

Submarine groundwater discharge as a source of nitrogen to the Laholm Bay, southwest Sweden.

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Summary.

Nitrogen originating from agricultural activities causes excessive eutrophication in the Laholm Bay and other Swedish coastal areas.

An unknown portion of this nitrogen is transported directly to the nearshore and bottom sediments by submarine groundwater discharge.

Since 1986, near-shore and submarine groundwater discharge has been studied in the Laholm Bay by combining various geophysical, hydrogeological and other methods, such as reconnaissance drillings, geoelectrical and seismic soundings, airborne infrared thermal scanning, porewater salinity surveys, and seepage meter measurements.

An area of approximately 25 km² which is drained directly to the sea via groundwater has been studied in detail. Most shallow groundwater enters the sea within the foreshore, near the shoreline, or in a distance of less than 30 m from the shore. A part of the deeper groundwater probably enters the sea via nearshore seepage zones, 30 to 100 m from the shoreline. In addition, there are indications of a hydraulic connection between deeper semi-confined aquifers and several minor, high-permeable areas located farther offshore.

In spite of high nitrate concentrations in groundwater of arable areas, low nitrate concentrations have been found in nearshore groundwater, particularly during summer. Most of the groundwater nitrate is obviously removed by denitrification or other processes before reaching the sea. It is suggested that similar nitrate-reducing zones might be created artificially in other areas in order to reduce high nitrate leaching rates.

Introduction

Losses of nitrogen from cultivated land are thought to be responsible for the eutrophication of marine coastal areas in several parts of the world. Agricultural activities also frequently result in the pollution of shallow groundwater reservoirs by nitrate. Traditionally, most of agriculturally derived nitrogen has been believed to be transported toward the sea by rivers. Direct inputs of nitrate by groundwater have not been considered. There are several reasons why these inputs might be important in some areas (11):

a) Nitrate concentrations in groundwater are commonly several orders of magnitude higher than concentrations in unpolluted sea water. Thus, even minor inputs of nitrate-rich groundwater may have significant effects on the eutrophication in the sea. For example, in the Laholm

coastal plain the groundwater usually contains about 10 mg/l NO₃-N (26), whereas the sea water in the Bay contains only about 0.15 mg/l NO₃-N before the spring bloom, and much less during summer (6).

b) Groundwater nitrate influences directly the benthic communities and near-bottom water layers, and may not be mixed and transported away by the wave and current action as easily as river water does.

c) There may be differences in the timing of groundwater and river water inputs to the sea. Groundwater inputs are likely to be less variable throughout the year with respect to both magnitude, temperature and nitrate concentrations.

Until recently, nutrient inputs by groundwater to marine coastal areas have been studied mainly outside Europe, e.g. in USA (1,2,9,21,22), South Africa (17), Australia (12) and elsewhere (4,15,27).

In Sweden, studies of the relationship between groundwater and sea water have almost exclusively dealt with sea-water intrusion and related problems (5,16). Only occasionally have submarine groundwater discharges been studied or discussed, e.g. in connection with airborne infrared imagery surveys (7,23), or when investigating pockmarks and other peculiar bottom structures observed in some areas (e.g., the Stockholm Archipelago) (25).

In the Laholm Bay, as well as in other South Swedish and Danish coastal areas, several serious fish kills and oxygen depletions in the near-bottom water have been reported during the last decade. Nitrogen losses from extensively cultivated coastal lowlands are believed to be responsible for a great deal of these problems (6). Recently, a number of restrictive measures have been suggested in order to lower N losses by 50% within the next few years.

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Site description and geohydrological conditions

The Laholm Bay is situated at the SW Swedish coast as a part of the Kattegat (Figure 1). The mean water depth of the Bay is about 10 m, and the area is about 300 km². Bottom sediments consist of clay and silt, covered mostly by a thin, variable sandy layer. Smaller areas with gravel also occur (Figure 2). Water salinity above the halocline ranges usually between 15 and 22 ‰ (i.e., ca 2200 to 3100 mS/m). Under the halocline, which usually lies in the depth of 10 to 20 m, salinity is higher, about 25 to 33 ‰ (ca 3430 to 4680 mS/m) (6,10).

Geologically, the area is rather heterogeneous, being covered by variable layers of glacial and littoral sediments. Minor outcrops of gneisses and granites occur in the near-shore zone, but in general the bedrock is found 20 to 100 meters below the surface. In the southern part sedimentary bedrock of Cretaceous age occurs. The border between sedimentary and precambrian bedrock (i.e. gneisses and granites) is striking NNW-SSE and continues outside the coast. Most of the Laholm coastal plain consists of a flat lowland, gently sloping towards the sea. This lowland covers 770 km², up to the elevation of 40-55 m a.s.l., and consists mostly of cultivated land.

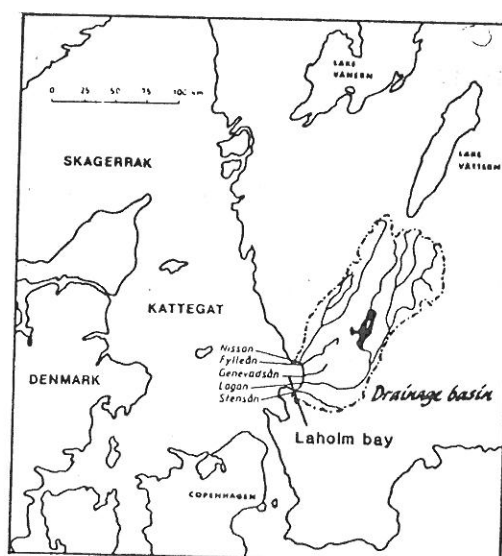


Figure 1: The location of the Laholm Bay in southwestern Sweden (6).

The near-coastal zone of the Laholm Bay consists of a relatively thin layer of littoral sand, 2 to 7 m thick. This upper sand creates a shallow, unconfined aquifer with relatively high hydraulic conductivities, commonly between 10^{-4} and 10^{-2} m/s. The surficial sandy layer is underlain by a thick sequence of low-permeable glacial clay. Under the clay highly permeable glaciofluvial and till-like sediments are found. These make up a lower, confined or semi-confined aquifer, often exhibiting artesian flow when penetrated in the lower, near-coastal areas. This deeper aquifer is fed from several inland areas, where glacial clays are thinning out and numerous glaciofluvial esker and delta sediments are present in unconfined conditions (Figure 3) (13,18).

Most of our investigations were done within a 19 km long coastal strip running from the river Stensån northwards (Figure 1). This area is drained by three main rivers, namely Stensån, Lagan and Genevadsån. In addition, 25 km² is drained directly towards the sea, mainly via groundwater (Figure 2).

Shallow groundwater discharging at or above the shoreline is directly observable as: (i) short drainage ditches dug in the southern, built-up part of the area; (ii) visible groundwater discharges within the foreshore, sometimes coloured by iron and manganese precipitates; (iii) a groundwater-discharging horizon just under the mean sea level, clearly visible during low sea level periods.

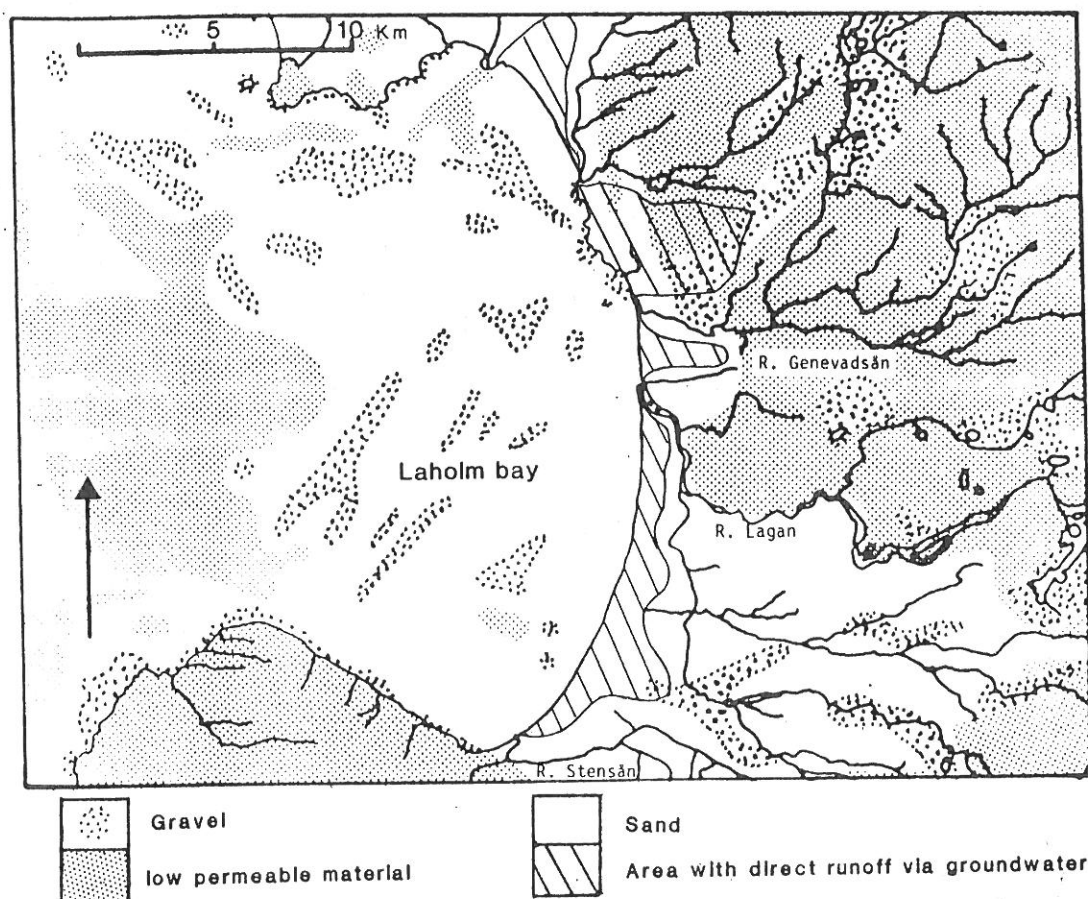


Figure 2: Hydrology and surficial geology of the Laholm Bay and the adjacent coastal plain (compiled from 10, 13, 18).

True submarine groundwater discharges have also been observed in some areas and originate probably in both shallower, unconfined and deeper, semi-confined aquifer. Up to date, most of these discharges have been found at a distance of less than 100 m from the shoreline, but several discharge areas located 1 km from the shore are also suspected.

Methods

Available geological data (stratigraphy, permeability etc.) were completed by a number of shallow (1.5 to 7 m) auger holes and reconnaissance drillings. These holes were also equipped with 25 mm plastic tubes slotted near the bottom, in order to sample water and measure groundwater levels. Unfortunately, many observation tubes were lost due to vandalism and/or sand movements during heavy autumn storms.

Stratigraphy of deeper layers and salt water intrusion were investigated in several places by applying geophysical methods: geoelectrical and seismic sounding.

Nearshore groundwater discharge zones have been mapped by visual observations (particularly during low sea level periods), thermal infrared scanning (7), porewater salinity surveys along the shoreline, and seepage meter measurements.

Pore water from different sediment depths down to 1.5 m has been sampled by means of a 10 mm OD stainless steel pipe equipped with a filter tip of sintered bronze (Krebbsöge AG, W Germany) or other porous material (depending on the grain size of the sediment), and an inner PVC tubing (3 mm ID), connected to a 50 ml injection hose.

Advection water streams which are created in seabed sediments due to small pressure differences caused by groundwater discharge and/or wave + water level movements, have been measured by so-

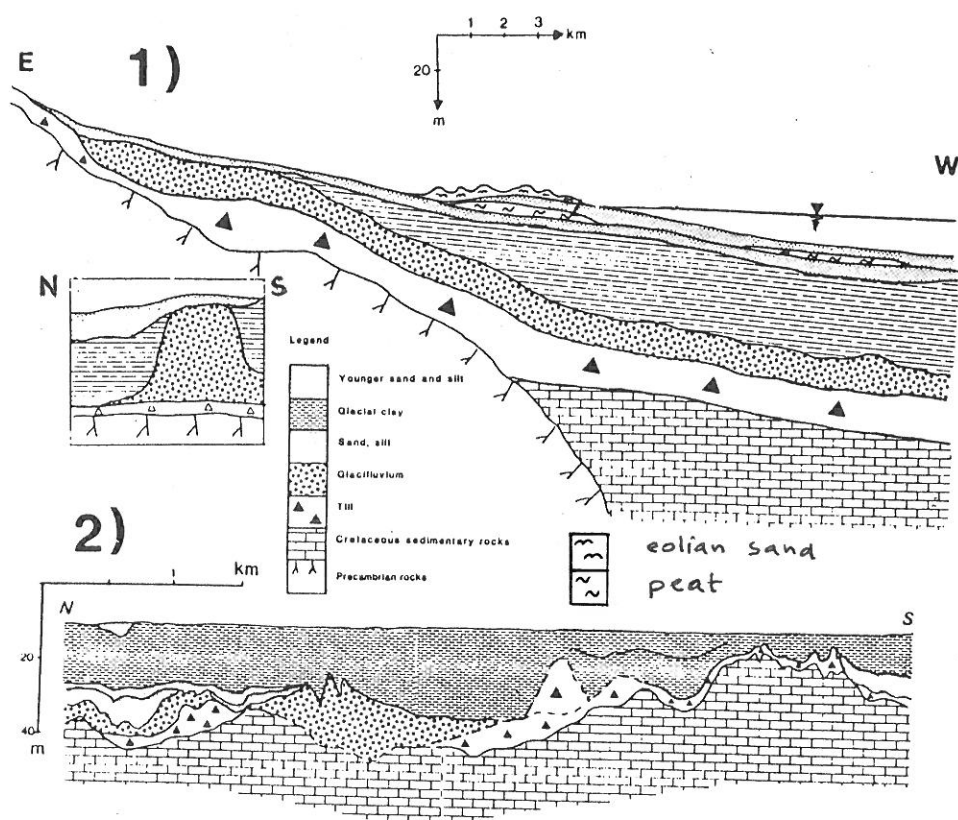


Figure 3: Cross-sectional geological/stratigraphical profiles of the Laholm-area. 1/ A schematic profile from E to W. 2/ A section, N - S, from the southern parts of the Laholm Bay, c. 3 to 4 km from the beach, compiled from seismological investigations by the Swedish Geological Survey.

called seepage meters. These consist of a bottomless container laid on or pressed slightly into the sediment and connected with a readily inflatable plastic bag (Figure 4). In our study, a smaller type of seepage meter (area 0.0625 m^2) made from a plastic barrel has been used, similarly as in (15) and (27). Different modifications of seepage meters with regard to their area (up to 1.2 m^2) and depth of penetration into the sediment have also been tested and will be reported elsewhere.

Water temperature and specific conductance (mS/m) were measured in situ by portable meters. Concentrations of nitrate and ammonia were determined in HgCl_2 -fixed water samples by using auto-analyser (Technicon no.2) and, partly, by test-kits (HACH® Co), frequently checked against the auto-analyser results. Relative differences in specific conductance of sea sediment were also measured in situ by lowering the unprotected probe of a portable conductance meter directly into the sediment. It has been found in laboratory tests, that values obtained in this way are closely correlated with the salinity of pore water, but are also influenced to a certain extent by the grain size of the

sediment (the finer grain-size, the higher apparent specific conductance of the sediment).

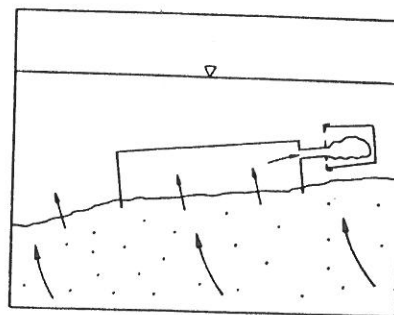


Figure 4: Seepage meter and its function (modified from ref. 14)

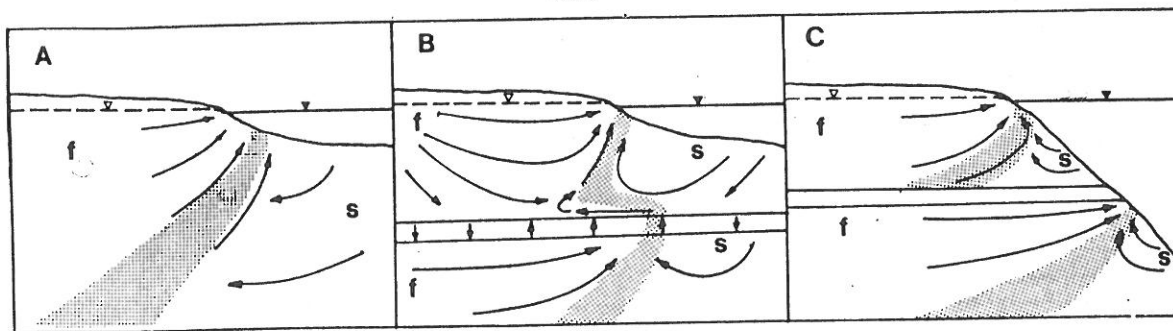


Figure 5: Some possible configurations of the interaction between fresh groundwater (f) and salt sea water (s). In shaded areas occurs mixing due to the diffusion and advection.. A/ unconfined aquifer; B/ two aquifers separated by a semi-permeable layer; C/ unconfined and confined aquifers, separated by an impermeable layer (modified from ref. 3, 8 and 11)

Results and discussion

Interaction between groundwater and sea water

Under geologically homogenous and hydraulically stable conditions the groundwater discharge into the sea will have one of the patterns shown in Figure 5.

In practice, however, this theoretical pattern is almost always modified by some of following factors:

- heterogeneity of geological materials with respect to their permeability and stratigraphy;
- fluctuations in groundwater and/or sea water levels and pressure variations at the bottom caused by wave action and other water movements;
- changes in the sea water and porewater salinity due to inputs (via rivers, rain etc.) or outputs (evaporation) of fresh water.

The Laholm Bay receives fresh water inputs from several rivers, surficial brackish water from the Baltic via the Öresund, and deeper, saline sea water from the Kattegat and Skagerrak. As the bay is strongly wind-exposed, varying weather conditions often lead to sudden changes in the salinity of near-shore water. During high water levels and/or storm weather periods, beaches are washed by the well mixed sea water of higher salinity. During calm periods, this water is either diluted by the inflowing fresh groundwater, or becomes more saline due to the evaporation or outfreezing processes.

All these factors lead to a rather high local and temporal variability in the salinity and nitrogen content of the near-shore porewater (for examples,

see Figures 6 and 7). Usually, however, most groundwater enters the sea within the first 10 to 30 m of the shoreline.

Seepage meter measurements have only partly supported groundwater discharge patterns suggested from porewater salinity observations. Even if maximal seepage rates are usually found in the locations nearest the shoreline, high seepage rates have also been recorded at relatively large distances from the shore, where significant inflows of fresh groundwater are less probable (Figure 7). These high seepage rates are probably caused by advection streams within the sediments, created by the wave and tidal action ("tidal pump" and "sub-tidal pump" of Riedl and others - 19,20,24). Advection streams are known to play an important role in the water, oxygen and nutrient cycling within shallow (down to 200 m water depth), sandy sediments. Forthcoming investigations of their importance in the Laholm Bay are currently under preparation.

In several places, strong submarine groundwater discharges have been observed. This was the case of several small brooks or ditches, infiltrating into the sand only some 10 to 20 meters before reaching the shoreline. Measurements of spec. conductance in the porewater and bottom sediments have shown that also here, most of the water entered the sea within the first 30 m from the shoreline.

Finally, an extensive seepage zone has been recorded some 30 to 100 m offshore in the southern part of the area (Figure 7). Seepage rates in this area were as high as $4.73 \text{ } \mu\text{m/s}$ (i.e., $4.73 \text{ ml/m}^2 \cdot \text{s}$), and the bottom consisted of cobbles, stones and sand. Nitrogen concentrations, however, were low. It is believed that this area is in direct hydraulic connection with a partly buried esker found on the surface some 2 to 8 km landwards, and also with

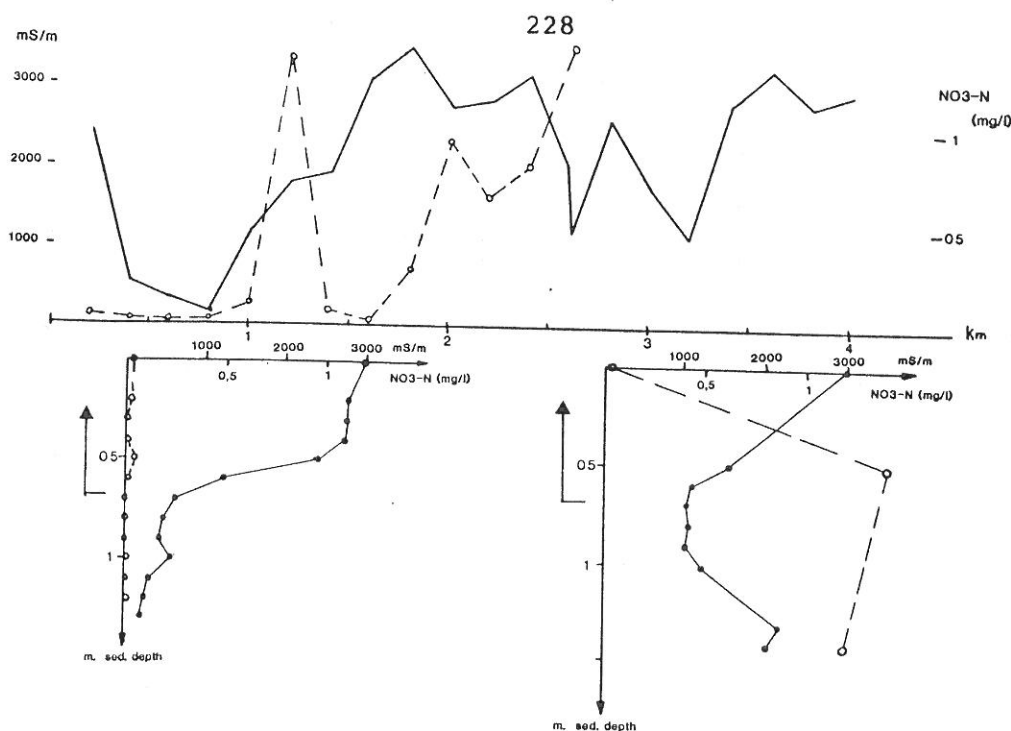


Figure 6: Spec. conductivity (full line) and nitrate concentrations (broken lines) in the water sampled along the shoreline at sediment depth of 50 cm (above) and in depth profiles (below). May 16, 1987, shoreline just south of river Lagan.

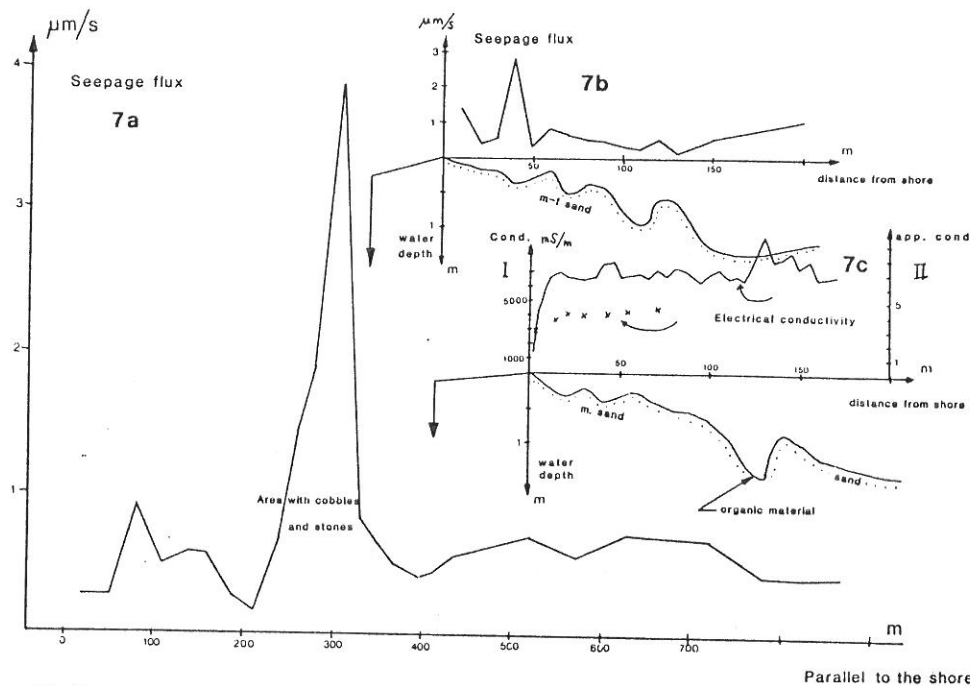


Figure 7: Seepage rates and spec. conductance profiles in the southern part, north of river Stensån, July 23, 1987. 7a/ S-N profile parallel with the shoreline in a water depth of 50 cm (c. 20 to 30 m from the shore); 7b/ Seepage flux and bottom relief in an E-W profile, perpendicular to the shoreline; 7c/ spec. conductance in the bottom-near water (I) and apparent spec. conductance measured 1 to 3 cm down in the sediment (II) in an E-W profile.

two small submarine ridges consisting of stones and cobbles and located ca 1 km offshore at a water depth of 10 m. These connections, however, have not yet been proven satisfactorily. Similar hydraulic communications between the semi-confined aquifer and submarine bottom formations are suspected also in other parts of the Laholm Bay.

Estimation of total water and nitrogen runoff

Between the rivers Stensån and Lagan, an area of approx. $10 \times 1.5 \text{ km}^2$ is drained directly towards the sea (Figure 2). In the near-shore, built-up areas, more than 30 short drainage ditches have been dugged through big eolian beach dunes in order to lower locally high groundwater levels and to facilitate water runoff. During 1986-88, these ditches were sampled at several occasions. The ditches transported totally between 16 and 40 l/s of water and 1 to 4 kg/d of $\text{NO}_3\text{-N}$.

The annual water runoff from this area is 350 mm (13), which corresponds to 170 l/s in total. Thus, ditches transport only 10% of the total groundwater runoff.

The total transport of groundwater nitrate to the sea is more difficult to estimate. Sometimes, mainly during winter and spring, nitrate concentrations in coastal seepage areas are higher than those in the adjacent ditches or sea water (Figure 6). During summer, however, or in areas with visible iron and manganese precipitates, nitrate concentrations in the groundwater reaching the sea are low, or unmeasurable. Obviously, most of the groundwater nitrate is lost to the atmosphere on its way from the arable land to the coast, or converted to bacterial biomass or ammonia. As a conservative estimate we may conclude that the total nitrogen runoff from this area is less than 40 kg/d, i.e. less than 10 kg/ha.yr.

These estimates are only preliminary. A coupled hydrogeological/hydrochemical model of the area, which is currently under development, will hopefully give estimates with higher accuracy. This model should also be applicable for the evaluation of water and nutrient transport via groundwater in other coastal areas.

Nitrate-removing zones

The above estimated loss of nitrogen, though preliminary, is low when compared to the mean annual losses of nitrogen calculated by Fleischer et al. (6) for different parts of Laholm Bay's drainage area: 65 to 92 kg/ha for coastal farmland, 56 to 84 kg/ha for the transitional region, and 10 to 34 kg/ha for South Swedish uplands. It is obvious that

near-coastal, non-agricultural area may act as an effective filter removing most nitrate brought in by groundwater flow.

In this removal, two mechanisms are likely to be of a key importance:

- (i) denitrification in land areas where peat layers are found in the soil profile. Such areas are common in the southern parts of the Laholm lowland (18) and groundwater there is often low in nitrate (T. Kindt, pers. comm.). It is speculated, that reduced near-shore groundwater precipitating iron and manganese may originate from such peat-containing areas.
- (ii) Denitrification in the near-shore zone, mainly due to the decomposition of organic material, frequently thrown up and imbedded within the beach sand during stormy periods. Such organic-rich layers have been encountered many times during our study, and are probably responsible for commonly observed high ammonia levels (up to 7 mg/l $\text{NH}_4\text{-N}$) in the near-shore porewater. Nitrate-removing zone of this type has been studied in the area just north of the river Genevadsån, where shallow groundwater some 90 m from the shore contains 6 to 10 mg/l $\text{NO}_3\text{-N}$. Yet, hardly any nitrate reaches the sea. The most active denitrification zone is probably less than 20 m wide.

Other authors studying the transport of groundwater nitrate to coastal areas have usually reported a close correlation between low salinities and high nitrate concentrations within groundwater seepage zones (2,4,12). In these areas, an effective denitrification was probably limited by the scarcity of oxidizable organic carbon (22). Our results indicate, however, that nearshore coastal areas may remove nitrate effectively. We suggest that similar nitrate-removing zones might be created in other areas, e.g. along rivers within coastal farmland where high nitrate leaching rates are common. We feel that such zones or artificial filters based on similar principle might be more effective in nitrate removal than other measures suggested in the literature (6), such as large-scale modifications in agricultural practices, or restoration of formerly common non-regulated streams and wetlands.

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