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Groundwater flow conditions in the coastal bedrock area of the Gulf of Finland

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The coastal area and archipelago of the Gulf of Finland mostly comprises bedrock terrain with a generally thin soil cover and represents a distinct hydrogeological regime. The bulk of the bedrock area consists of relatively unbroken blocks with small, hydraulically uniform systems. The direct groundwater flow from the blocks to the sea is restricted to the blocks bordering the sea. The blocks are crossed by faults and fractures, which locally form long broken zones inside the rock mass. A single fault can catch water from several blocks and also from the soil cover. Most groundwater in the coastal strip flows to the sea through the bedrock fault zones, which are thought to represent the most favourable flow conditions. The dimensions of hydraulically uniform horizons, hydraulic conductivities and hydraulic gradients of the fault zones are poorly known. The estimated groundwater flow distance from the land to the sea in the faults reaches 8–10 km, thought the average distance may only be around 2 km. In the block areas the flow distance is even shorter, down to about one kilometre. On the whole, the amount of groundwater discharging directly to the sea from this regime (excluding overlying sand and gravel deposits), which has a surface area of around 2100 km^2, is approximately 4 $m^3 s^{-1}$. This is a third of the total direct discharge to the sea in the coastal areas of Finland.

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INTRODUCTION

The coastline of the Baltic Sea has a varied hydrogeological environment. The southeastern coast-line between Denmark and Russia comprises soil as well as consolidated sedimentary strata (Fig. 1) which, being generally thick and having often high effective porosity, can store large amounts of groundwater. Discharge to the sea is continuous and the hydraulic connections can reach for tens of kilometres from the shore. By contrast, the Finnish–Swedish coastline of the Baltic Sea, including both the Gulf of Finland and the Gulf of Bothnia, comprises mainly Precambrian basement with scattered, mostly thin soil cover. Having only low porosity and limited hydraulic connections the ability of the bedrock to store and conduct groundwater is negligible compared with the sedimentary strata. However, because the length of the coastline in Finnish–Swedish side represents roughly two third of the total shore length of the Baltic Sea, its role as regards discharge should not be underestimated. Unfortunately the flow conditions in the bedrock itself are poorly known, complicating the discharge estimations. Around the Gulf of Finland, the discharge from the soil cover (excluding sand and gravel deposits, which constitute a separate hydrogeological regime) represents only minor part of the total inflow.

In this study the groundwater flow conditions and possible flow distances from the coastline are discussed in order to create a basis for a discharge estimation. The total amount of direct groundwater inflow to the Baltic Sea is also discussed. The study is based on combining a model of the geological structure of the bedrock with observations obtained from bedrock and from the overlying soil during hydrogeological field work. Such work has been carried out around the towns of Hyvinkää, Helsinki, Porvoo and Vantaa (*cf.* Fig. 2) as well as in many other sites along the coastal area. Field studies have included observations: of hydraulic connections (by pumping tests); of the hydraulic heads of aquifers and adjacent strata as well as of nearby wells; of head differences between different parts of crystalline bedrock (including fault zones); and of hydraulic connections between bedrock and the overlying soil (Salmi, 1985). Field investigations have mostly been made in dry seasons.

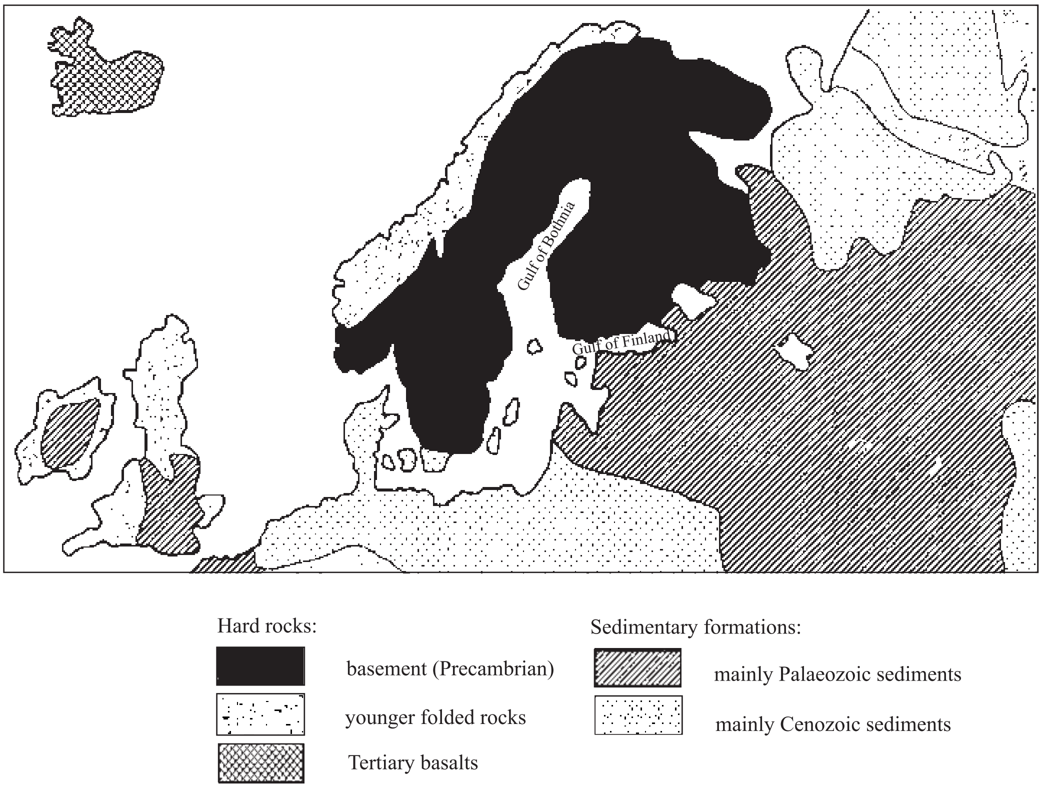

Fig. 1. Geological features of northern Europe according to the Tectonical Map of Europe (Encyclopaedia Fennica, 1965)

OVERALL GEOLOGICAL AND HYDROGEOLOGICAL STRUCTURE OF THE STUDY AREA

The study area is the coast on the northern side of the Gulf of Finland including part of the archipelago. The central, representative part of this area is shown on Figure 2.

Morphologically, the area is a peneplain, which has developed over almost two thousand million years. Five kilometres from the seashore, the ground surface (especially in valley-areas) has typically ascended only some ten metres above sea level. Bedrock is well exposed, particularly on low hills, separated from each other by soil covered valleys.

The main rock types are gneisses, migmatites and granites, the last including Rapakivi-granite in the eastern part of the area. The scattered soil cover, mostly under ten metres thick, consists most commonly of silt, clay and ground moraine over low-lying ground and partly washed moraines in the hills. Eskers and ice-marginal and littoral deposits comprise the most important, if local, sand and gravel deposits (Fig. 2).

The average porosity of the bedrock is 0.1–0.5% (Salonen *et al*., 2002) representing for the most part effective porosity. In the upper part of the rock (up to 100 m below the surface) the hydraulic conductivity varies roughly between 10^{-6} and 10^{-8} m s^{-1} (Ahlbom *et al*., 1991). The silt and clay, which have almost no effective porosity, conduct practically no groundwater, but promote surface runoff and evaporation. The composition of the moraines is variable, from clay-silt moraines to sand moraines. The porosity of moraines is at most 17% (Salonen *et al*., 2002). In ground moraines the average effective porosity is mostly below 5% and hydraulic conductivity is poor, between 10^{-7} and 10^{-9} ms^{-1}. The effective porosity of washed moraines is higher, approximately 5–10%. The hydraulic conductivity varies usually between 10^{-5} and 10^{-7} ms^{-1}. Sand and gravel deposits have effective porosities of 20–30%. The horizontal hydraulic conductivity commonly reaches 10^{-1} ms^{-1} (Mälkki, 1979), but varies e.g. by ice-marginal formation of Hanko area usually between 5×10^{-5} ms^{-1} to 10^{-3} ms^{-1} (Peltonen, 2002).

Groundwater occurs in more or less separate zones in both the soil and bedrock. The groundwater level is close to the ground surface. The low gradient of the ground surface, especially in valleys, means also that the hydraulic gradient of the groundwater level towards the sea is generally low, at an estimated 2–4%. In hill areas, the gradient — if measurable — is much higher. Very often water is, however, partly "dammed" in small separate joint- and fracture systems near the top of the hills (*cf*. Fig. 5). Flow towards the valleys takes place partly as overflow, mainly during wet seasons when the storage capacity of the joints is exceeded. Because of this, the estimation of hydraulic gradient in block areas is difficult.

In the hill areas where bedrock is commonly exposed, approximately 30% or more of the precipitation infiltrates into the bedrock, depending on the intensity of jointing and of rainfall. During small or even moderate rains the surface runoff can be, on well jointed exposures, small compared with the precipitation, indicating a high infiltration coefficient. During heavy rain the surface runoff is high, and infiltration decreases. The evaporation time is short in those conditions and, because vegetation is sparse, evaporation represents only a minor part of the water balance. The conditions change from outcrop to outcrop and it is not possible to determine the exact water balance.

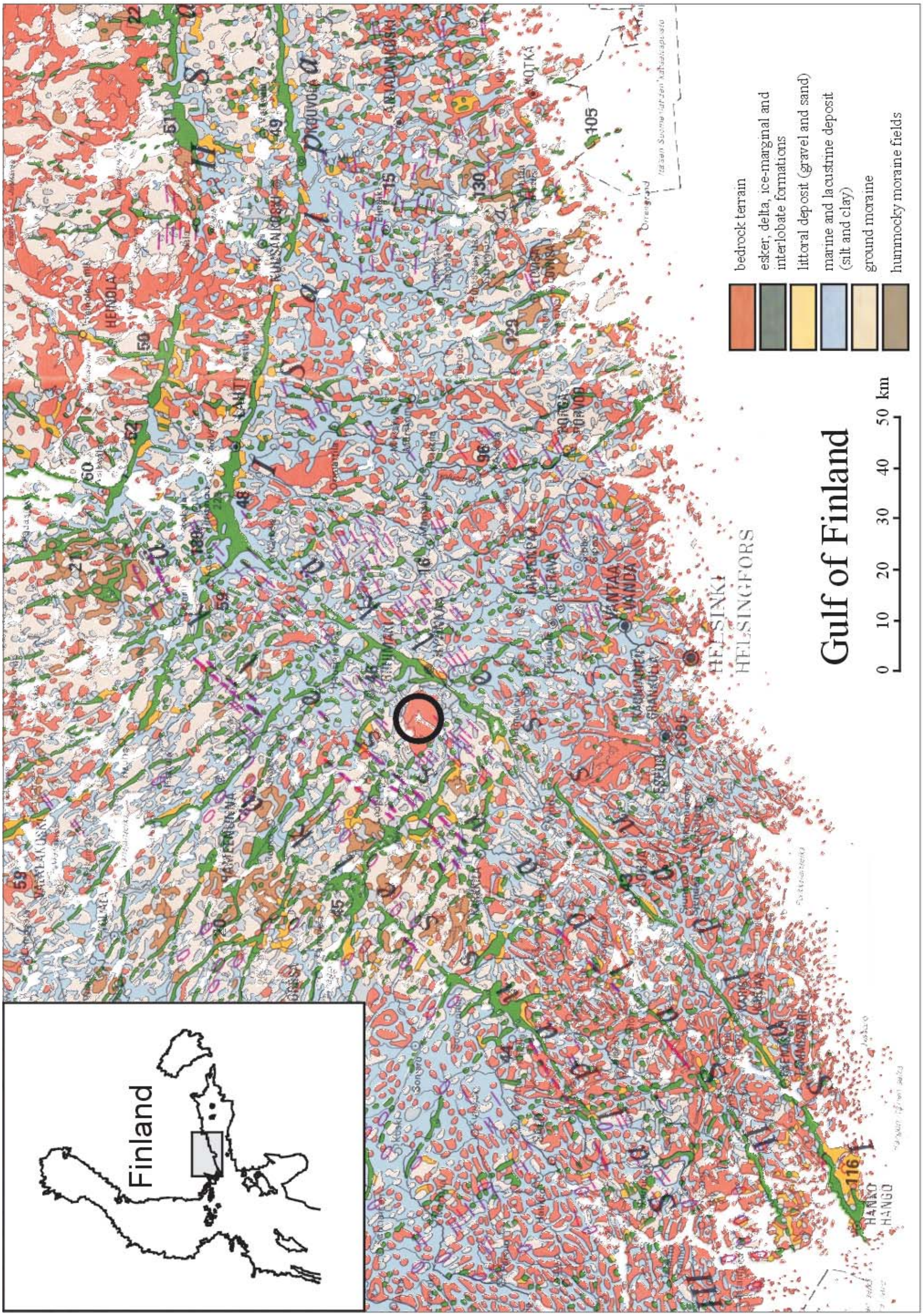

Fig. 2. Quaternary deposits of Finland (southern coastal area) from the map by Kujansuu and Niemelä (1984, modified)
The circle indicates the site of the area shown in Figure 4

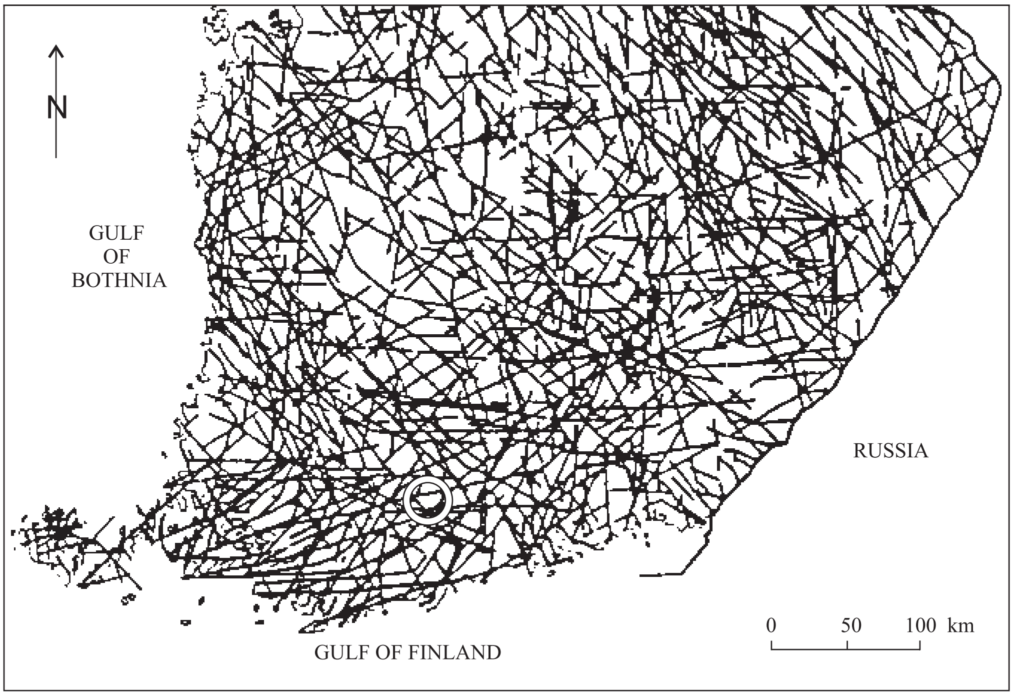

Fig. 3. Main fault zones of South Finland (Vuorela, 1982)

The circle indicates the site of the area shown in Figure 4

Fig. 4. Blocks of rock mass cut by faults, Hyvinkää, South Finland (Mälkki, 1999)

For location of map area see Figures 2 and 3

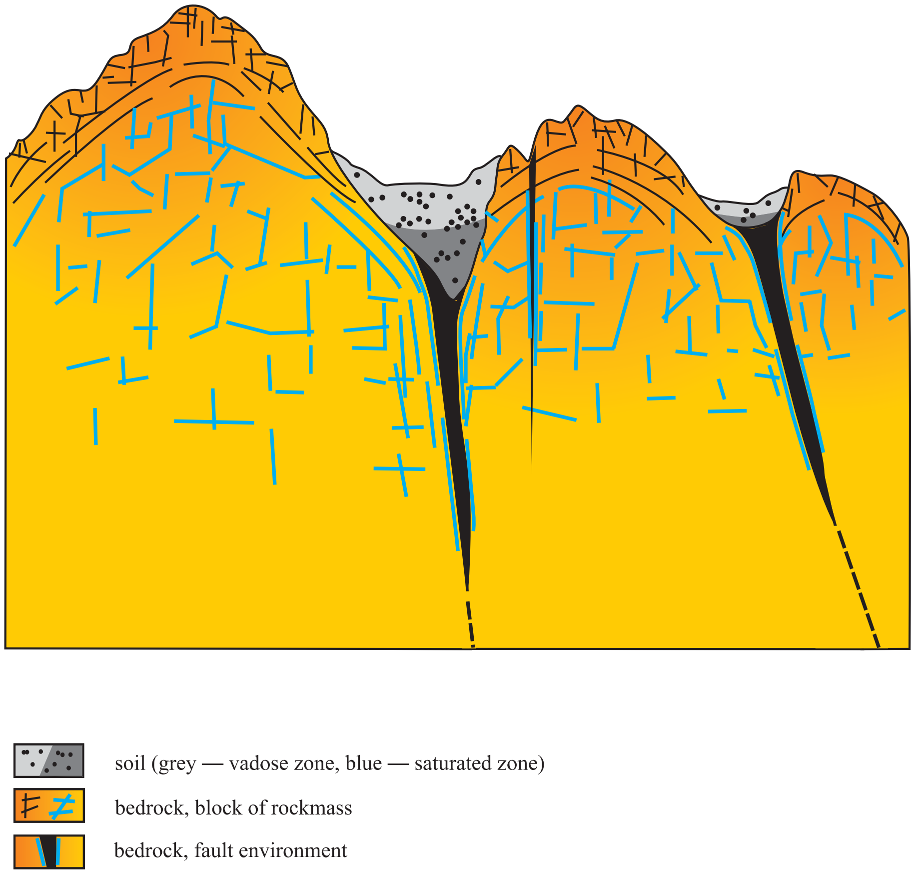

Fig. 5. A schematic cross-section along the line A–A' in Figure 4

The height of the cross-section is 400 m

In soil-covered parts of the hill areas the general flow mechanism is as follows. The soil layers transmit part of the infiltrated rainwater directly into the bedrock. Part of the infiltrated water is stored in small groundwater basins in the soil, before reaching bedrock or discharging to the ground surface. In valley areas the soil cover is generally only slightly permeable and the groundwater recharge from precipitation is low.

Because a soil cover is frequently lacking and the permeability of most common soil deposits (clay, silt and ground moraine) is generally lower than that of the underlying bedrock, most groundwater flow takes place with in the bedrock, making the transport capability of the latter decisive.

STRUCTURE AND HYDROGEOLOGICAL PROPERTIES OF THE BEDROCK

The bedrock has a dominant block structure (*cf.* Fig. 2) caused by intense faulting, fault lines being commonly observed (Fig. 3). Large blocks (several tens of km^2 in area) bordered by major faults are divided into smaller units by minor faults and fractures the latter usually not exceeding 3 km^2 in area.

The rock mass within the blocks is jointed (Fig. 5), the joints being variously oriented and arranged commonly in two or more parallel intersecting sets.

The relief of the groundwater surface within a block is roughly parallel to the topography but is more gently sloping and at the most ten to twenty metres below the ground surface. In detail the groundwater level is more complicated. Wells drilled into different sites within a block have different water levels and are generally low-yielding. In the granite areas of central Finland the observed average yield is 17 m^3d^{-1}; the continuous yield is probably smaller (Mäkelä, 1993). The catchment area of such a well probably does not exceed a few hectares. This suggests the presence of several more or less separate joint sets within one fault block (*cf.* Fig. 7). Often the uppermost part of the joint sets is, however, connected with more or less horizontal joints, occurring typically only near the ground surface and as extensive units (Fig. 5). These represent secondary joints developed “recently” near the erosion level. The frequency and dimensions of this type of joint may be estimated by the fact that the uppermost parts of the joint systems are generally not filled with water, which must migrate more or less horizontally. Recharged rainwater fills the sets of short joints only up to the levels of the long horizontal joints. These joints transmit the “overflowing” water toward the valleys which mostly follow fault zones.

A study performed in Sweden (Ahlbom *et al.*, 1991) outlined two patterns fundamental to the hydrogeology of rock types comparable to those occurring in the study area. Firstly, the hydraulic conductivity is normally at most 10^{-6} ms^{-1}in the

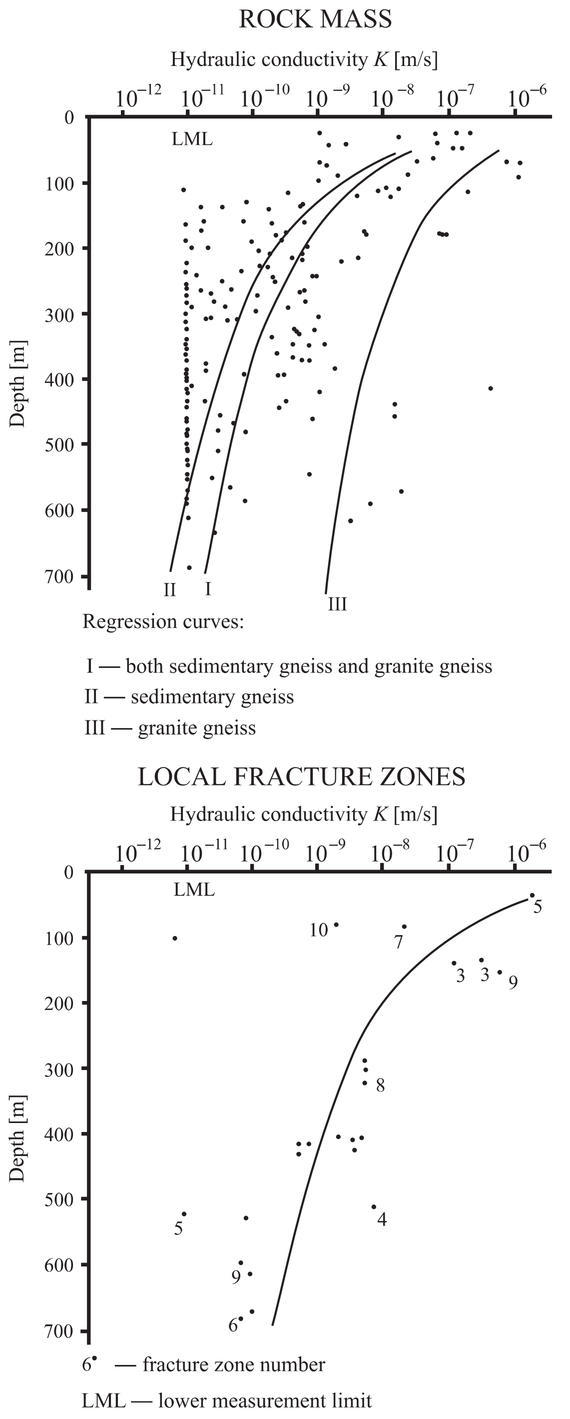

Fig. 6. Hydraulic conductivity versus depth in the Fjällveden area, Sweden (Ahlbom *et al*., 1991), simplified drawing

most favourable rock mass (granite gneiss) and lower in the other rocks tested (Fig. 6). Secondly, the hydraulic conductivity decreases rapidly with the depth: at 200 m depth the water inflow to a drilled well is in general negligible compared with the inflow to the uppermost levels.

The fault lines separating the blocks reach even hundreds of kilometres in length, most faults being however, only generally some kilometres long. The important hydrogeological feature of the faults is the very intensive jointing, which is dominantly oriented parallel to the fault and can extend down for over one kilometre. According to Ahlbom *et al*. (1991) the hydraulic conductivity of local fractures does, however, not deviate much from that occurring in the blocks of granite gneiss. Apparently the conductivity of these fractures does not represent the conductivity of the strongly permeable fault zones.

There are only scattered observations on the permeability properties of the large faults. Calculations made from data from wells drilled into large fault zones at Leppävirta, East Finland, the hydraulic conductivity at the well sites varied from 7.9×10^{-5} to 5.0×10^{-6} ms^{-1} (Leveinen *et al*., 1998). This together with the steady and moderate yield at the water plant — *ca*. 400 m^3d^{-1} (Leveinen, pers. comm.) — compared with yields from wells on the block areas indicate at least locally good hydraulic conductivity. The dominant fault parallel jointing suggest also extensive hydraulic connections along the fault direction (of magnitude 2–4 kilometres?). No systematic studies have yet been made concerning the dimensions of hydraulically uniform fault zones and associated hydraulic gradients. An important question arises: what is the ability of a fault to conduct water?

Any fault of at least moderate size is crossed by other faults. This also means that the continuity of the original joint sets of a fault is cut, though hydraulically not completely. Because the fault frequency is high — small faults at least can be found in almost every square kilometre — conductivity disturbances are common. The hydraulic conductivity along the fault changes continuously and segments with low hydraulic conductivities occur forcing the groundwater to discharge. Furthermore, observations in mines and tunnel constructions also indicate that the hydraulic properties vary markedly within individual faults e.g. due to decomposition of the broken rocks. There must also be considerable differences between differently oriented faults due to rock type, age of fault, fault direction versus structural trends in the rock and soon. It can be concluded that only minor parts of the fault zones have good permeability conditions and long-distance flow (>5 kilometres) is possible.

The rock blocks and the fault zones represent the main hydrogeological elements of the bedrock, differing considerably from each other but acting, as regards groundwater flow, most commonly together.

DIRECT GROUNDWATER FLOW TO THE SEA: ESTIMATION OF FLOW DISTANCES AND AMOUNT

The flow conditions at the seashore are presented schematically in Figure 7. The hydrogeological pattern described above indicates that the groundwater flow is generally directed from the central parts of the blocks in all directions, toward the bordering faults. So, the typical flow distance from the blocks direct to the sea is very limited, seemingly below one kilometre. The average groundwater flow distance along the faults does not usually exceed 2 kilometres but in favourable conditions it may reach 8–10 kilometres. Faults oriented roughly perpendicular to the coastline are the most potential groundwater-conducting zones — assuming that they represent hydraulically favourable conditions. Therefore the average width of the coastal zone, from where the groundwater

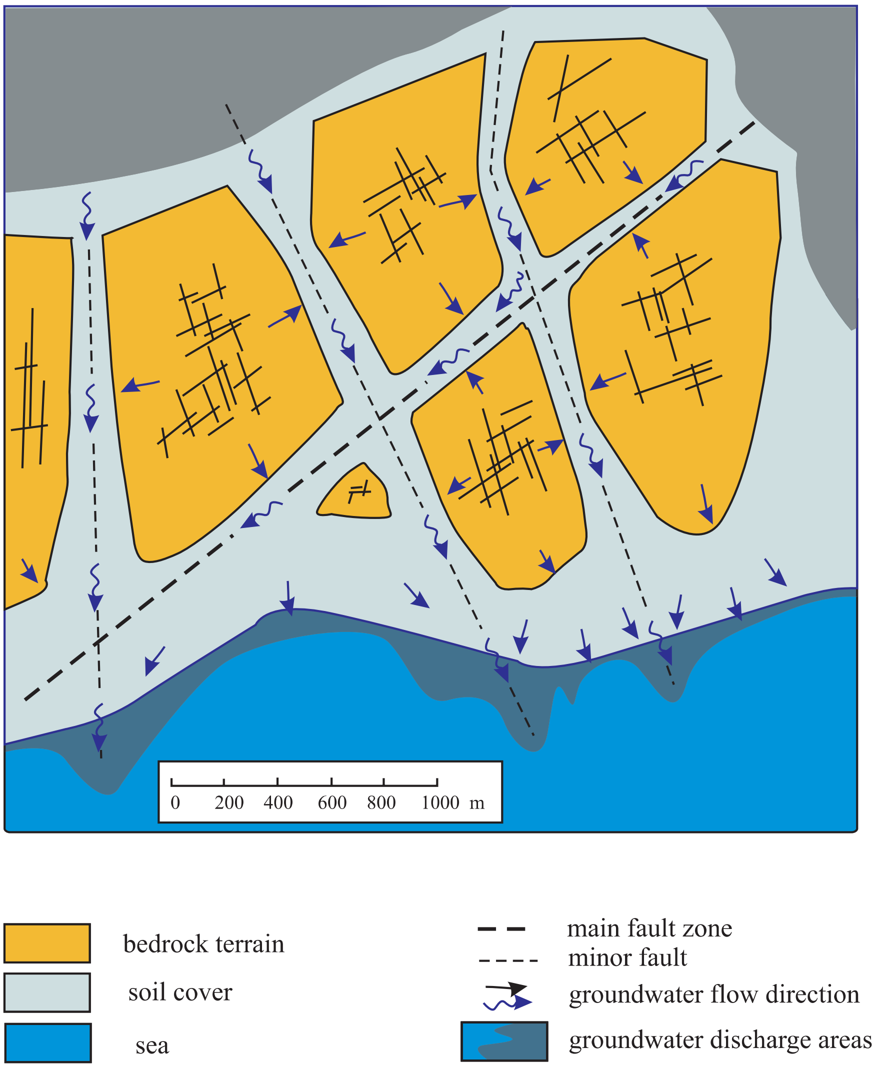

Fig. 7. Groundwater flow pattern in the bedrock and direct discharge to the sea (schematic drawing)

discharges directly to the Gulf of Finland, is likely to be on average 1.5 kilometres. The total length of the coastline of the mainland and archipelago of the Gulf of Finland is approximately 2000 km (the total with the Gulf of Bothnia is 6300 km; Kuusisto, pers. comm.). Because the coastline is winding and broken (Fig. 2) and part of the islands are too small to be calculated in this way, the real length of the coastline of Gulf of Finland amenable to flow calculations must be shorter. A length of 1400 km might be more realistic. So, the total area from which groundwater flows directly to the sea may be approximately 2100 km^2.

Because of the constantly changing hydrogeological conditions and difficulties in determining parameters (for example hydraulic gradients) for groundwater flow calculations, the only way to estimate the direct groundwater flow to the sea is to combine the hydrological data with the surface area calculated above.

Investigations of small catchment areas comparable in properties to the coastal area suggest that, the estimated groundwater runoff varies between 0.3 and 2.0 ls^{-1}/km^2 (Seuna, 1982). The coastal area is well exposed promoting groundwater recharge. The total exposed area including the archipelago is 42% (Kuusisto, pers. comm.). Over the mainland part of the coast as well as on the large islands, the exposed area is smaller due to a more extensive soil cover, probably being 25–30%. On basis of this and of results from small catchment areas, the groundwater runoff of the coastal areas may be estimated to be 1.80 ls^{-1}/km^2. The surface area being 2100 km^2, the amount of direct groundwater flow to the sea is 3780 ls^{-1}, or round 4 m^3s^{-1}.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The hydrogeological conditions of the coastal area of Gulf of Finland are discussed based on experience of practical groundwater investigations. The average width of the coastal zone, from which the direct groundwater inflow to the Baltic Sea takes place, is *ca.* 1.5 km. The calculations of the direct groundwater inflow have been made principally combining hydrological and hydrogeological methods (see Peltonen, 2002). The results indicate clear differences between different coastal parts.

The hydrogeological regime in the coastal area of the Gulf of Finland with a direct inflow of *ca*. 4 m^3s^{-1}, described above, represents the first of the three main hydrogeological regimes occurring in the coastal areas of Finland. The second regime consisting of sand and gravel deposits, of glaciofluvial and littoral origin, produce a direct discharge of about 2 m^3s^{-1} to both Gulf of Finland and Gulf of Bothnia. The discharge takes place directly from the soil to the sea. The third, largest regime mainly comprises areas covered by fine soil, discharges groundwater at *ca*. 6 m^3s^{-1}. The groundwater flow takes place partly through the bedrock and partly direct from the soil to the Gulf of Bothnia. The total direct groundwater inflow from Finland to the Baltic Sea is 12 m^3s^{-1} (Peltonen, 2002).

Throughout the coastal zone the groundwater flow conditions change considerably. Only scarce observations exist regarding the hydraulic properties of the bedrock and the quantitative distribution of the main hydrogeological elements — blocks and faults. Future investigations of hydraulic conductivities in particular, commonly occurring hydraulic gradients and lengths of the hydraulically uniform zones within faults should have high priority.

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