Dualism of geology and geotechnical engineering: two parallel approaches to define lake water infiltration into an interlobate esker

J Mansikkamäki¹, A Hyvönen², N Putkinen² and H Kallio²,

¹ AFRY Finland Oy, Hatanpääinkatu 1, 33900 Tampere, Finland
² Geological Survey of Finland, Vuorimiehentie 5, FI-02151 Espoo Finland

Juho.Mansikkamaki@afry.com

Abstract. This case study is a modern example of how geologists and engineers have worked together to reconcile groundwater abstraction from the Pispalanharju aquifer and urban planning of the shore of Lake Näsijärvi in the vicinity of the Hyhky pumping station, located in the Tampere region of southern Finland. The authorities have been concerned about the potential impact of urban development on the important aquifer system to which the lake shore region is possibly connected. Before the study, it was estimated by the authorities that the infiltration rate into the esker from Lake Näsijärvi could be up to 1000 m³/day, forming a significant source of groundwater. Two parallel studies were conducted to examine water infiltration from the lake to the esker. The effects of a proposed land reclamation project on the shore of Lake Näsijärvi were modeled with the finite element code Plaxis 2D. Coupled analysis was conducted to analyze both the flow conditions and deformations in these conditions caused by the fill. An essential part of the geotechnical modeling was the creation of the present state of the shore complex, which already includes manmade fills and structures and a low permeability lake bottom next to the esker. Combining observations with geological and geotechnical data was highly important in the task. The amount of water flow to the esker was estimated from the analysis, and the values were compared with the results of hydrogeological analysis. For the hydrogeological studies, thousands of soil investigations were interpreted by different methods to fit a geological concept that formed the basis of geological cross-section construction work (2.5D), which was then used for groundwater flow modeling by GMS. Both GMS and Plaxis modeling simulations predicted that, due to the low conductance of silt and clay materials found on the shore of Lake Näsijärvi, the amount of water infiltrating in the direction of the esker is very limited, being only 60 to 155 m³/day. Hence, the dualism of hydrogeology and geotechnical engineering hypothesized in this case study was confirmed by modeling results.

1. Introduction

Urbanization is increasing worldwide and groundwater management of the cities becomes more critical. Balance of sensitive groundwater sources and demanding construction activities emphasizes rigorous geotechnical design. In this case a land reclamation project is planned to area, where lake
water is infiltrated into the Pispalanharju Esker which is an important aquifer for groundwater abstraction.

The land reclamation project is related to the new city district of Hiedaranta in Tampere, Finland, the location of which is indicated in Figure 1. Hiedaranta is planned to eventually comprise a smart and sustainable city district with homes for 25,000 residents and 10,000 jobs. The city district will consist of two main subareas: the center, which is the former yard of a pulp mill, and the Lake City, which is planned to be constructed on a new land reclamation area.

Figure 1. The location of the planned land reclamation area, 4 km west of the city center of Tampere, Finland.

In the land reclamation area, there is an old fill on the shore of Lake Näsijärvi. The fill, which is approximately 60 m in width, was carried out for the construction of a highway in 1970, as shown in Figure 2. The fill material is sand and gravel from a nearby esker. The lake bed is typical for the area: the first 0.5 to 1.0 m consists of silt with a high organic content, while the next 2 to 5 m consists of overconsolidated clay and clayey silt. In some of the layers, the clay content exceeds 30%, but these layers are usually rather thin.

The water level of Lake Näsijärvi is 18 m higher than that of Lake Pyhäjärvi. The Tammerkoski rapids connect these lakes in the heart of the City of Tampere. At the location of the planned land reclamation area, the distance between the lakes is only approximately 550 m. This part of the city is called Hyhky, and is also the site of a water abstraction plant. Before this study, it was estimated by the authorities that in the proposed reclamation area, infiltration into the esker from Lake Näsijärvi could be up to 1000 m$^3$/day, the lake being a significant and important source of groundwater. The groundwater area is protected by law and no negative change in water quality is permitted. Therefore, a comprehensive study regarding the amount of infiltration was needed to be able to confirm whether land reclamation would be feasible for the location.

The main aim of the study was to evaluate the amount of water that is presently infiltrated from the proposed land reclamation area into the esker using hydrogeology and geotechnical engineering applications. Two different approaches were selected to achieve a more comprehensive view of the
current infiltration. First, infiltration was analyzed using a 2D finite element code and then with a more comprehensive 2.5D geological concept conducted using a hydrogeological model. This article introduces these calculations and presents a comparison of the calculation results. A secondary objective of the analyses was to evaluate the types of changes in water infiltration that the new land reclamation will cause and how it might affect the flow in the groundwater area.

For geological reasons, the area is very interesting but demanding. Hydrogeologists of the Geological Survey of Finland conducted a flow analysis of the extensive groundwater area while geotechnical consultants conducted a plane strain 2D FE analysis of the shoreline, where the changes that would be caused by the planned fill were also studied. These two studies were independent and they both determined the amount of infiltration in the present state from very different starting points. Therefore, it is interesting to compare how such a sensitive variable as the rate of water flow was modeled and examine how comparable the results were.

The dualism of hydrogeological and geotechnical modeling has been used and introduced in the literature to some extent, for example in a complex stability case presented by Fagerlund et al. [2]. However, based on a review of the literature, publications regarding the hydrogeological and geotechnical modeling of extensive infiltration problems are lacking.

2. Data workflow in conceptual geological and groundwater flow modeling

During the very first steps of the project, both geotechnical and geological drilling data were subjected to classification guided by sediment grain sizes. During the course of the evaluation, some tens of high quality boreholes and other ground surveys were selected to construct control points for the geological cross-section work conducted over the study area. Thousands of boreholes were then used to provide secondary information for the foundation of geological interpretations. Geological subsurface mapping was guided by an interlobate esker conceptual model that included characteristic sedimentary units and was subsequently applied in groundwater flow modeling. A thick gravel layer with high water conductivity rests on the bedrock. The conceptual model includes glacial till, because non-permeable till-dominated lenses are found in the esker, and elsewhere over wide areas, glacial till dominates the

Figure 2. Old fill and the proposed new land reclamation area.
overburden. Esker sand and silt overlie the gravel on the esker flanks and they are typically covered by littoral gravel, with the sand and silt becoming gradually finer-grained downward from the top of the esker. Basinal silts and clays on the lower elevations overlie a glacial till bed. In a natural environment, non-permeable lake sediments would prevent lake water infiltration into the esker, but here this is not always the case. Geological mapping results were used for the groundwater flow model, which is strongly affected by the water conductivity of the sediments (see Tables 1 and 2).

3. Geotechnical modeling

3.1. Model inputs

The geotechnical modeling was conducted using the PLAXIS 2D v2017 finite element code. A close-up of the model geometry is presented in Figure 3. The most important parameters for this case were the permeability parameters, especially in the silt layers, which are dominant for the problem. The soil investigations considering the permeability parameters included disturbed samples from which the grain-size distribution of different layers had been studied, odometer tests of silt layers, CPTU soundings, and CPTU dissipation tests. In addition, a breakwater was constructed in Lake Näsijärvi, only 200 m from the planned land reclamation area. The breakwater was instrumented and, from the settlement observations, the permeability of the silt layers was back analyzed.

In addition to the permeability of the soil layers, the gradient of flow was important input information in this case. The water level of the lake was well known and there were several representative groundwater wells in the esker. The groundwater level in the esker was rather constant, being at a level 4 m lower than Lake Näsijärvi. This information was utilized in the analysis.

![Figure 3. A simplified cross-section used in the finite element (FE) analysis.](image)

The silt layers are structured, consisting of thin layers of finer and coarser silt that are visually detectable. Therefore, the permeability in a horizontal direction is many times higher compared to the vertical permeability, which was also considered. The permeability parameters used, which are presented in Table 1, take into account the direction of water flow. One should note that, for example, for blasted rock, realistic $K$-values are higher than that used in the model. The values were adjusted due to numerical reasons, as the difference in permeability should not be too high in adjacent layers.

Table 1. Water conductivity values of different soils used in the finite element (FE) analysis.

| Soil layer                                      | Conductivity $K$ (m/s) |
|------------------------------------------------|------------------------|
| 1) Old fill; sand and gravel                   | $5 \times 10^{-5}$     |
| 2) Lake bed; organic sediments and clayey layers | $5 \times 10^{-9} \ldots 1 \times 10^{-7}$ |
| 3) Silt layers; varying from clayey silt to coarse silt | $1 \times 10^{-7}$     |
| 4) Silt layers; varying from fine silt to silty sand | $1 \times 10^{-6}$     |
| 5) Periphery of the esker; sand and gravel with some silt content | $1 \times 10^{-4}$   |
3.2. Results of geotechnical modeling

The main result of the geotechnical modeling in the context of this study was the amount of groundwater that infiltrates the esker in an approximately 800-m-long area of the Vaitinaro shore where land reclamation is planned. The main routes of infiltration are the former shoreline inside the old fill area and through the silt layers to the esker. Based on the analysis, it was concluded that the infiltration is up to 60 m$^3$/d for the whole of the planned reclamation area when manmade structures are not taken into account. The most important of these manmade structures is an old tunnel that penetrates the silt layers, probably increasing infiltration locally in the middle of the area.

4. Flow modeling

4.1. Background to groundwater flow modeling with GMS software in the Tampere Hyhky area

A groundwater flow model was constructed for the Tampere Hyhky area with Groundwater Modeling System (GMS) software. This was a so-called MODFLOW model (modular 3D finite-difference groundwater flow model). The "steady state" was a 1-layer model, because it was estimated from the structural survey data on the formation of the interlobate esker aquifer that the amount and accuracy of structural information was sufficient to produce a single-layer MODFLOW model.

4.2. Aim and purpose of the groundwater model

The generic aim of groundwater modeling in the Hyhky area was to obtain a general and uniform understanding of the groundwater levels and also groundwater flow and discharge directions along the modeled aquifer area. For the Hyhky groundwater abstraction plant located in the modeling area, the objective was to obtain a forecast calculated by the flow modeling program of the extent and area around the exploitation wells affected by the current groundwater intake, especially taking into account infiltration of water from the adjacent Lake Niisijärvi along the shoreline in Vaitinaro and Lielahti.

The flow modeling software (GMS) calculates the groundwater level (m a.s.l.) and the groundwater flow directions and flow rates in the modeling area from various numerical values of the input data entered into the MODFLOW model. In GMS software, the above-mentioned procedure is often carried out using the conceptual model approach.

4.3. Grid-level (a.s.l.) assessment and geology of the Hyhky modeling area

A shaded Quaternary map of the area of interest and its surrounding areas is presented in Figure 4. Geologically, it belongs to an interlobate zone between an active Western Finland ice stream lobe and the Suupohja passive ice area in the west [7]. Interlobate zones are lateral margins of former ice stream lobes typically representing wide areas of sediment accumulations of subglacial origin. In the vicinity of Hyhky, the Quaternary deposits are dominated by sands and gravels that form an interlobate esker (Ylöjärvi-Pispala esker) and a tributary esker (Nokia esker) deposited during the last deglaciation. Underneath the sediments, a bedrock fault zone crosses the Hyhky area from east to west. An adjacent bedrock fracture zone between a Paleoproterozoic mica schist and mica gneiss contact forms a storage area for bedrock groundwater, acting as a possible supplementary source for the main groundwater aquifer.

During the course of the subsurface geological characterization, information from thousands of boreholes was subjected to a validation process, and some tens of borehole logs for cross-section production were created using Groundhog Desktop software [8]. The rest of the borehole logs were used as secondary information for seven sediment units, which were mapped to best describe the hydrogeological environment of the sediment cover.
The Hyhky flow modeling area (see Fig. 4 below, red rectangle area) was defined as a grid for groundwater flow calculations covering the layer from the ground down to the bedrock surface. The grid size of a single lattice was defined as 10 x 10 meters, but a densified lattice mesh was used around the exploitation wells. The modeling program calculates the position of the groundwater pressure level (m a.s.l.) for each grid lattice cell.

The surface level of the grid used in flow modeling was determined from the interpolated ground level (m mpy, N2000), the source of which was obtained from a laser scanning point cloud (National Land Survey of Finland). In the laser scanning dataset used by GTK, the ground position is represented as an interpolated raster surface with a single raster size of 2 x 2 m.

4.4. Bedrock surface

In the flow model, a bedrock surface height model (Fig. 5) created by interpolation (ArcMap, Topo to Raster) was used as the base of the calculation grid. The interpolated height model of the bedrock surface is based on existing research data, such as drillings, groundwater well installations, gravity measurements, and ground penetrating radar (GPR) soundings.

4.5. Recharge: Precipitation and infiltration

In the interlobate esker area that was subjected to flow modeling, the main factor complementary to groundwater is infiltration rate of annual precipitation. The amount of rainwater infiltrating deeper into the soil and from there to groundwater is affected, for example, by vegetation quality and human activities (e.g. asphalted areas, gravel sites, populated areas, and fields).

In general, in natural areas where the mineral soil material consists of sand and gravel, the total amount of rainfall infiltrating into groundwater is approximately 30–60% according to Airaksinen [1] and 50–60% according to Zaitsoff [9] and Lemmelä [4]. In the Hyhky groundwater flow model, the infiltration rate from precipitation was generalized over the whole groundwater modeling area as being 55% (330 mm/y) of annual precipitation.

Figure 4. Quaternary map of modeling area
4.6. Hydraulic conductivity (K-values)
The most important factor for groundwater modeling is to divide the aquifer area to be modeled into hydraulic conductivity zones according to the location of the mineral soil material of different grain sizes in different parts of the aquifer (Fig. 6). For each conductivity zone of the modeling area, the initial value of the conductivity coefficient, or the so-called K-value, was set and was based on the literature (see Table 2). The K-value in the 1-layer model represents the average horizontal hydraulic conductivity (HK) of the various sets of mineral soil materials, which are assumed to be isotropic, inside each conductivity zone saturated with groundwater. As the modeling progresses, the K-values are calibrated manually (trial-and-error method) if needed, as well as using PEST software.

Table 2. Water conductivity values for different sediments according to Airaksinen [1] and Fetter [3].

| Mineral soil material                  | K-value, m/s [1] | Soil material               | K-value, m/s [3] |
|---------------------------------------|------------------|-----------------------------|------------------|
| Gravel                                | $10^1$ – $10^7$  | Well-sorted gravel          | $10^2$ – $10^4$  |
| Sand                                  | $10^3$ – $10^5$  | Well-sorted sand            | $10^3$ – $10^5$  |
| Fine sand (coarse silt)               | $10^5$ – $10^7$  | Fine sand, silty sand       | $10^5$ – $10^7$  |
| Moraine (till)                        | $10^6$ – $10^8$  | Moraine                     | $10^6$ – $10^8$  |

4.7. Sink and sources: Surface water bodies (lakes and ponds)
The aquifer area subjected to flow modeling is situated between Lake Näsjärvi in the north and Lake Pyhäjärvi in the south. Larger water bodies within or adjacent to the aquifer area may be wholly or partly in contact with groundwater and thus act as drainage points for the aquifer groundwater, or surface water absorption sites, respectively. Discharges of groundwater from the aquifer to the lake may not always occur in the shoreline area, but discharge sites may be located further into lake.

Where the modeling area is bordered by lakes and ponds (including larger streams), the shorelines are usually defined as constant water surface arcs according to the surficial water table level (m mpy), and the so-called general-head boundary (GHB) condition could then be enabled (see Fig. 6).

When defining shorelines as arcs with the GHB condition, it is possible to control how easily water flows (or moves) through the GHB arc according to the conductance coefficient generic to the GHB
condition. In practice, the conductance coefficient defined for the GHB condition can control the amount of water entering or leaving the flow model, i.e., taking into account any sediment and mineral layers that are less conductive (silt, clays) along the shoreline.

Arc conductance was calculated using Equation 1, where $K$ is the hydraulic conductivity of the lake bottom clay/silt layer (Table 1), $A$ is the gross cross-sectional area, and $L$ is the flow length, i.e. the average thickness of the clay/silt layer along the lake shoreline.

$$C = \frac{KA}{L}$$ (1)

The conductance value obtained represents conductance per unit length. When using GMS software, it automatically computes the appropriate cell conductance values that are assigned to the grid cells.

4.8. Sink and sources: Exploitation wells and springs

In the modeling area, there is one groundwater abstraction plant (the Hyhky abstraction plant), from which an average of 1 900 m$^3$/d of groundwater is pumped from several exploitation wells. This amount of groundwater was entered into the flow model as the starting value for pumping.

The Tahmela spring is situated near Lake Pyhäjärvi, east of the modeling area. According to water isotope surveys, from time to time most of the water flowing from the spring is originally from the lake Näsijärvi. So the lake water pouring out of Tahmela spring is not connected directly to Hyhky groundwater but being considered mostly as perched water.

5. Flow modeling results

5.1. MODFLOW modeling concepts for the Hyhky groundwater flow model

The groundwater flow model for Hyhky area was constructed in GMS software using the MODFLOW-2005 program with the Layer-Property Flow (LPF) package. With the LPF package, it is possible to define the horizontal ($K_h$ or $HK$) and vertical hydraulic conductivity ($K_v$ or $VK$) for each layer. In a 1-grid layer model, as in the Hyhky modeling case, only $HK$ needs to be defined. MODFLOW then computes the cell-by-cell conductances using the $K$-values and the layer geometry. A preconditioned conjugate gradient solver (PCGN) with improved nonlinear control was used with MODFLOW-2005.

Several groundwater flow modeling runs were performed for the Hyhky area using GMS software. As a result, it was discovered that the current volume of water could not be pumped from the Hyhky groundwater aquifer reservoir without the supplementation of water from Lake Näsijärvi. However, the water isotope samples from the Hyhky exploitation wells contained no or very low concentrations of isotopes indicating the presence of lake water. In addition, according to GPR results for the shore of Lake Näsijärvi, an impermeable or poorly permeable layer of clay or silt (or both together) is present that extends along the entire shoreline, sealing the groundwater of the interlobate esker aquifer from the lake water above. This also contributes to the fact that the water level of Lake Näsijärvi is higher than the groundwater level in the vicinity of the interlobate esker aquifer, which mostly consists of sand and gravel. One possible source of supplementary groundwater for the aquifer is bedrock, as a fault zone and fracture zones in the bedrock exist in the vicinity of Hyhky.

According to groundwater chemistry analysis in the Hyhky modeling area, groundwater pumped from the Hyhky groundwater exploitation wells was from a sand and gravel formation (from the main aquifer), but part of it was also considered to be groundwater initially stored in the bedrock fault and fracture zones.

5.2. Hyhky groundwater flow simulation results

The Hyhky groundwater flow model (a MODFLOW model) was constructed with GMS software using a conceptual modeling approach presented in Chapter 3. The conceptual model that was
generated was run using MODFLOW-2005 in GMS software with the implementation of supplementary bedrock groundwater (see Chapter 4.1).

Figure 6 presents a flow modeling simulation of the current amount of groundwater pumped from the exploitation wells at the Hyhky abstraction plant, i.e. 1900 m$^3$/d, while the aquifer consisting of sand and gravel obtains as much as 520 m$^3$/d of supplementary groundwater from bedrock fractures. The water catchment of Lake Näsjöjärvi is based along the Vaitinaro shoreline, mainly at two sites (V1 and V2), and in Santalahti at a single site (S1) based on the structural interpretation of GPR data [6]. Notably, location V2 is a manmade tunnel, which might locally increase the infiltration of water.

The purple line delineates the capture area of three Hyhky area exploitation wells, extending to the Lielahiti–Santalahti area. The blue curves shown on the map are the groundwater torture levels (m a.s.l.) calculated by MODFLOW. The red vector arrows represent programmatically simulated groundwater flow directions and flow rates (the larger the arrow inside the modeling area is, the greater is the groundwater flow rate).

With the Hyhky water intake at its current level (i.e. 1,900 m$^3$/d) and a supplement of groundwater from bedrock fractures (520 m$^3$/d), the groundwater flow model predicts that the amount of lake water from Lake Näsjöjärvi absorbed along the Vaitinaro shoreline is 155 m$^3$/d, of which 120 m$^3$/d is absorbed through the two narrow points (V1 and V2). The amount of lake water infiltrated from the Santalahti shore area is 330 m$^3$/d.

![Figure 6. Material conductivity values (K-values) below the groundwater level in the Hyhky aquifer area.](image)

6. Conclusions
Two different approaches were introduced to estimate lake water infiltration into an esker. Based on a 2D plane strain geotechnical FE model, it was concluded that water infiltration on the Vaitinaro shore of Lake Näsjöjärvi is 60 m$^3$/d, and hence insignificant for the flow system when the manmade structures are not taken into account.

Based on comprehensive geological surveys of the Hyhky area of Tampere [5], [6], [8] and hydrogeological modeling, it was concluded that the groundwater is supplemented by lake water infiltration of 155 m$^3$/d on the Vaitinaro shore of Lake Näsjöjärvi. According to both analyses, the amount of infiltration is only a fraction of the 1000 m$^3$/d originally assumed and rather insignificant.
when compared to the total amount of groundwater pumped (1 900 m$^3$/d) from the abstraction wells at Hyhky groundwater intake plant.

According to these results, it can be concluded that the geotechnical 2D analysis conducted before the additional survey data estimated a 2 to 3 times lower rate of infiltration compared to the flow modeling (60 m$^3$/d vs. 155 m$^3$/d). The deviation is not significant if it is compared with the total amount of flow. It appears to be the case that the local infiltration sites (V1 and V2) are difficult to utilize with 2D tools. Ultimately, both modeling approaches yielded similar water infiltration rates, even though the background of the models was very different. This implies that the assessment of flow gradients and conductivity properties of the soil layers was successful in both analyses.

This case study demonstrated that rather simple geotechnical 2D FE calculations can be used to analyze the infiltration of a wide and complex area with satisfactory accuracy. In more simple cases without local discontinuities in the stratigraphy or manmade structures, the accuracy of a 2D model can be very good. Furthermore, based on the study, comprehensive hydrogeological modeling is a preferable method for capturing a general view of groundwater flow in an esker and local variations in infiltration.

With any method, the interpretation of stratigraphy and soil parameters is essential. It is important to first identify the most critical soil layers and define the properties of such layers, preferably via different approaches. When comprehensive data on groundwater levels in the design area are available, the modeling results can be calibrated against actual measurement data, which will clearly improves the model accuracy and minimizes the risk of significant errors.

The dualism of hydrogeological and geotechnical modeling confirmed the amount of infiltration in this case study. A similar approach could be beneficial in most extensive construction projects in areas where complex groundwater systems exist.

Acknowledgements
The authors are grateful to the City of Tampere, whose common interest in the precious groundwater and urban development project, led by Director of Development Reijo Väliharju, has made it possible to conduct such comprehensive investigations and analyses over several years. We especially thank Matti Holopainen, M.Sc., from Ramboll Finland, whose work with the soil investigations and geotechnical design has been a backbone of the study. In addition, the extensive work of many experts has been exploited in this study, which we gratefully acknowledge.

References
[1] Airaksinen J U 1978 Maa- ja pohjavesihydrologia (Pohjoinen, Oulu) p 248
[2] Fagerlund G Royle M Scibek J 2013 Integrating Complex Hydrogeological and Geotechnical Models – a discussion of methods and issues (Slope stability 2013, Brisbane, Australia, Vol 1)
[3] Fetter C W 2001 Applied Hydrogeology (Prentice Hall) p 596
[4] Lemmelä R 1990 Water balance of a sandy aquifer at Hyyrää in southern Finland. Turun yliopisto, Turku (Turun yliopiston julkaisuja Sarja A II, Biologica-Geographica-Geologica 73) p 340
[5] Mäkinen J 2018 Report, Hyhkyn – Pispalan välisen pohjavesialueen maatutkaluotauksen rakennetulkinta, Geo-Work Oy (Maantieteen ja Geologian laitos, University of Turku)
[6] Mäkinen J 2019 Report, Lielahden – Santalahden välisen ranta-alueen maatutkaluotauksen rakennetulkinta, Geo-Work Oy (Maantieteen ja Geologian laitos, University of Turku)
[7] Putkinen N et al. 2017 High-resolution LiDAR mapping of glacial landforms and ice streams in Finland (Bulletin of the Geological Society of Finland 89) pp 64-81
[8] Ahonen et al. 2018 Report, Hyhkyn alueen maaperän 3D- ja pohjaveden virtausmallinnus (Geological Survey of Finland)
[9] Zaitsoff O 1982 Oripäään pohjavesialueen vesitaseesta (Vesihallitus, Helsinki. Vesihallituksen monistesarja 131) p 89