, nitrate is not degraded in the oxic zone and the observed disappearance of nitrate in the riparian zone is likely due to the presence of microniches in the meltwater sand and gravel layer enriched with organic matter or pyrite, where nitrate degradation may occur. Moreover, it is possible that simultaneous discharge of nitrate-free groundwater into the riparian zone and stream bed may dilute the nitrate concentration in the groundwater in the riparian zone. At present we do not possess field data on a sufficiently detailed scale to support this hypothesis.

The stream water at the 15 measuring stations contained less than 5–6 mg/L of nitrate in the three sampling rounds in August 2016, October 2016 and January 2017, as expected with the highest values in January 2017 (Fig. 5C). At all the stations we have monitored, the riparian zone seems to be efficient in removing nitrate from the groundwater. However, leaching of nitrate from the nearby agricultural areas through drainage pipes can bypass the riparian zone and enter the stream system.

A river gauging station was established by the Ministry of Environment and Food of Denmark in December 2016 at the same position as station 1 in the present study. The gauging station measures the total river flow and nitrate runoff from the Hagens Møllebæk catchment to Skive Fjord. The preliminary results of this study indicate that it is useful to establish a dense monitoring system along streams to complement the new gauging monitoring station. We expect that this type of instrumentation can deliver the necessary insight to locate where nitrate-mitigation measures will be most effective.

Conclusions

After the first six-months' monitoring period (2016–2017), it seems likely that the nitrate loads to the streams in both summer and winter conditions almost entirely arise from nitrate transported by agricultural drains to Hagens Møllebæk. However, a longer monitoring period of two to three years is required to conclude this with more confidence.

In the Hagens Møllebæk catchment, riparian zones along the stream reaches with widths from a few metres to 10 m seem to be very efficient in removing nitrate from groundwater before it discharges into the stream. However, drainage pipes allow nitrate-rich water to enter directly into the stream system bypassing the riparian zone.

Acknowledgements

This work was funded by the Innovation Fund Denmark through the project Future Cropping. The authors wish to thank Bo V. Iversen and Peter K. Engesgaard for constructive comments.

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