Three-dimensional geologic modeling and visualization of the Virttaankangas aquifer, southwestern Finland

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Abstract A need exists for a reliable and long-term water supply for the 285,000 inhabitants of the Turku area in southwestern Finland. In response to this need, there are plans to replace the present water supply from the surface sources with artificially infiltrated groundwater from a Quaternary esker aquifer called the Virttaankangas aquifer. New sedimentological studies of the Virttaankangas area have revealed the complexities of the esker system and its surrounding glacial, glaciofluvial, and glaciolacustrine geology. This led to the characterization of the hydrogeological units of the aquifer, the result of which has been a three-dimensional (3-D) truly integrated solids model that represents the geometry, interrelationships, and hydrostratigraphy of the study area. The 3-D model was made with EarthVision geologic modeling software. The 3-D geological model of the Virttaankangas aquifer can be used for planning the infiltration of river water into the aquifer and to understand the geologic and geographic boundaries of the hydrogeologic units hosting the groundwater reserve and the geologic relationships between the units. Another major outcome of this study is a powerful visualization tool that will be provided to municipal and government authorities who must understand the geologic complexities involved with water-resource planning prior to their decision making.

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Résumé La région de Turku, dans le sud-ouest de la Finlande, a besoin d'alimenter en eau ses 285.000 habitants sur le long terme et de façon durable. Pour faire face à ce besoin, des plans sont proposés pour remplacer l'actuelle alimentation en eau à partir des eaux de surface par de l'eau souterraine provenant de l'infiltration artificielle dans un aquifère quaternaire d'un cordon sableux fluvio-glaciaire (esker), l'aquifère de Virttaankangas. De nouvelles études sédimentologiques de la région de Virttaankangas ont fait apparaître la complexité du système de l'esker et de son environnement géologique glaciaire, fluvio-glaciaire et glacio-lacustre. Ceci a conduit à la caractérisation des unités hydrogéologiques de l'aquifère, dont le résultat a été un modèle des matériaux en trois dimensions réellement intégré, qui représente la géométrie, les interrelations et l'hydrostratigraphie de la région étudiée. Le modèle 3-D a été réalisé au moyen du logiciel de modélisation géologique EarthVision. Le modèle géologique 3-D de l'aquifère de Virttaankangas peut être utilisé pour gérer l'infiltration de l'eau de la rivière dans l'aquifère et pour comprendre les limites géologiques et géographiques des unités hydrogéologiques stockant l'eau souterraine, ainsi que les relations géologiques entre les unités. Un autre résultat majeur de cette étude est l'outil puissant de visualisation qui sera fourni aux collectivités et aux autorités gouvernementales qui doivent comprendre quelles sont les complexités géologiques impliquées dans la gestion de la ressource en eau avant de prendre leurs décisions.

Resumen El área de Turku, en el sudoeste de Finlandia, necesita una fuente de abastecimiento de agua fiable y a largo plazo para sus 285.000 habitantes. Como respuesta a esta necesidad, hay planes para sustituir el abastecimiento actual de aguas superficiales por aguas subterráneas infiltradas en el acuífero de Virttaankangas, constituido por un "esker" cuaternario. Estudios sedimentológicos recientes en dicha área han revelado la complejidad del sistema de "esker" y de su geología, formada por materiales glaciales, glaciofluviales y glaciolagunares. Estos estudios han permitido la caracterización de las unidades del acuífero, las cuales han sido implementadas en un modelo tridimensional (3-D) que representa la geometría, relaciones e hidroestratigrafía del área. El modelo 3-D se ha realizado mediante el software geológico 'EarthVision'. El modelo 3-D del acuífero de

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Virttaankangas puede utilizarse para planificar la infiltración de aguas del río en el acuífero y para identificar los límites geológicos y geográficos de las unidades hidrogeológicas que almacenan las aguas subterráneas, así como para conocer las relaciones geológicas entre dichas unidades. Otro resultado importante de este estudio es la generación de una herramienta poderosa de visualización que será de ayuda para las autoridades municipales y gubernamentales que deben entender la complejidad geológica asociada a la planificación de los recursos hídricos como paso previo a la toma de decisiones.

Keywords Three-dimensional models · Geologic modeling · Hydrogeological units · Esker aquifer · Visualization

Introduction

According to the cost and benefit study of Bhagwat and Ipe (2000), the benefits of traditional geological mapping outweigh its costs many times over and these benefits are particularly realized for groundwater applications (Bhagwat and Berg 1991). Traditional geological maps show the two-dimensional (2-D) distribution of deposits at land surface based on interpretations of land forms, field examination of exposed materials, and information from shallow excavations or drilling.

In contrast to traditional 2-D geological maps, three-dimensional (3-D) geological maps and models can provide the most sophisticated and detailed geological information and therefore the greatest potential benefits to users. Three-dimensional mapping shows the complexities of subsurface geology mapped from land surface to designated depths. Deposits are differentiated by comparing their physical properties, vertical sequences, and lateral distribution patterns with modern models of sediment deposition. Recently, considerable attention has been placed on developing new methods for interpretation, description, and portrayal of the 3-D structure of unconsolidated deposits in order to enhance strategies for sustainable use of groundwater and its protection (e.g., Berg and Thorleifson 2001). The detailed distribution of the thickness, depth, lateral extent, stratigraphy, and sedimentology of aquifers and aquicludes can be displayed by using 3-D visualization software to produce multiple cross sections, block diagrams, slice maps, etc. (Berg et al. 1999; Soller et al. 1999). This provides for the most complete picture of the subsurface geology—as true a representation of reality that presently exists—and an internally consistent and directly integratable conceptual model that can be used by hydrogeologists to begin the process of modeling groundwater flow and direction. In addition, 3-D visualization is also regularly employed as a tool of analysis and communication, as addressed by Voss (1999).

This paper discusses the development of a 3-D computer-based geological model of the Virttaankangas aquifer in southwestern Finland. The 3-D geologic model that has been developed for this project is a truly integrated solids model that represents the geometry, stratigraphy, hydrostratigraphy, and sedimentology of aquifer and aquiclude units, their interrelationships, and their ability to receive recharged river water and discharge the water to a distribution system. This detailed and directly integratable model is the first of its kind in northern Europe and is the cornerstone of the Virttaankangas artificial groundwater recharge project. Following completion in 2007, this project will be the largest and most ambitious artificial groundwater recharge project in northern Europe. The size of the model area is 54 km^2 which covers the whole area planned to be used for infiltrating river water into the aquifer (Fig. 1).

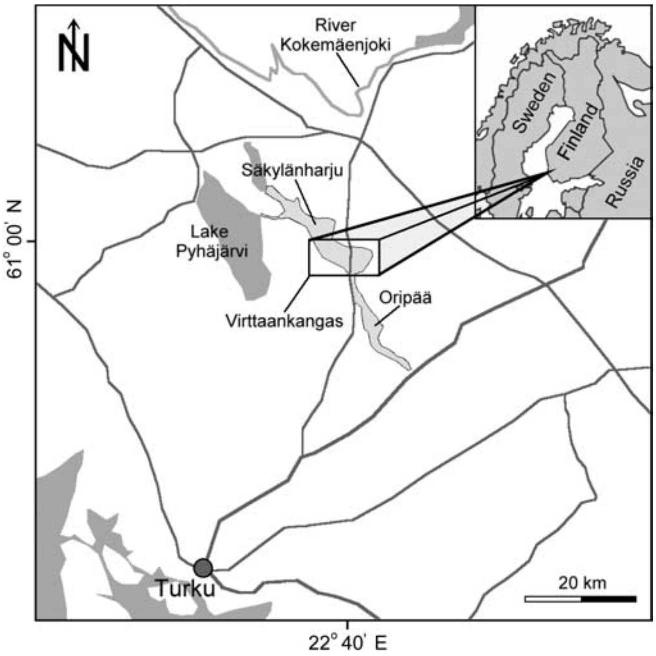

Fig. 1 Location of the study area and surrounding esker areas

The reliance on groundwater as a drinking water source in Finland has increased significantly during the last decade. At present, it comprises about 61% of total water use (Finnish Environment Institute 2003). The city of Turku and its surrounding area has always been dependent on river water as the primary source of drinking water. However, there has been an increasing need for a more reliable and long-term water supply due to seasonal quality and quantity problems.

The idea of getting additional potable water for the Turku region from the Virttaankangas aquifer was first introduced in the 1960s. However, the present water project was not launched until 1999 with the aim of providing groundwater from artificially infiltrated water from the River Kokemäenjoki, located 28 km north of Virttaankangas. The regional water company (Turku Region Water Ltd.) is planning to pump and pre-treat approximately 110,000 m^3 of water per day from the nearby river [this is about 0.5% of the mean flow of the river (Jaakko Pöyry Infra 2001)], infiltrate the water via

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elaborate sprinkler systems into the Virttaankangas aquifer, and then pump artificially recharged groundwater to a waterworks plant and to the 285,000 inhabitants of the city of Turku and its surrounding area, about 66 km south of Virttaankangas (Fig. 1) beginning in the year 2007.

During the last few years, the enhanced capabilities of computing technology have led to new ways of presenting the outcome of sedimentological studies. Some of the studies have focused on describing more detailed features of limited areas (Langsholt et al. 1998; Asprion and Aigner 1999), whereas other studies have covered large areas with less detailed interpretations. Anderson (1989) emphasized the importance of conceptualizing large-scale hydrogeologic trends in glacial and glaciofluvial sediments based on a method adapted from sedimentologic facies modeling. Although some of the more detailed features of the sedimentological models cannot be modeled at the same level of detail in the 3-D hydrogeological models, the sedimentological models provide predictive capability on the extent and location of hydrogeological units, particularly in areas of sparse data.

The 3-D hydrogeological model reported in this paper provides a new approach to validate and choose a conceptual model to be used in flow and transport models. Because the internal architecture of materials in the 3-D solid geological model is well understood, the boundaries of the 3-D geological model represent the actual (or as close to reality as possible based on available detailed data) physical limits of the aquifer units, which can be used directly in flow modeling. In addition, the 3-D model can include some hydraulic data or interpretation of the trends in hydraulic properties within the modeled units. By contrast, a traditional conceptual model is validated on the basis of the calibration scheme and is repeatedly changed in order to produce the best fit for the model (e.g., Anderson and Woessner 1992). These changes can also apply to the physical limits of the aquifer units. Even though the inverse modeling techniques have proven to be of importance in validating the conceptual models for flow modeling (Poeter and Hill 1997), they still lack the ability to produce the physical limits of the aquifer units comprehensively. Compared with the traditional approach of groundwater flow modeling, as presented by Anderson and Woessner (1992), the use of a 3-D model reduces the need to modify the parameters describing the architecture of the modeled area.

Moreover, flow models and 3-D geological models can be developed jointly. This avoids discrimination of the geological settings and it verifies some assumptions in the 3-D model by testing it with the help of flow models.

Geology of the Study Area

The Virttaankangas aquifer is part of southwest Finland's largest esker chain. Recent sedimentological studies have clarified the complex structure of the Quaternary deposits and provided predictive models of the distribution and character of the deposits, which led to the idea of studying and characterizing the hydrogeological units of the aquifer by combining the sedimentological information with all the drilling and geophysical data from the area. The hydrogeological characterization and mapping included the delineation of the major esker aquifer units and the confining silt and clay unit, all of which had been discovered in many previous field investigations, but never mapped in detail.

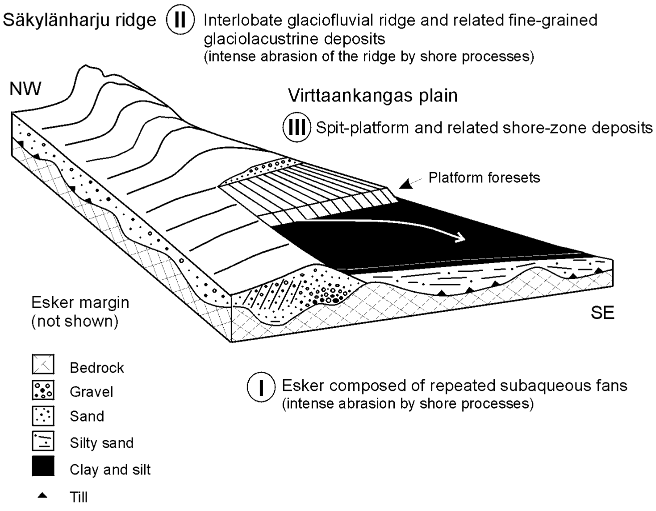

Fig. 2 Structural zones of the Säkylänharju–Virttaankangas complex

The Säkylänharju–Virttaankangas esker (a morphological term) is an interlobate feature, which formed between the sublobes of the retreating Baltic Sea ice-lobe (Punkari 1980; Kujansuu et al. 1995) during the Late Weichselian deglaciation of the Scandinavian Ice Sheet. The interlobate origin is supported by the morphology and the exceptionally large size of the esker ridge, by tributary eskers, and by recent sedimentological studies of the esker (Mäkinen 2001a).

A new depositional model of the Virttaankangas plain, the large sandy deposit on the eastern side of the esker chain, by Mäkinen and Räsänen (2003) shows that the uppermost 10–20 m of the plain is composed of littoral sand and gravel and does not represent glaciofluvial to glaciolacustrine sedimentation as originally thought (Glückert 1971; Turku Region Water Ltd. 1991). Littoral sands and gravels (Fig. 2) were formed by the development of a spit-platform during the forced regression of the ancient Baltic Basin about 11,000–10,500 years ago.

Hydrogeologic zones reflect the complex structure of the esker. According to Mäkinen (2001b), the core of the interlobate esker, which cannot be detected morphologically, formed as a time-transgressive feature composed of repeated ice-marginal subaqueous fans fed by a subglacial meltwater tunnel. These fans were associated with a transition from proximal gravels to medial large-scale foresets, and finally to distal fine-grained glaciolacustrine deposits. The coarse-grained part of the esker core is about 500–600 m wide.

Apparently, changes in depositional conditions of the esker led to the development of interlobate ice-marginal crevasse deposits, which form the main Säkylänharju glaciofluvial ridge (Fig. 2). They show a transition from proximal gravels to medial sands and then to distal glaciolacustrine fine-grained sediments. Due to glacio-isostatic rebound, the main ridge and also the upper parts of the fans were subjected to intense wave-induced erosion, whereas the distal sediments were superimposed by littoral spit-platform deposits. The fine-grained deposits underlying the littoral sands and gravels hold a perched groundwater table on the northeastern side of the Virttaankangas plain.

Methods

The depositional model and the results of recent sedimentological studies from other parts of the esker system (Mäkinen 2001b) provide a key to interpret glaciofluvial and glaciolacustrine depositional stages within the Säkylänharju–Virttaankangas area. By combining this information with morphology, drill hole logs, ground-penetrating radar (GPR) profiles, seismic soundings, results of pumping and recharge tests, and pit observations, a detailed internally consistent 3-D geologic model has been developed.

The 3-D model of the Virttaankangas aquifer was made using EarthVision software and it was done cooperatively with the Illinois State Geological Survey. Data were prepared and compiled into 2-D matrices using the Surfer program at the University of Turku in Finland. The data also included ASCII-xyz data of the different units of the model. These units represent a simplification of the hydrogeology of the area. However, detailed sedimentological information of specific units and detailed information of the internal variation of units are still obtainable, if desired, in the sedimentological model and via calibration of the flow model with the help of aquifer tests.

The matrix of the bedrock surface and the elevation matrix of the land surface were left out of the interpolation process of the EarthVision program. These matrices acted as the fixed lower and upper surfaces of the whole model. Therefore, other layers did not intersect with these surfaces. The field data that fell between these surfaces representing the other modeled units were prepared and weighted to avoid loss of the most accurate information during the interpolation process. The data included drilling logs, sedimentological logs, GPR soundings, seismic soundings, gravimetric measurements, and permeability tests. This material was compared and combined with the information obtained from the sedimentological model of the area. Some solutions were introduced to weigh the field data according to its reliability (e.g., Arnold et al. 2001; Keefer and Larson 2001; Ross et al. 2001), but there are no standards for that operation. In this study, the sedimentological information of the area was the main tool to interpret the information obtained from the primary data, as discussed later. The model domain covers 54 km^2 and has 121 rows and 181 columns consisting of 50×50-m cells.

The land surface elevation was based on the digital elevation map (DEM) of the area. Most of the elevations of individual drilling sites and elevations of the groundwater monitoring wells were measured before the start of this study. These elevations were checked again so that they matched with the DEM. For those study sites with no elevation data, the elevation of ground surface at the location was obtained from the DEM. The land surface elevation and the locations of drilling sites are presented in Fig. 3. The locations of geophysical measurements in the study area are presented in Fig. 4.

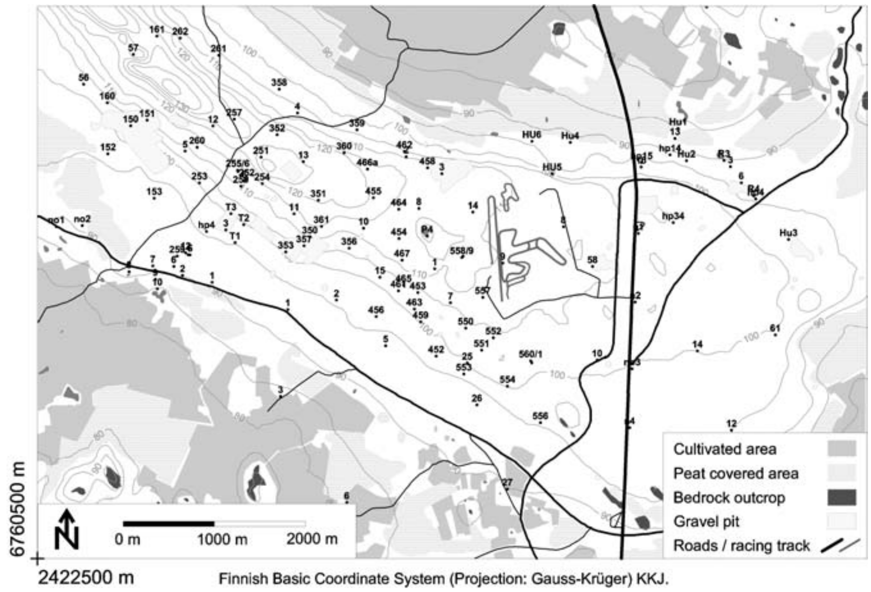

Fig. 3 Drilling site locations and land surface elevation. Contour interval is 5 m

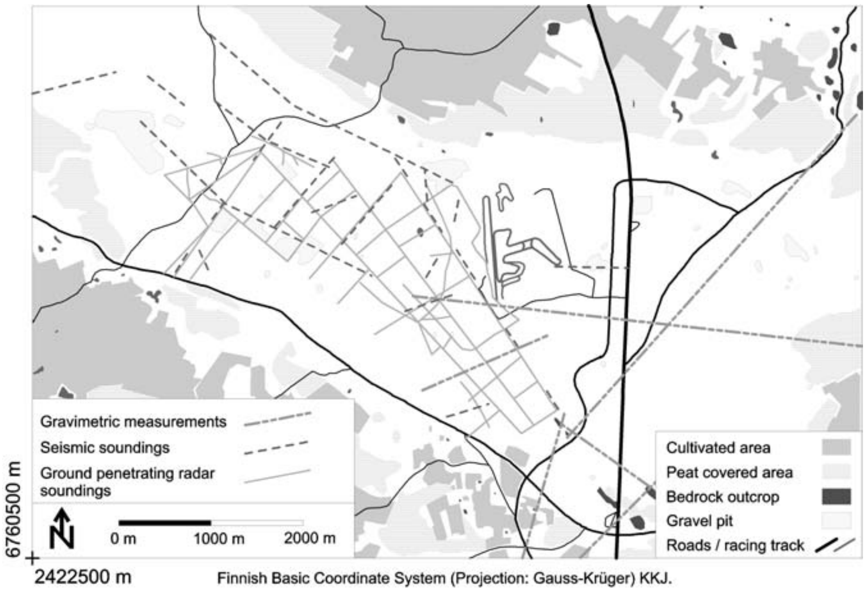

Fig. 4 Locations of geophysical measurements

Determination of the Hydrogeologic Units of the Virttaankangas Aquifer

The 3-D hydrogeological model includes the following units: relatively impermeable bedrock, one till unit, two glaciofluvial and/or glaciolacustrine units, a glaciolacustrine clay and silt unit, and a littoral sand unit. Division of the 3-D model into these units was based on the accuracy of the primary data—these units were those most reliably identified from the drilling logs and geophysical data with the help of interpretations obtained from the sedimentological model. They were first mapped as 2-D layers using Surfer.

All the data included in the 3-D model were carefully evaluated and checked against the data obtained from the sedimentological model. The interpretation of the hydrogeological units was achieved quite accurately from the sedimentological data. In addition, the sedimentological interpretation of the extent of different sedimentological units provided important information of the grain-size distribution of the sediments in different areas of the 3-D model.

The glaciofluvial coarse-grained unit includes the proximal and medial parts of the subaqueous fans and coarsest part of the large-scale ice-marginal crevasse deposits of the main Säkylänharju ridge (Fig. 2), which mostly consist of gravel and coarse- to medium-grained sands. Alternatively, the distal parts of the subaqueous fans belong to the fine-grained glaciofluvial/glaciolacustrine unit, which also includes the fine sands and silts of the spit-platform deposits.

The glaciolacustrine clay and silt unit has been mapped individually in the 3-D model and it includes the silts and clays formed by glaciolacustrine sedimentation during the buildup of subaqueous fans and extensive ice-marginal crevasse deposits. These fine-grained deposits hold a perched groundwater table on the eastern and northeastern side of the Virttaankangas plain. However, the lower and slightly coarser parts of these glaciolacustrine sediments are included in the fine-grained glaciofluvial/glaciolacustrine unit mentioned above.

Littoral sands and gravels were formed by development of a spit-platform during the forced regression of the ancient Baltic Basin about 11,000–10,500 years ago. These deposits form the uppermost unit of the 3-D hydrogeological model. In addition, the 3-D model includes the bedrock unit, which acts as a relatively impermeable lower boundary. A till unit, with a discontinuous distribution over the study area, may directly overlie the bedrock.

Assigning Hydraulic Properties to the 3-D Model

Some of the K-values that were assigned to units are based on the measured values of the hydrostratigraphical units, such as the littoral sand unit. Others are based on assumed K-values based on grain size (Freeze and Cherry 1979; Zheng and Bennett 1995) and sedimentological variations from the sedimentological model. All of the K-values can be used only as initial data for the groundwater flow model calibration. It should be noted that the 3-D geological model does not include any numerical data on hydraulic properties of the units. However, the location and extent of these units give an overview of their grain-size distribution and variation of hydraulic conductivity. Furthermore, Hill et al. (1998) pointed out that hydraulic conductivity values measured in the field are not as directly applicable to a numerical model of the system and often are not consistent with how these data are used in model calibration.

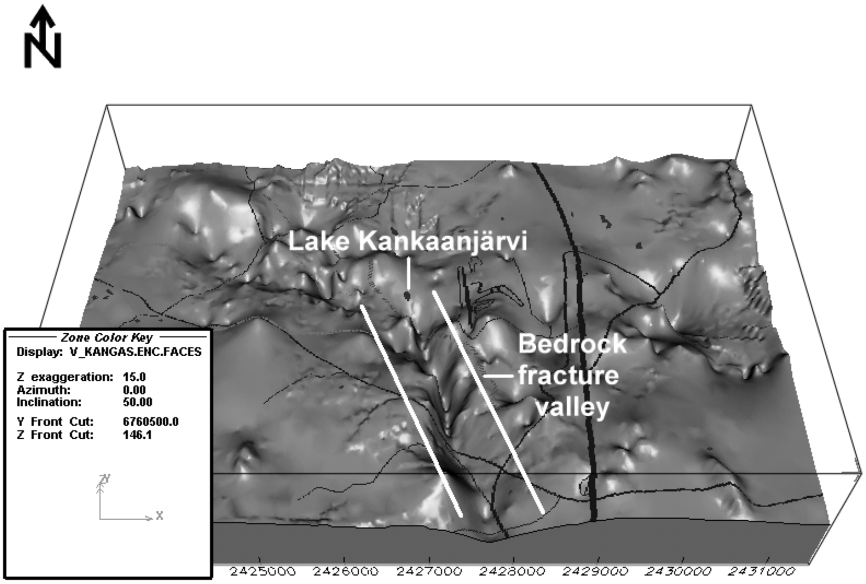

Fig. 5 View of the 3-D model showing the bedrock surface

Results and Discussion

The modeling of the Virttaankangas aquifer started in March 2001 and the first version of the 3-D geological model was finished at the end of September 2001. This 3-D model was included in an EarthVision Viewer program, which provides the user with an easy-to-use graphical interface, and runs under Windows 2000 or Windows NT. The EarthVision Viewer program allows the user to rotate and slice the model in all three dimensions, remove or add units, make selected units transparent, etc. These features allow the user to focus on any area of interest, observe large-scale interrelationships between aquifers and aquicludes in a fully integrated solids model, and still be able to view the more detailed area within the context of the whole aquifer area and its surroundings. The 3-D model can be sliced at 50-m intervals in x- and y-directions and at 2-m intervals in the z-direction. Examples of some of the model features are presented at http://users.utu.fi/akartimo/3dmodel/english. The 3-D units were also converted back into 2-D matrices, which represent the upper surfaces of all the modeled units. These 2-D matrices can further be used, for example, in Surfer and MODFLOW programs.

A deep bedrock depression/fracture valley about 100 m wide and up to 90 m deep (measured from the land surface) was detected by gravimetric measurements (Geological Survey of Finland 1992), seismic soundings, and borings in the southern and central part of the study area (Fig. 5). This fracture valley has controlled the location of the esker and especially the deposition of its coarsest material for a distance of almost 15 km from Oripää to Virttaankangas (Fig. 1). The coarsest esker material forms a positive relief feature in the northwestern part of the study area, which indicates a change of the depositional conditions from repeated ice-marginal subaqueous fans to large ice-marginal crevasse deposits of the main Säkylänharju ridge.

Clays do not occur above an elevation of 105 m above mean sea level in the study area. A clay (and partially silt) layer, which causes a perched water table, has been outlined in the model with a dotted line (Fig. 6). On the northeastern side of the coarsest part of the esker are some silt layers at elevations greater than 105 m which have been connected to the more uniform silt and clay layer. This area has also been outlined with a dotted line in the annotation file of the 3-D model (Fig. 6). It should be noted that in this area there is more than one silt layer, which is also recorded by the drilling data, and that these silt layers are dipping to the northeast away from the esker. Based on this information, this portion of the study area is not suitable for artificial recharge because the needed rates and volumes of infiltrated water cannot be obtained in a consistent manner. The grain-size distribution and hydraulic conductivity variation within the mentioned units are presented in Table 1.

Possible further research work should include:

1. Validation in some areas with the help of new field data. These studies may include additional hydraulic conductivity measurements of the littoral sand unit.
2. Detailed study of the continuity of the glaciolacustrine silt and clay unit, which holds the perched groundwater table. GPR surveys and new drill hole data would be most useful. This unit is important for controlling the artificial recharge because it affects both the horizontal and vertical flow of groundwater.
3. Adequate study of tributary eskers on the western side of the main esker. Only the tributary esker branch, which seems to control the outflow from the Myllylähde spring (Fig. 7) by being the preferential flow channel for groundwater, has been studied enough to be included into the 3-D model. The annotation files

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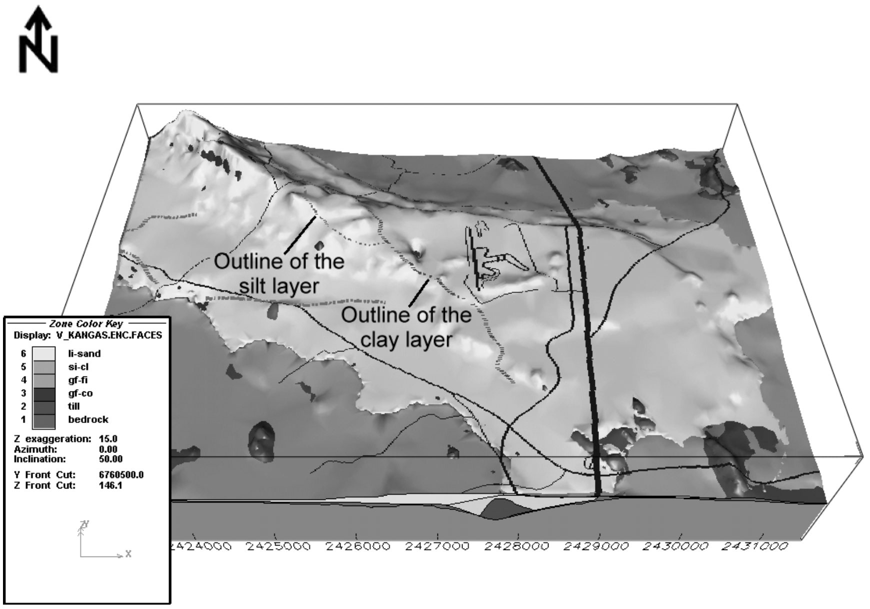

Fig. 6 Outlines of the silt and clay layers, which hold a perched water table on the eastern and northeastern part of the Virttaankangas plain

Table 1 Variation intervals of grain-size distribution and estimated/measured K-values in hydrogeological units of the 3-D model

Unit	Grain size distribution	Hydraulic conductivity (K) (m s^{-1})	Variation of the material within the unit
Till	All grain size classes	10^{-8} to 10^{-6}	Sandy till of relatively uniform quality, in the bottom of the unit fine-grained basal till (Kukkonen et al. 1993)
Glaciofluvial coarse	Medium sand–gravel (>0.25 mm)	10^{-4} to 10^{-0}	Mainly coarse sand and gravel. Part of the material medium sand, with very few finer interbed layers. The coarsest material in the bedrock fracture valley south from the Kankaanjärvi kettle hole lake (Fig. 7). Fining trend towards the edges of the unit. Morphologically undetectable kettle holes
Glaciofluvial fine	Silt–fine sand (0.004–0.25 mm)	10^{-7} to 10^{-4}	Fining trend of the material towards east to the Virttaankangas plain. Morphologically undetectable kettle holes cause internal variation of the material within this unit. Finer deposits also in the distal parts of the subaqueous fans
Clay–silt	Clay–silt (<0.063 mm)	10^{-11} to 10^{-7}	The unit holds a perched water table only in the eastern and northeastern side of the esker. In that area the unit is dipping to east and northeast away from the esker
Littoral sand	Medium sand–gravel (>0.25 mm)	10^{-4} to 10^{-1} (partially measured)	Upwards coarsening sets. Gravelly parts closest to surface. Cross-bedded sand of uniform quality, with almost no traces of silt and clay. Material is fining to east

included in the 3-D model include the location interpretations of the other tributaries.

4. Addition of the groundwater table to the model. The groundwater table could be presented as a cutting layer that divides the 3-D model into saturated and unsaturated parts, both of which can include a variable number of hydrogeological units. Available interpretation of the groundwater table is not yet validated and needs some refinement. Because of this, the version of the 3-D model presented in this paper does not include this feature. However, it can easily be introduced into later versions of the model.

The Finnish eskers are good aquifers because of their hydraulic properties and their ability to yield adequate groundwater supplies. However, because sand and gravel is so close to the surface, these aquifers are highly vulnerable to contamination. In addition, the complex internal structures of the eskers have been difficult to locate and describe in an understandable manner and the evaluation of the effect of these structures on groundwater flow has been problematic.

Based on experiences obtained from the Virttaankangas investigations, 3-D geological models have proved to be important tools to improve the quality of groundwater flow models. In many Finnish aquifers the hydraulic properties of the materials can change very rapidly both horizontally and vertically. This results in a need to find the most precise geological and hydrogeological boundaries to the conceptual models as are possibly attainable.

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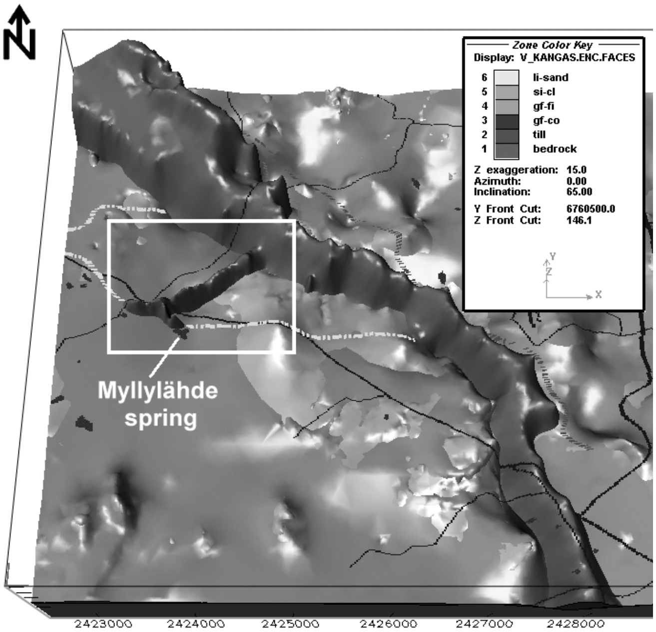

Fig. 7 Coarsest part of the tributary esker included in the 3-D model and location interpretations of other tributaries (*light-colored dotted lines*)

The 3-D models provide a method to control the calibration process of the groundwater flow and contaminant transport models.

Conclusions

The 3-D geological model developed for the Virttaankangas study area is the key to understanding sedimentological environments of deposition and complex geologic and stratigraphic relationships and to protecting economically important aquifers. Development of these 3-D models can reduce overall project costs because they provide a tool that allows water resource managers and hydrogeologists to predict the geologic and hydrogeological conditions of the aquifer area and thereby reduce the number of drill holes and monitoring wells needed to characterize an area.

Most importantly, the modeled 3-D information on the different earth materials allows for different end-users, such as hydrogeologists, to develop their groundwater flow and transport models. The groundwater flow model of an area must be capable of producing the most accurate results for different infiltration and pumping scenarios. The internally consistent and directly integratable 3-D geological model is constructed such that units conformably lie upon one another and lower units do not reside above upper units. This, in combination with the sedimentological model, provides the hydrogeologist with a ready-made conceptual model for the area where the geology is well understood and units are delineated according to predictive geological principals. Therefore, the geological model can be directly input into MODFLOW or other groundwater flow models, assigning of hydrologic parameters to units by hydrogeologists can be done more precisely, and the overall time spent for model development is reduced.

The 3-D hydrogeological model of the Virttaankangas area can be used to validate and to improve the quality of groundwater flow models. The control over the flow velocities is important because the quality of the water depends on the time that it takes infiltrated water to flow through the esker material. Also, the flow from the springs around the esker area should be maintained at the present level during all pumping situations. This requires special care in handling the boundary conditions and the limits of modeled hydrogeological units. The 3-D hydrogeological model can be of great importance in setting these boundaries and limits to the groundwater flow model.

Because there is a diverse group of end-users, modelers must be cognizant of the quality of their data and model and the ability of their data and model to be user-friendly. The versatile possibilities of aquifer visualization are particularly important for municipal and government authorities, who must ultimately decide on options for land-use and water-resource planning and who provide funding for water resource and protection strategies.

The 3-D hydrogeological model of the Virttaankangas aquifer is an important tool for finding the areas suitable for artificial recharge. Because the modeling will be used directly by water-resource planners to provide potable water to one of the largest cities in Finland, this investigation should provide a ready and immediate example of the benefits of concurrent geological and hydrogeological mapping and modeling.

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