# Detection of potential pathways for contaminants into the Päijänne Tunnel in Finland

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The potable water for a million people residing in the Helsinki metropolitan area is conveyed from Lake Päijänne along the 120 km-long Päijänne Tunnel. Information on the hydrogeology of the tunnel is vital for land-use planning, particularly in the southern part of the tunnel line where industrial activity and pressures to build underground constructions are increasing. In a project commissioned by the Helsinki Metropolitan Area Water Company, the areas vulnerable to contamination and possibly hydraulically connected to the tunnel have been identified and spatially analysed in relation to risk activities and infrastructure. The project complements an earlier study in which potential risk activities were located and characterised. Relevant information on the soil, groundwater and bedrock-fracturing conditions along the length of the tunnel was extracted from tunnel construction documentation and areal environmental datasets, and assembled as overlays in GIS format. As a result, a description of the environmental geology of the tunnel zone has been produced, and the estimated area of influence has been delineated as a support to land-use planning.

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## Introduction

The Päijänne Tunnel is a 120 km-long, unlined water conveyance tunnel from Lake Päijänne in Asikkala to Silvola reservoir at the border of Helsinki and Vantaa municipalities. The tunnel is located at an average depth of 50–70 m in Svecofennian granite and migmatites, overlain by glacial and glaciofluvial overburden. The cross-sectional area of the tunnel varies from 13.5 $m^2$ to 18 $m^2$. The tunnel was constructed during the period 1973-1982 and has since been in almost constant use. The current flow rate under natural pressure is 2.9 $m^3/s$. The hydraulic connection between the tunnel's water and groundwater is indicated by a groundwater level decline, in most cases temporary, observed at the time of tunnel construction and during subsequent maintenance work (Pokki 1979). For the northernmost 100 km, the pressure level of the tunnel water is commonly lower than the local groundwater level. Due to the hydraulic connection and hydraulic gradient towards the tunnel, the water is subject to risk of contaminant transport. The cave-ins that occurred in 1997 and 1998 demonstrate the dynamics of the tunnel system and emphasize the significance of regular groundwater monitoring within the area of tunnel influence (Mikkola & Viitala 1999). The purpose of the study was to compile the abundant, scattered tunnel data, to identify potential pathways for contaminants, and to present an accessible hydrogeological description of the tunnel zone in order to promote sound land use and land-use planning.

## Methods

Information on the soil cover, bedrock fracturing and groundwater conditions, collected in the planning and construction stages of the tunnel project (Niini 1968) and during subsequent studies, was converted into a GIS-compatible format and spatially analysed to detect potential flow paths. A summary of the data types used in the study is presented in Table 1. Data analysis and map production were carried out using ArcView desktop GIS software with a Spatial Analyst extension.

Observations on bedrock fracturing and tunnel reinforcements as indirect indicators were visualized against a background of a superficial deposit relief map to locate fracture zones. Figure 1 shows a tunnel section as an example of the source data used for overburden thickness and reinforced zones, the latter of which were also available in numeric form. The superficial deposit relief map (Fig. 2) was constructed by combining a digital elevation model and a digital soil map by a method similar to the one used by Palmu (1999). A bedrock map of the tunnel and aeromagnetic data were applied in recognising bedrock structures on an areal scale, and in estimating the continuation of fracture zones detected by drilling or seismic sounding, as observations in the tunnel or inferred from reinforcement data. Groundwater inflows, measured with Thompson weirs at the time of tunnel construction, provide information on hydraulic conductivities of fracture zones and were utilised in qualitatively estimating the risk of contaminant transport. Supporting observations for locating zones of leakage were recorded in October 2001 during visits to selected sections of the tunnel.

Digital soil data at a scale of 1:20 000 were applied to outline the surface distribution of soil types with high permeabilities. To give a rough estimate of the relative perme-

Table 1. Geological and technical data utilised in the study.

| Data type | Source | Significance | Application | Limitations |
|---|---|---|---|---|
| Tunnel reinforcements | CON | heavy support indicative of significant fracturing | location of fracture zones | not all fracture zones hydraulically conductive |
| Seismic profiles | PSV | thickness, soil type and stratigraphy of overburden; topography of bedrock surface | estimation of flow direction and overburden permeability | error +/- 10%, non-uniform coverage |
| Drill logs | TECH<br>CON | thickness, soil type and stratigraphy of overburden; topography of bedrock surface, bedrock fracturing | estimation of flow direction and overburden permeability | commonly restricted to the uppermost few metres |
| Digital Elevation Model | NLS | topography indicates bedrock fracturing and probable directions of surface and groundwater flow | fracture zone interpretation, estimation of flow direction | |
| Map of Quaternary deposits, scale 1:20 000 | GTK | surface soil type | combined with stratigraphy for permeability estimation | only refers to the uppermost metre |
| Groundwater inflow measurements | PSV | indicates hydraulic properties of fracture zones | relative importance of fracture zones for groundwater flow and contaminant transport | inaccuracy of the Thompson weir measurements |
| Classified groundwater areas | FEI | hydrogeological conditions in significant formations of the overburden | direction of groundwater flow, depth to groundwater surface | information scarce on many of the smaller areas |
| Aeromagnetic data, scale 1:100 000 | GTK | abrupt changes in intensity indicative of faults and fracture zones | supports fracture zone interpretation, recognition of bedrock structure trends in regional scale | interpretation subjective, preferably coupled to independent observations by other methods |
| Risk activities | FEI | current hazards | identification of areas already at risk | hazard situation evolves constantly |
| Roads and railways | FEI | transport routes of hazardous chemicals | | |
| Records of well drawdown | PSV | indicates the area of tunnel influence | estimation of flow connection quality | various factors contribute to drawdown |
| Groundwater level measurements | CON | flow, groundwater relative to ground surface | interpretation of flow direction | also individual measurements that give no information on fluctuations |
| Map of lithologies and structures from the tunnel | GTK | minor structures (e.g. cleavage) commonly indicate the orientation of major features | estimation of fracture zone orientation | at surface fractures form broad zones; fracturing subparallel to surface difficult to observe; 3D geometry difficult to estimate due to curving of fracture planes |

Abbreviations: CON=consultants, PSV=Helsinki Metropolitan Area Water Company, TECH=geotechnical departments of cities, NLS=National Land Survey of Finland, FEI=Finnish Environment Institute, GTK=Geological Survey of Finland

ability of areas, the soil type was combined with stratigraphic information from drill logs, where available. The coverage of seismic profiles and drill logs is non-uniform, but in areas of high observation point density, a continuous bedrock surface was roughly interpolated by also accounting for the elevation data from outcrops. An example of interpolated bedrock surface topography is shown in Fig. 3. The slope of the bedrock surface gives some indication of the direction of DNAPL transport and groundwater flow in bedrock fractures.

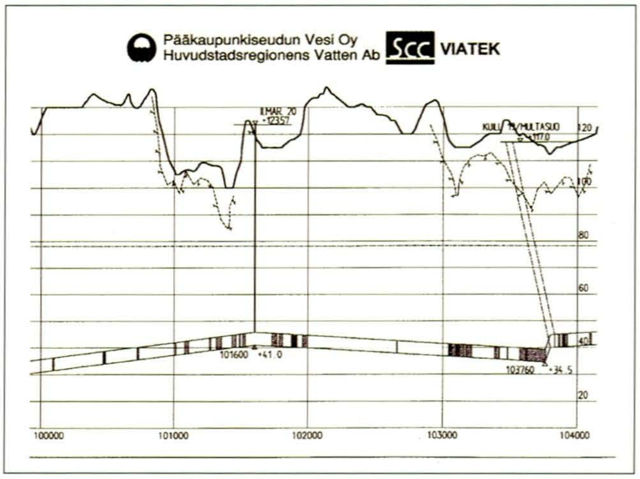

Fig. 1. A tunnel section showing the overburden thickness and reinforced zones, extending between the kilometre readings 100 and 104. The section coincides with the southern part of the tunnel line displayed in Fig. 3. By permission from Pääkaupunkiseudun Vesi Oy (Helsinki Metropolitan Area Water Company).

Field studies for groundwater supply have been carried out by consultants, particularly in the extensive esker systems of Jäniksenlinna in Tuusula and Kukkolanharju in Hämeenkoski, as well as in the First and Second Salpausselkä ice-marginal formations. In addition to consultant reports, descriptions of groundwater areas resulting from mapping and classification carried out by the Environment Administration, mainly in the 1980s (Britschgi & Gustafsson 1996) and protection plans for groundwater areas, provide information on groundwater conditions. Data such as groundwater flow directions and groundwater levels in individual glacial drift aquifers, variable in detail, were applied to delineate the area of influence.

The well drawdowns resulting from water pressure decrease in the tunnel indicate the quality of hydraulic connection to groundwater in the overburden. In most areas along the tunnel line, the drawdown observations are inadequate in number to allow outlining of the actual area of influence. Consequently, the extent of hydraulic connection had to be inferred from groundwater levels, soil type information, topography and bedrock surface elevation, depending on availability. The delineation of the inferred area of

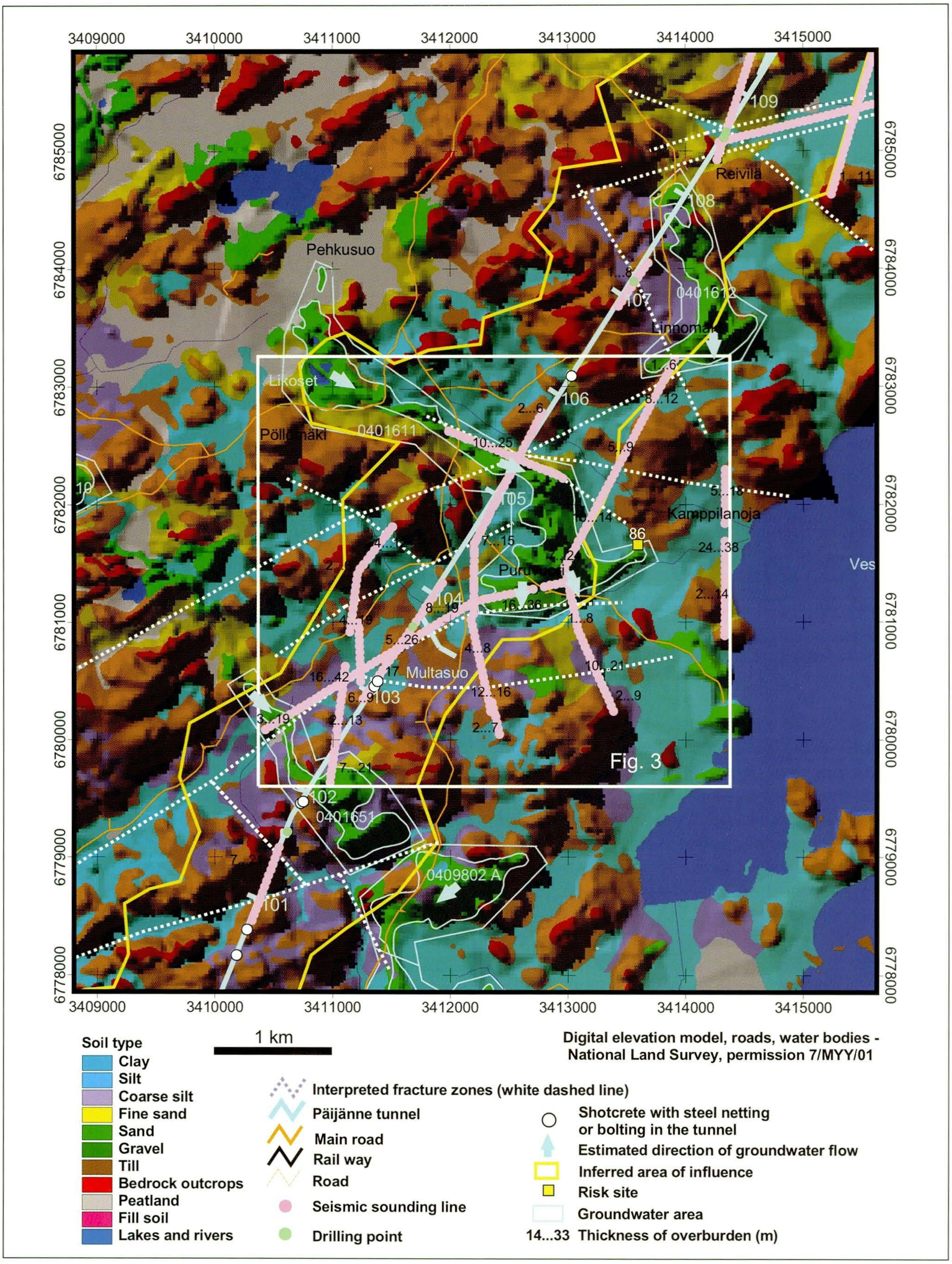

Fig. 2. Superficial deposit relief map of the Viitaila area (modified from Lipponen 2001). Digital elevation model: National Land Survey of Finland; soil type map, scale 1:20 000: Geological Survey of Finland.

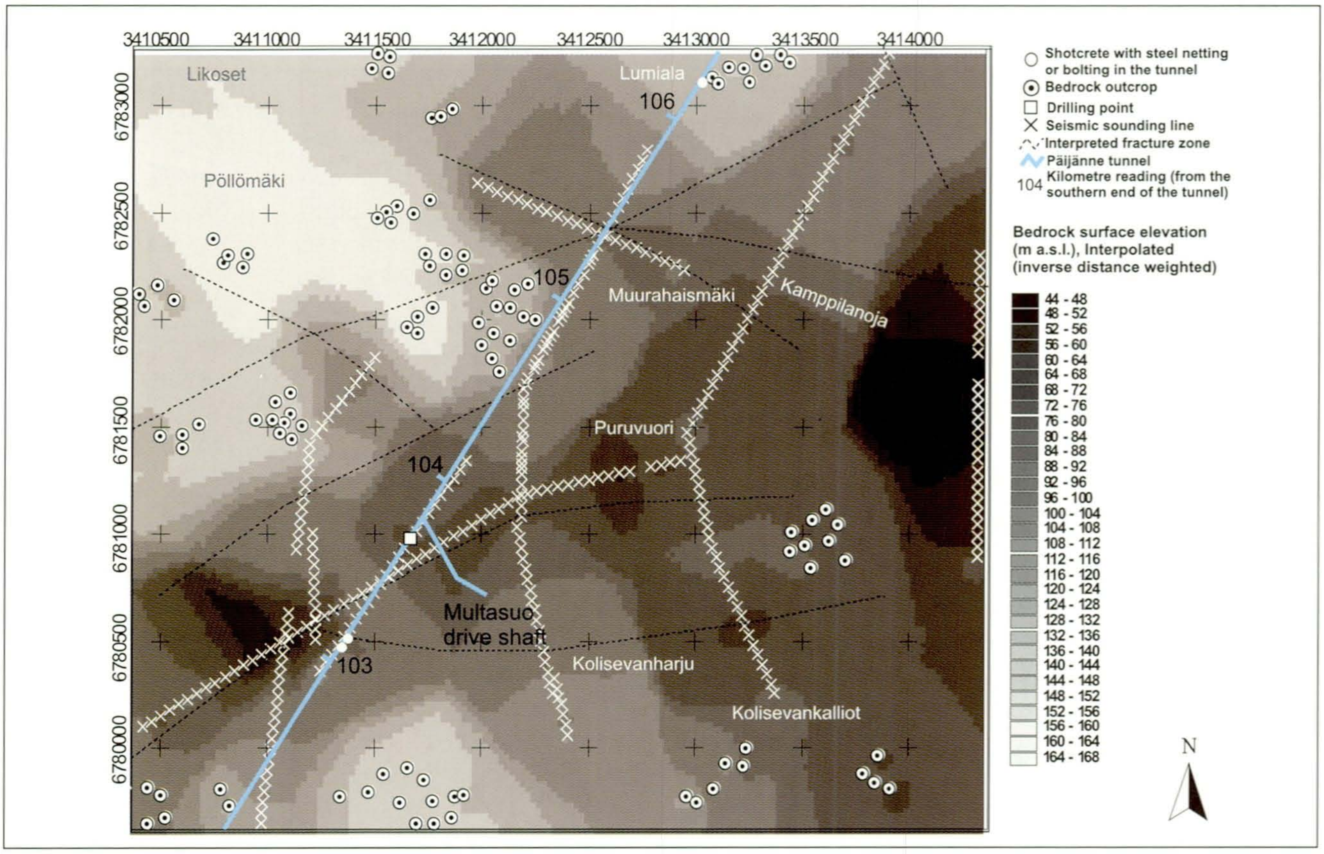

Fig. 3. Observation points for the bedrock surface elevation and interpolated bedrock surface topography in Viitaila (modified from Lipponen 2001). The tunnel reinforcements and the interpreteted fracture zones are also shown. The area is outlined in Fig 2.

influence was carried out by visualising the parameters in GIS and analysing the spatial relationships.

Potential risk sites identified by Haavisto (1998) and main roads that also represent transport routes for hazardous chemicals were viewed in relation to the soil type and bedrock-fracturing information to evaluate the risk arising from current activities. Figure 4 displays the main infrastructure in relation to the Päijänne Tunnel as well as the distribution of potential risk sites.

## Results

Based on the extent of coarse-grained superficial deposits, groundwater flow direction and the location of bedrock fractures, the inferred area of influence was delineated in the vicinity of the tunnel. The area of influence is the recommended zone of cautiousness for locating or monitoring risk activities that could potentially contaminate soil or groundwater. From within the area, contaminant transport is considered possible, and therefore the tunnel should be taken into account in land-use planning. The possible hydraulic connection would need to be assessed on a case-by-case basis. Along fracture zones and eskers, the area of influence was extended farther from the tunnel. The delineation aims at covering the enlarged area of influence prevailing at times of increased hydraulic gradient during a tunnel repair.

The areas considered vulnerable to contamination were identified and their relevant characteristics indicated. The areas deemed vulnerable displayed a combination of features including several of the following criteria: 1) markedly fractured bedrock (observed or alternatively indicated by heavy reinforcement), especially if associated with groundwater inflow; 2) a thin or highly permeable soil cover or a permeable layer at depth; 3) relatively thin bedrock roof; or 4) a major transport route or potential risk site located in the immediate vicinity of the tunnel. A description of the geology, hydrogeology, essential tunnel structures and potential risk activities with supporting maps was produced for each section of the tunnel.

The greatest natural risk of contaminant transport is linked to fracture zones with groundwater leakage. Fracture zone interpretation is most reliably done by iteratively viewing topographical lineaments, bedrock surface depressions and visualisations of fracture zones detected inside the tunnel. The risk associated with hydraulically conductive fracture zones is further increased when the zones are overlain by a thin or highly permeable soil cover. In some locations, the contaminant transport risk may be greater from the flanks of topographic depressions, where the overburden is commonly thinner than immediately above the deeply weathered central part of a fracture zone. Even outside frac-
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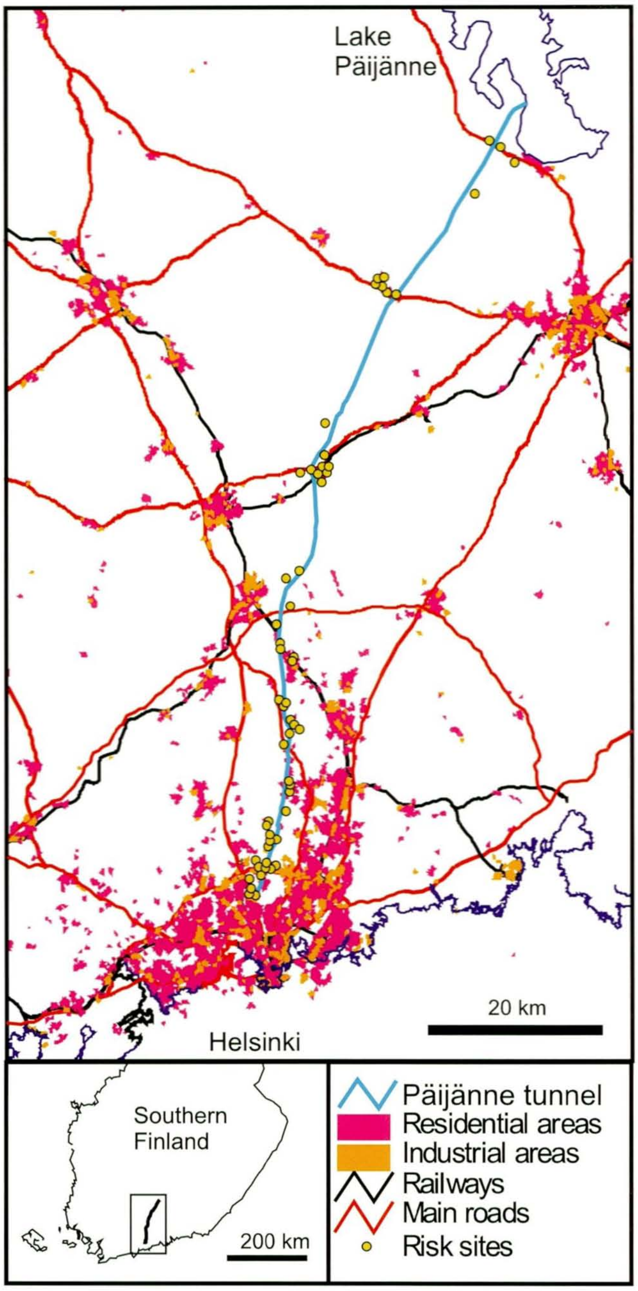

Fig. 4. Generalised map of the Päijänne tunnel in relation to residential and industrial areas, risk sites and roads. The potential risk activity is concentrated in the Helsinki Metropolitan area in the south, and in the vicinity of the main roads crossing the tunnel. The residential and industrial areas are from the National Land Survey's (NLS) land-use database. Roads and water bodies - NLS permission 7/MYY/01.

ture zones, locally significant groundwater inflow was observed to leak from horizontal fracturing, particularly in granitic rocks. It is beneficial to consider the surface and tunnel data in combination, to verify whether those fracture zones with surface expression are significant for groundwater flow at the tunnel level.

Eskers with relatively high groundwater flow rates also present potential flow paths. Coarse-grained soil types with high permeability increase the risk of a contaminant being transported down with percolating groundwater and reaching bedrock fractures. However, despite the groundwater storage available, not all the esker systems displayed high groundwater inflow at the tunnel depth. Apparently, the soil type in the contact zone overlying the bedrock surface and the openness of fractures determine whether the groundwater stored in the overburden leaks into the tunnel. The significance of the contact zone on the groundwater inflow was earlier emphasized by Olofsson (1991).

The present study demonstrates the use of GIS as a powerful tool for data overlays of fractured zones in bedrock, overburden characteristics and groundwater conditions for producing an integrated description of the geological and hydrogeological environment. Spatial analysis of the natural environment with infrastructure and hazardous activities allows risk assessment on a scale dependent on the quality of the data.

The pressure level in the tunnel is a major factor affecting the groundwater flow in the vicinity of the tunnel. A marked pressure drop at the Kalliomäki pumping station, approximately 64 km south of Lake Päijänne, from elevation +78 m to +42 m (asl) steepens the hydraulic gradient towards the tunnel south from the station. Farther to the south, the pressure level gradually approaches the local ground surface and even exeeds it in places, which diminishes the inflow. The flow towards the tunnel is inferred to have been highest at the time of construction and during subsequent maintenance work when the tunnel had to be emptied of water. According to the measurements, groundwater inflow appeared smaller during the repair work in autumn 2001 than at the time of construction for most tunnel sections in the northernmost 64 km of the tunnel.

## Conclusions

Potentially hazardous activities should be minimised in the areas indicated in the study as being vulnerable to contamination and possibly in hydraulic connection with the tunnel. Further study and quantitative risk analysis should be considered if there is a potential contamination source in the vulnerable area.

Due to the weathering of fracture zones, ageing of tunnel reinforcements and effects of construction and excavation on groundwater flow patterns, a regular monitoring of groundwater conditions within the zone of influence around the tunnel is vital.

The present study demonstrates the applicability of ordinary geological observations and engineering records in an environmental assessment. Municipal and environmental authorities can utilise the information on the sensitivity of areas as a guide in land-use planning. The hydrogeological description can also be applied to directing protective measures and to estimating the extent of action required in the case of a chemical spill.

Risk sites are concentrated in the southern part of the tunnel, where development is most intense, and in several locations where main roads cross the tunnel. Caution is recommended for the extensive underground constructions planned in the vicinity of Helsinki-Vantaa Airport and the Helsinki metropolitan area's main ring road, since the excavations may create flow paths by disturbing the rock matrix and also because fracture zones with associated groundwater inflow have been detected in the area.

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