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Groundwater flow models of the shallow aquifer in Hanko

Prepared by
Samrit Luoma

Prepared for
ELY Centre Uusimaa,
Hanko City, and
Hanko Water and Waste Water Work

Centre for Economic Development, Transport and the Environment

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Tiivistelmä

This study was carried out as part of the POAKORI project with the aim to construct the groundwater flow model for the shallow aquifer of the Hanko groundwater area (#0107801). Based on the geological and hydrogeological data, the Hanko groundwater area was divided into two aquifers; the east and the west aquifers, by a thick fine-grained unit that deposits in the NW-SE direction from Lindnäsudden in the northern coast of the Baltic Sea to south and south-east of Fermion Oy, and south of Motocross-rata. Consequently two steady-state groundwater flow MODFLOW models were constructed for both aquifers. Model 1 was constructed for the west aquifer represents a semi-confined aquifer of the lower groundwater level, which is partly bounded by the fine-grained unit in the northern part of the aquifer. The river package (RIV) from MODFLOW was used to estimate the leakage of the fine-grained bed as the recharge from the perched groundwater in the fine-grained area. A calibration with good correlation (R^2 0.94) was performed for the simulated and observed groundwater levels from 88 observation wells measured during May-June 2017. The simulated water balance indicated the total inflow of the model domain of 4134.65 m^3/d, which consists of 1365.97 m^3/d from the leakage of the fine-grained unit, 2499.51 m^3/d from the groundwater recharge, and 269.18 m^3/d from sea-water at the shoreline in the Hopearanta water intake area. The water budget showed a sufficient water for the current pumping rate of 1808.00 m^3/d. However, the high pumping rate from the water intake wells along the coastline could lower down the groundwater level and induce more sea-water into the aquifer. Model 2 was constructed for the unconfined aquifer, covered the areas of the perched groundwater in the west aquifer and the main groundwater in the east aquifer. The calibration was performed for 77 observation wells and generally shown good correlation (R^2 0.94) between the simulated and observed groundwater levels. Poor calibration was found in the finer-grained aquifer areas such as in Furunäs, and the high uncertainty still remains in some areas such as in southern Oy Forcit Ab due to the lack of calibrated points. The water balance showed the total inflow of model 2 of 4324.50 m^3/d, which obtained from the recharge in the perched groundwater area of 1572.33 m^3/d and in the main groundwater area of 2752.17 m^3/d.

Asiasanat (kohde, menetelmät jne.)
Hanko, the First Salpausselkä, groundwater flow model, groundwater, perched groundwater

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Contents

Summary

1 Introduction 1
2 Study site 1
3 Conceptual model and assumptions 2
4 Groundwater flow models 7
4.1 Model 1: The main groundwater in area 1 7
4.1.1 Boundary conditions 7
4.1.2 Model input parameters 7
4.1.3 Model calibrations 8
4.2 Model 2: The perched- and the main groundwater in area 2 8
4.2.1 Boundary conditions 8
4.2.2 Model input parameters 9
4.2.3 Model calibrations 9
5 Results 9
5.1 Model 1 9
5.2 Model 2 13
6 Model limitations 16
7 Conclusions and recommendations 16
8 Acknowledgements 17
9 References 17
Appendix 1. Leakage calculation using the River Package 19

1 INTRODUCTION

This study was carried out as part of the POAKORI project (Kemiallisesti huonossa tilassa olevien pohjavesialueiden kokonaisvaltainen riskinhallinta) – a cooperation project between the Pirkanmaa- and the South Savo ELY Centres, the Uudenmaa ELY Centre, the Finnish Environment Institute (SYKE), the Geological Survey of Finland (GTK), WaterHope Oy and Ramboll Finland Oy with the aim to develop an operating model that can be used as a tool for risk assessments of groundwater contamination sites and for prioritization of risk management measures in the vulnerable groundwater areas to ensure that the greatest risk to groundwater areas are first to be cleaned up and/or protected. The operating model consists of the investigations of geological and hydrogeological characteristics of aquifer bodies, flow- and solute transport models, sensitivity-, vulnerability- and risk analysis, in order to create a new comprehensive approach to risk managements for the wellhead protection areas of the water intake wells and the whole groundwater area. The project has been implemented into two case study sites; the shallow groundwater areas in Mikkeli in eastern Finland and in Hanko in southern Finland. In the Hanko case study area, GTK investigated the detailed geological and hydrogeological characteristics and distributions of the aquifer in the First Salpausselkä ice-marginal deposit as reported by Luoma (2018a). The investigation results provide the geological framework for the further studies in the flow and solute transport modelling and also risk assessments and groundwater resources management of the study area.

The work presented in this report was aimed to construct the steady-state groundwater flow models of the shallow aquifer in the Hanko groundwater area based on the conceptual model constructed from the detailed investigation of geological and hydrogeological model from Luoma (2018a). The flow models were constructed for two areas cover the perched- and the main groundwater areas by utilizing all available geological and hydrogeological data. In addition the River (RIV) Package from MODFLOW code was used to estimate the leakage of perched groundwater in the fine-grained area.

2 STUDY SITE

The study area is located in the western part of the Hanko Peninsula in southern Finland, covers total area of 14.09 km^2 of the Hanko main groundwater area (#0107801) (Fig. 1). The shallow, low-lying coastal aquifer in Hanko consists of porous gravels and sands of First Salpausselkä ice-marginal end moraine formations, and is bounded by the Baltic Sea (Fig. 2). It is an important source of water for the residents of the Hanko town and the local industries. The Hanko area belongs to the temperate coniferous-mixed forest climate zone with cold, wet winters. The mean annual temperature is 6 ºC, with mean minimum and maximum temperatures of -4.2 and 16.6 ºC, respectively. The average annual precipitation was 620 mm during the period 1971–2000 (FMI 2018). Groundwater recharge mainly occurs twice a year during spring (late March to early April) and late autumn (November to early December) from the infiltration of snowmelt and rainfall (Luoma & Okkonen 2014). Groundwater mainly flows northwards and southwards into the Baltic Sea coastal areas and also towards the south–southeast into the wetlands and peatlands. The existing potential anthropogenic impacts from human activities in the area (FCG Suunnittelu ja tekniikka Oy 2013), e.g. local industries, shooting range, leaks of oil tank or landfill leachate, as well as the potential seawater intrusion due to sea level rise, could pose contamination risks to groundwater quality.

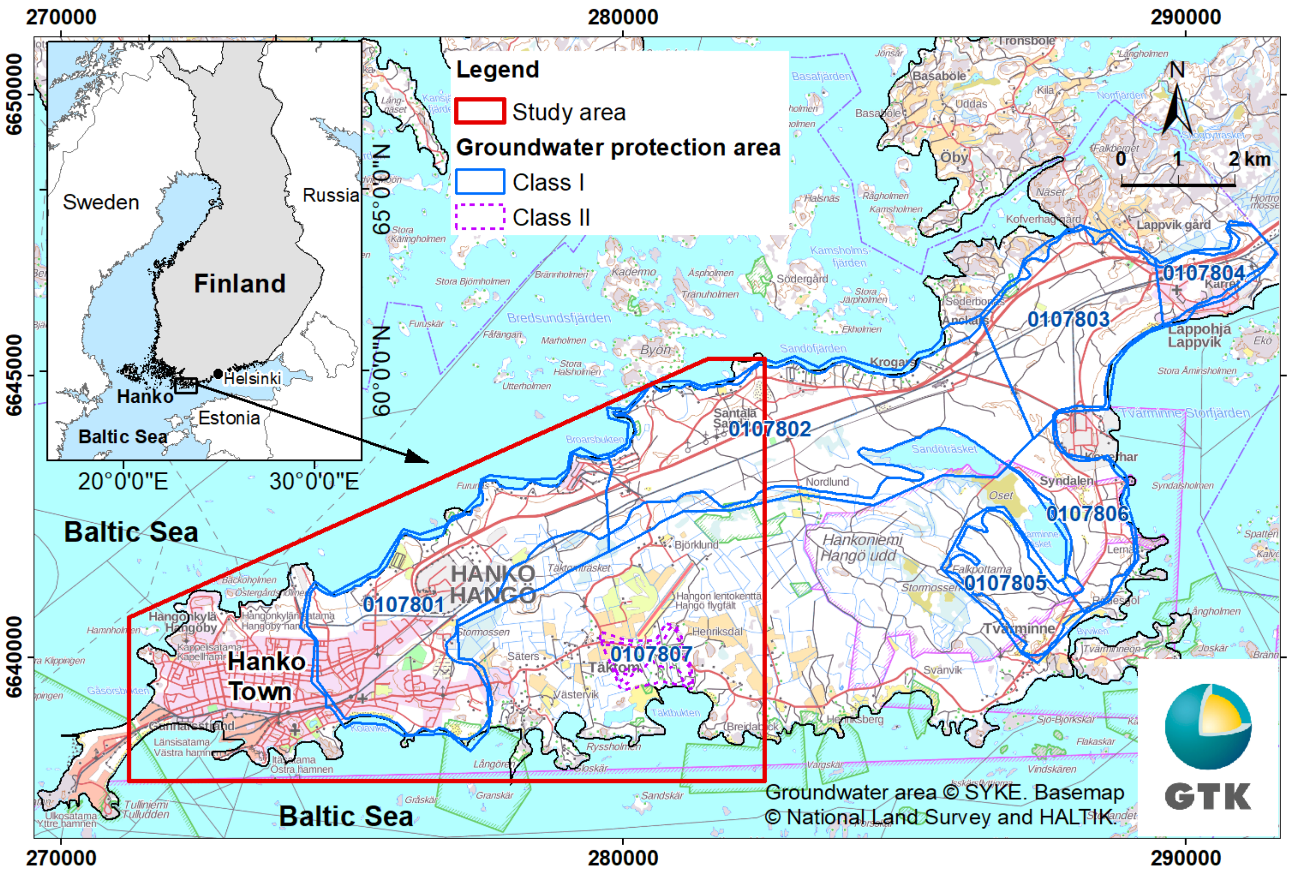

Fig. 1 Location of the study area.

3 CONCEPTUAL MODEL AND ASSUMPTIONS

The aquifer in the study area is situated in the First Salpausselkä ice-marginal formation deposited during the Weichselian and Holocence deglaciation of the Scandinavian Ice Sheet (Fyfe 1991, Kielosto et al. 1996). The First Salpausselkä ice-marginal formation consists of glacial till, gravel, sand and clay, together with postglacial littoral gravel, sand and clay (Fig. 2). The primary ice-marginal formation in Hanko was formed in deep water with a low narrow ridge (Fyfe 1991). When the ice sheet withdrew from the area, this formation was covered by fine-grained sediments, silt and clay layers of the Ancylus Lake and Littorina Sea. The sea level has been regressive since the glacial period due to isostatic land uplift. The primary deposit of the First Salpausselkä formation was partly exposed to sea waves and also to wind (Kielosto et al. 1996).

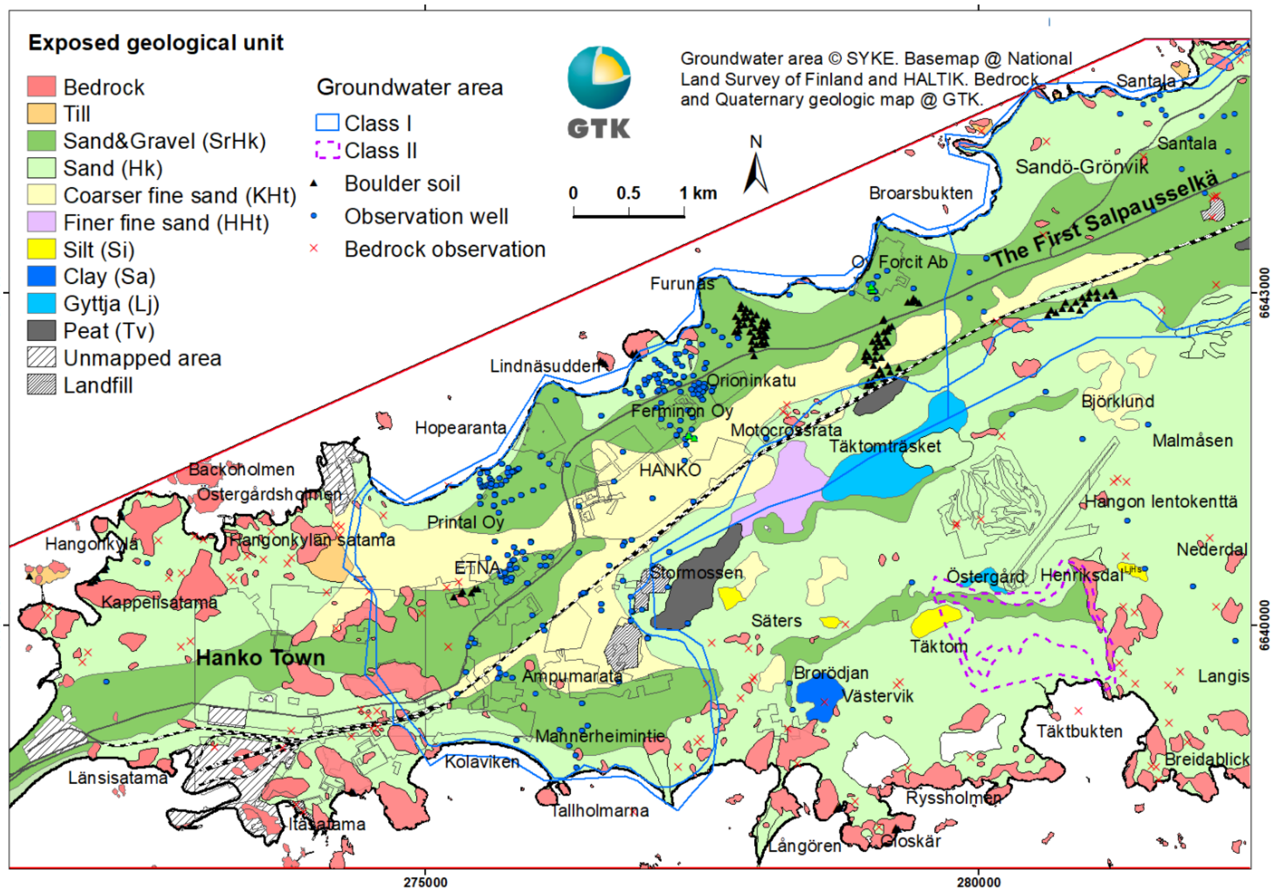

Fig. 2 The Quaternary geological deposit map of the study area.

Based on the geological and hydrogeological investigation report (Luoma 2018a), the Hanko groundwater area is separated from the Sandö-Grönvik groundwater area (#0107802) in the east by the threshold of the elevated bedrock topography (Fig. 3). In the west the Hanko groundwater area is bounded by the shallow bedrock surface topography and thin Quaternary deposit in the Hanko town area. While in the south and south-east, the Hanko groundwater area is bounded by fine-grained sediments such as silt, gyttja and clay in the wetlands and peatland areas. The thick fine-grained (silt & clay) unit extends across the groundwater area in the NW-SE direction, covers the areas from Lindnäsudden in the Baltic Sea coast to south and south-east of Fermion Oy, and south of Motocross-rata (Fig. 5). This thick fine-grained unit could possible divided the Hanko groundwater area into two aquifer areas (Fig. 5 and Fig.6): Area1, in the western side of the fine-grained unit, covers the areas between Hopearanta, Printal Oy, ETNA and the Hanko town; Area 2, in the eastern side of the fine-grained unit, covers the areas between Furunäs, Fermion Oy, Motocross-rata and Forcit Oy.

Area 1 consists of two groundwater levels: the lower and the upper groundwater levels. The lower groundwater level is semi-confined aquifer, where it is confined by the fine-grained unit.

The unconfined aquifer is observed in the southern part of the area, where the fine-grained unit is disappeared. The upper groundwater level represents the perched groundwater accumulated above the fine-grained layer. No perched groundwater is recorded from drilled boreholes in the fine-grained area in the south and south-east of Fermion Oy (SK101…SK901). These boreholes, however, were drilled with the objective to confirm the bedrock surface depth and it is possible that perched groundwater were not taken into account during the drilling operations (Esko Nylander, per.com. 2018). Hence, extent of the perched groundwater could possibly follow the extent of the fine-grained unit. Perched groundwater levels vary between 10-12 m a.s.l. in the middle of the groundwater area, which as same groundwater levels as in the Area 2. Therefore, it is possible that perched groundwater has connection with the groundwater in the Area 2.

Area 2 contains only one main groundwater level (except locally perched groundwater found in the Motocross-rata area). Groundwater level varies between 10-12 m a.s.l. in the middle of the groundwater area.

Fig. 6 presents a conceptual model of the aquifers in the Hanko groundwater area. More details of geological modelling are presented in Luoma (2018a).

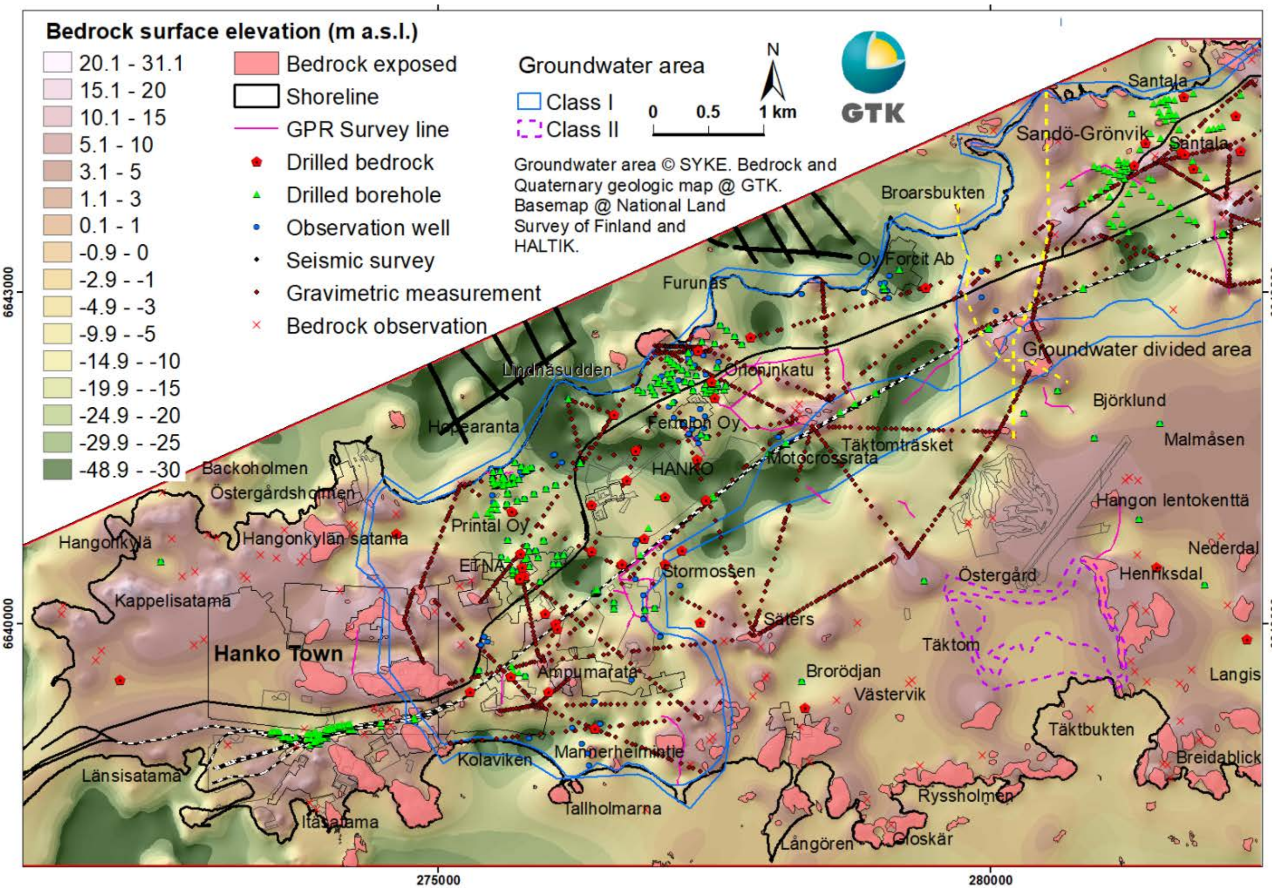

Fig. 3 Map of Bedrock surface elevation in the Hanko groundwater area.

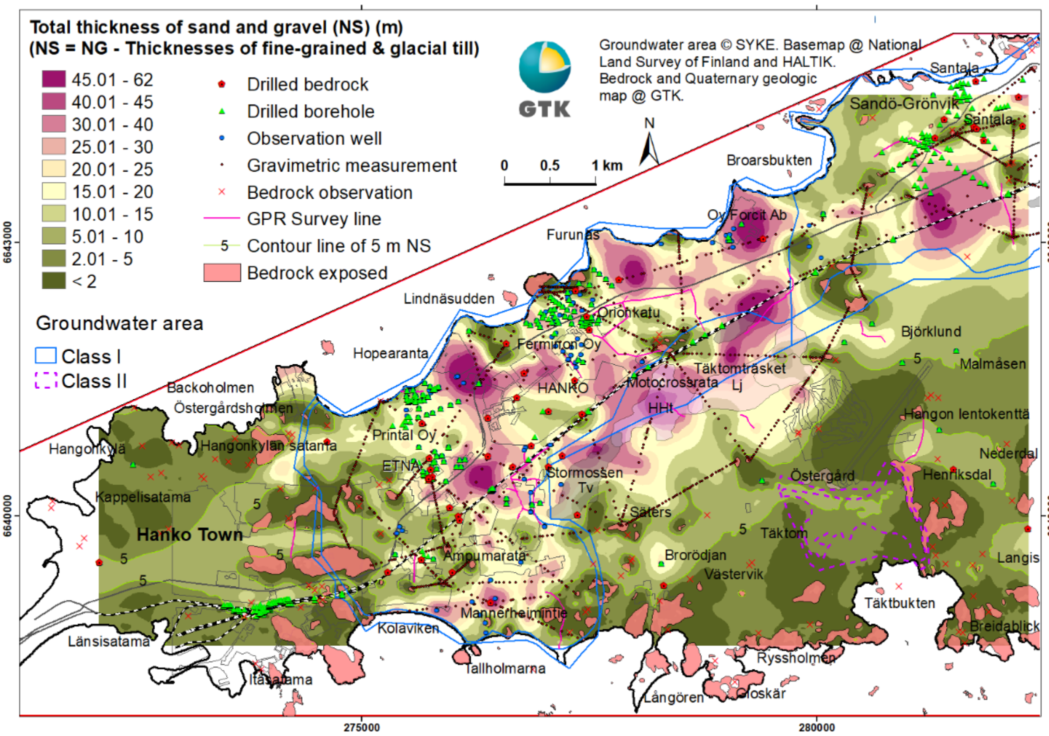

Fig. 4 Total thickness map of sand and gravel.

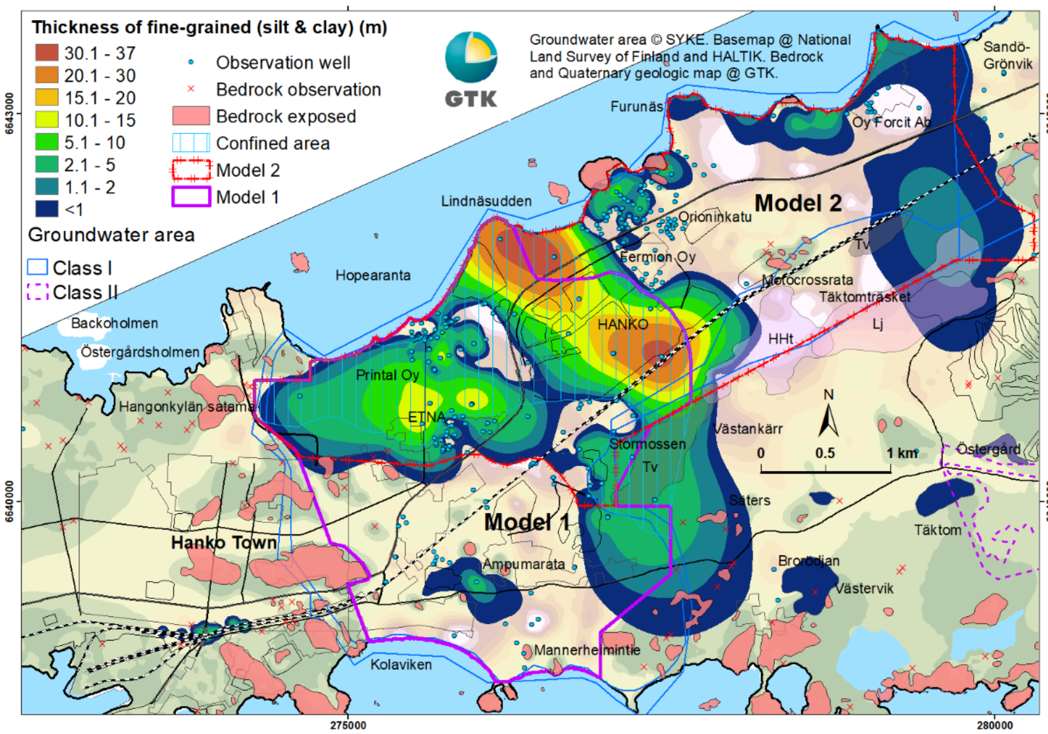

Fig. 5 Thickness map of the fine-grained unit and the modelling areas 1 and 2.

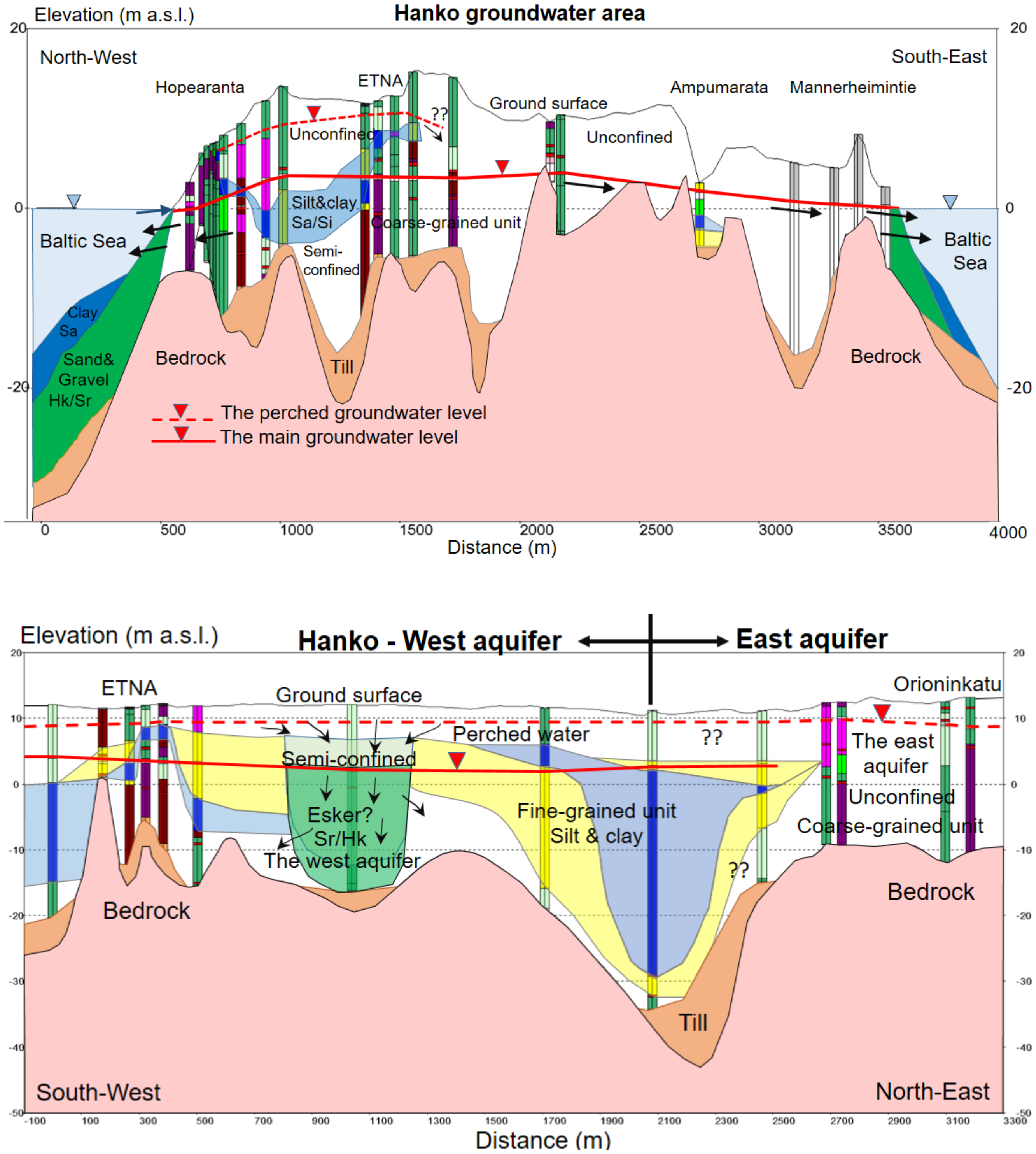

Fig. 6 Conceptual cross-sections of the Hanko groundwater area showing the sediments at the drilled boreholes and groundwater levels.

4 GROUNDWATER FLOW MODELS

Groundwater flow models were constructed by using MODFLOW 2000 code (Harbaugh et al. 2000) under the GMS (version 10.4) graphic environment. Based on the conceptual model and hydrogeological information, groundwater flow models were constructed for two models:

Model 1 – represents a semi-confined aquifer of the lower groundwater level in area 1, and **Model 2** – represents an unconfined aquifer from the groundwater in area 2 and the perched groundwater from area 1. Both models are steady-state and single-layer (Fig. 5). The details of model setups and simulations for both models are described in the following sections.

4.1 Model 1: The main groundwater in area 1

Model 1 consists of the aquifer with the lower groundwater level in area 1. The top of the model was the LiDAR DEM surface and the bottom of the model was the bedrock surface. Bedrock contains a very low hydraulic conductivity and was regarded as an impermeable layer forming the bottom boundary of the model. The thickness of the model varied from 1 to 62 m (average of 18 m). The model domain covers an area of 7.3 km^2 as shown in Fig 8. The model domain was discretized into 5 m x 5 m grid size and consists of a rectangular grid of 730 rows and 690 columns.

4.1.1 Boundary conditions

The model boundary conditions were assigned based on the geological and hydrogeological conditions, including specific head (CHD), drain, no flow and well boundaries (Fig. 8).

- **Specified head** boundary conditions (CHD) are located along the interface of the aquifer and the Baltic Sea coastline and was assigned at the 0.0 m sea level.
- **Drain** boundary condition is located in the south-east boundaries, where drain flows occur. Drain was assigned at 1 m below ground surface with conductance vary between 0.1 to 50 m^2/d. Drain boundary allows only groundwater flow out of the aquifer to the low-lying area.
- **No flow** boundary condition is located in the impervious bedrock area in the Hanko town. In these areas the bedrock surface is at shallow depth and the thickness of Quaternary sediment is generally less than 1 m. Also, in the bedrock exposed area within the model domain, the grid cells were assigned as no flow boundary condition.
- **Well**, which was assigned as point boundary condition, consists of two water intake wells in Hopearanta (HOP-K1 and HOP-K2) with the average groundwater pumping rate of 864 m^3/d for each well, and five groundwater protection pumping wells in the ETNA with the groundwater pumping rate of 16 m^3/d for each well (Hp4, Hp4B, Hp6, HP5B and HP1/08).

4.1.2 Model input parameters

Hydraulic parameters, including horizontal saturated hydraulic conductivity (Kh), anisotropy (a ratio of horizontal (Kh) and vertical hydraulic conductivity (Kv)), specific yield and porosity, were initially assigned to the model layer based on the hydrogeological data of the study area. The initial hydraulic conductivity (Kh) values for the model input were obtained from the soil analysis data and the slug test analysis performed in the Hanko area (Luoma & Pullinen 2011, Hänninen & Äikää 2006). The estimated K values corresponded to the stratigraphy, varying from 0.3-4.8 m/d in silty sand and fine sand, and up to 100 m/d in sand and gravel. Because it is a one-layer model, the spatial distributions of Kh values were assigned corresponding to the majority of the sediments in the model domain. The Kh values were finally adjusted during the model calibration process and were within the range of K values in the aquifer test data. A specific yield value of 0.25 and the effective porosity values of between 0.1 and 0.3 were assigned to the model domain area.

Groundwater recharge estimation depends on many factors including precipitation, soil type, vegetation, evapotranspiration, topography, depth to the water table, land use pattern. In this study, groundwater recharge was assigned as a net recharge, which is a total amount of infiltration that arrived at the groundwater table. In the Hanko town and industrial areas, some parts of ground surface are covered by impermeable materials, which prevents the infiltration. In the fine-grained area, recharge obtained from the leakage of the fine-grained bed. The River (RIV) Package of MODFLOW was used to estimate the vertical leakage of the fine-grained layer from the perched groundwater through the lower aquifer. Detailed calculation of the leakage is presented in Appendix 1.

4.1.3 Model calibrations

Groundwater level data measured during May-June 2017 from 88 observation wells were used in the calibration process using the automatic parameter estimation PEST (Doherty, 2010) and trial and error by manually adjusting the K values, groundwater recharge and conductance of the Drain and River bed boundaries until the best fit was obtained between the observed and simulated data. The maximum K value of 100 m/d and recharge of 0.00123 m/d (approx. 450 mm/year, 69% of total 650 mm/year) were set for the calibration.

4.2 Model 2: The perched- and the main groundwater in area 2

The model domain covers the area of 12.6 km^2 which consists of the groundwater area in the eastern side of the fine-grained unit (Furunäs-Fermion Oy-Orionkatu-Fortum-Forcit Oy) and the perched groundwater area in the western side (Fig. 5). The model domain was discretized into 10 m x 10 m grid size and consists of a rectangular grid of 379 rows and 632 columns. The top of the model was the LiDAR-DEM surface and the bottom was the bedrock surface in the eastern side and the top elevation of fine-grained unit for the perched groundwater area in the western side. The thickness of the model varied between 1 and 23 m (average 10 m).

4.2.1 Boundary conditions

The model boundary conditions consist of specific head (CHD), drain, no flow and well (Fig. 12).

- **Specified head** boundary conditions (CHD) are assigned into 2 areas: 1) at the coastlines along the interface of the aquifer and the Baltic Sea with the head stage at 0.0 m; 2) at the eastern boundary of the model that represents the possible flux of groundwater between the Hanko and the Sandö-Grönvik groundwater areas. The head stage of the boundary was set at the groundwater level in that area.
- **Drain** boundary conditions are located in the south and south-east boundaries, where drain flows occur. Drain boundary allows only groundwater flow out of the aquifer to the low-lying area. Same as Model 1, drain was set at 1 m below ground surface with conductance vary between 0.1 to 50 m^2/d.
- **No flow** boundary conditions are located in the impervious bedrock area in the west and in the east of the model boundaries. In addition, in the bedrock exposed areas within the model domain, the grid cells were assigned as no flow boundary condition.
- **Well**, which was assigned as point boundary condition, consists of the groundwater protection pumping wells in the areas of Fermion Oy (Furunäs well 078010007, 15 $m^{3/}$d, and K31, 5 m^3/d), and Forcit Oy (K14 and K10, ~10 m^3/d).

4.2.2 Model input parameters

Same as model 1, the input parameters for the model consist of horizontal saturated hydraulic conductivity (Kh), anisotropy (Kh/Kv), groundwater recharge, specific yield and porosity, were initially assigned spatially to the model layer based on the hydrogeological data of the study area and were finally adjusted during the model calibration process. The initial net groundwater recharge was assigned at the highest active cells and varied from zero up to approximately 42% of the total precipitation of 650 mm/year. A specific yield value of 0.25 and the effective porosity values of between 0.1 and 0.3 were assigned to the model domain area.

4.2.3 Model calibrations

Groundwater level data measured during May-June 2017 from 77 observation wells were used in the calibration process using the automatic parameter estimation PEST (Doherty, 2010) and trial and error by manually adjusting the Kh values, groundwater recharge and conductance of the Drain boundary until the best fit was obtained between the observed and simulated data. The maximum Kh value of 100 m/d and recharge of 0.00123 m/d (approx. 450 mm/year, 69% of total 650 mm/year) were set for the calibration.

5 RESULTS

5.1 Model 1

Fig. 7 presents the correlation between observed and simulated groundwater levels for the 88 observation wells, and Fig. 8 a map of simulated groundwater level, flow paths and flow directions of model 1. Eighty (80) of total observation wells has the residual (the differences between observed and simulated heads) less than one meter, and has a good correlation between observed and simulated heads with the correlation coefficient (R^2) of 0.94. Eight (8) of total has the residual between 1.0-3.0 m, where two observation points (HP0801 and HP0802) are located at the Hopearanta water intake wells and have influences from the pumping. Six of total wells (Hp4B, Hp7, Hp 10, Hp11 and Hp13A/B) are located in the area between Printal Oy and ETNA, in the fine-grained area where the main sediment is silt with some mixed of silt and fine-sand. Groundwater levels in this area vary between 2.93 and 6.6 m a.s.l. and have no clear correlation whether they belong to the upper (perched) or the lower aquifers. The calibrated K values range between 0.15 and 25 m/d (Fig. 9). The calibrated recharges range between zero and 0.00109 m/d (approx. 398 mm/year, 61% of total 650 mm/year) (Fig.10). The water budget of model 1 is presented in Table 1. The change of water balance between inflow and outflow was less than 0.01%. The total inflow of the model domain is 4134.65 m^3/d, which consists of 1365.97 m^3/d from the leakage of the fine-grained unit, 2499.51 m^3/d from the groundwater recharge, and 269.18 m^3/d from the inflow of sea-water at the shoreline in the Hopearanta water intake area. The total outflow consists of 2219.45 m^3/d from the discharge of groundwater to the sea, 1808.00 m^3/d from the pumping, and 107.57 m^3/d from the leakage in the area that groundwater level is higher than the perched water.

Table 1 Simulated groundwater budget of model 1.

	Model 1	
Sources/Sinks	Flow-in (m^3/d)	Flow-out (m^3/d)
Specific head at the shoreline	269.18	-2219.45
Wells	0.00	-1808.00
Drains	0.00	0.00
Leakage of the fine-grained unit	1365.97	-107.57
Recharge	2499.51	0.00
Total	4134.65	-4135.02

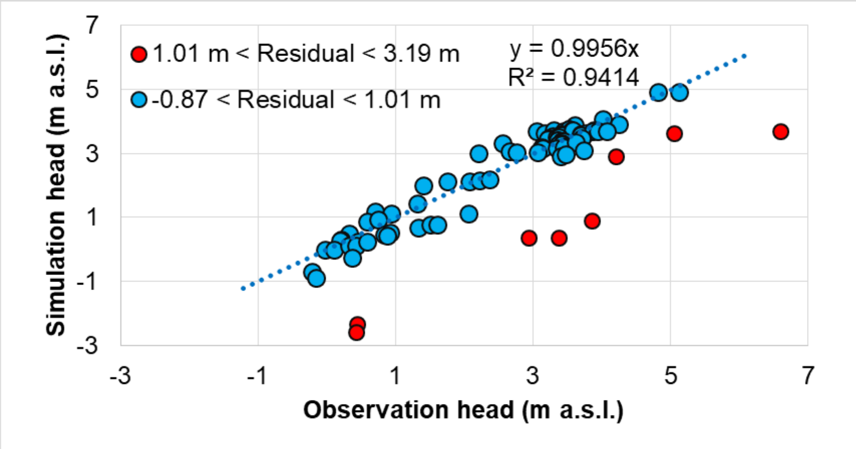

Fig. 7 Comparisons between simulated and observed groundwater levels for the 88 observation wells in model 1 with the least-square fit, R^2 value of 0.94.

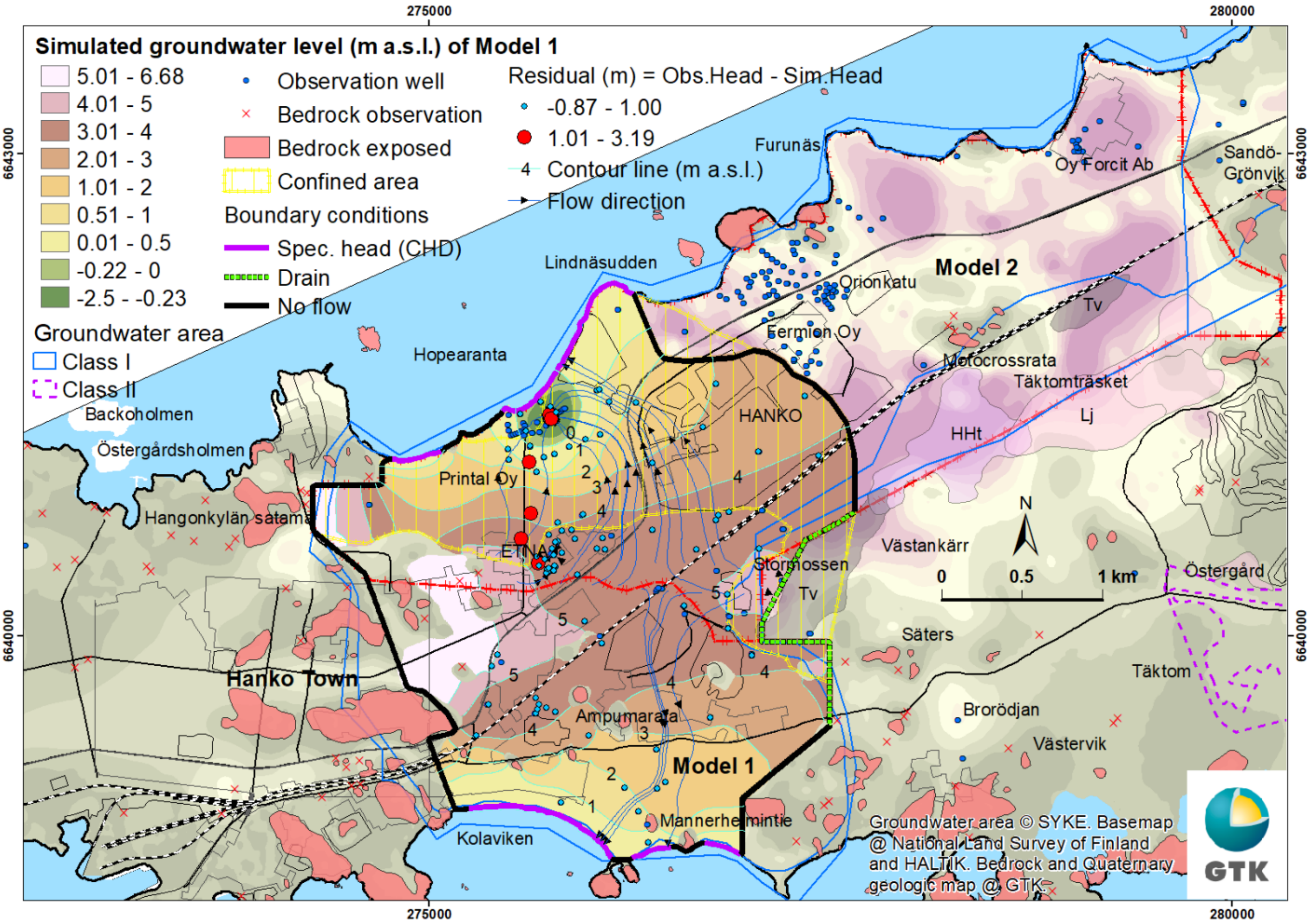

Fig. 8 Spatial distribution map of the calibrated simulation head with the residuals (differences between simulated and observed heads) from 88 observation wells.

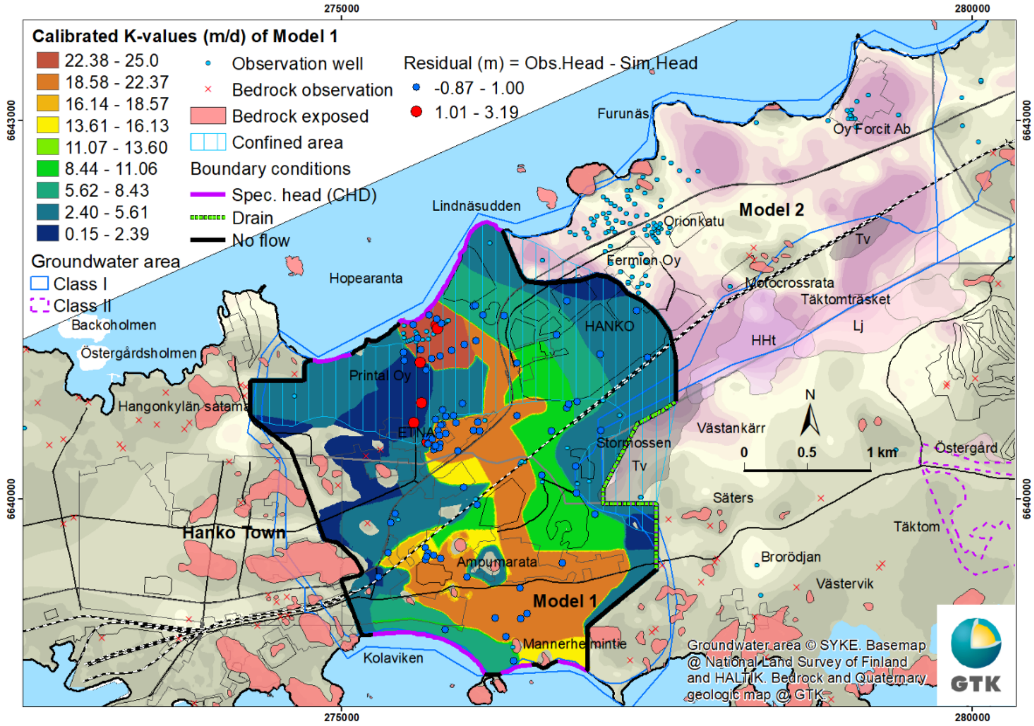

Fig. 9 Calibrated hydraulic conductivities (K-values) of the model 1.

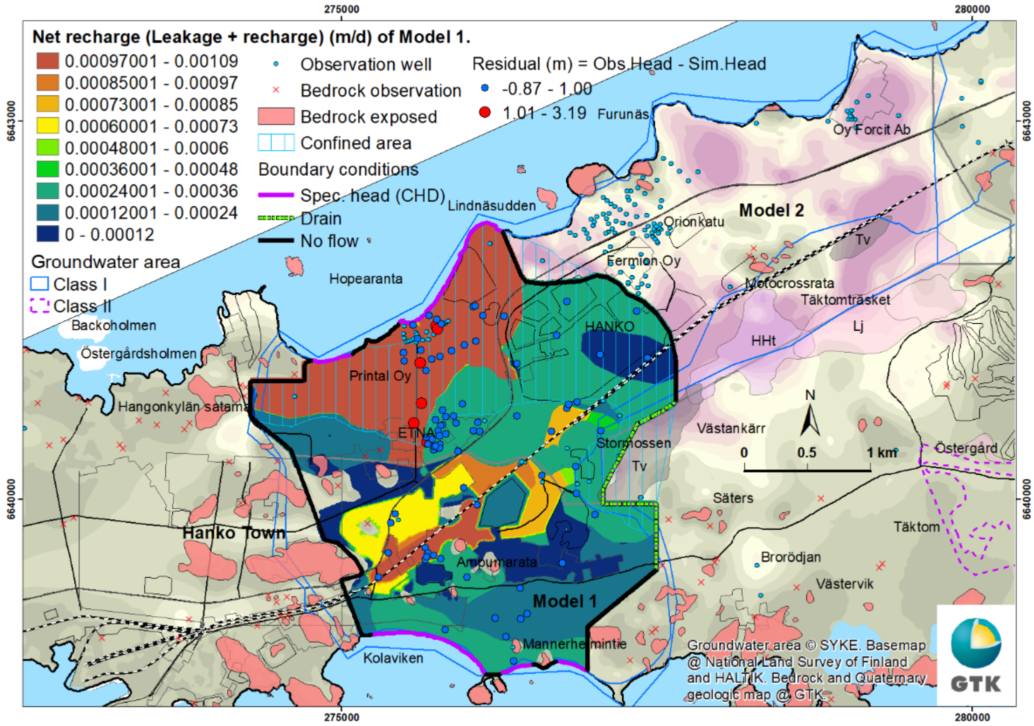

Fig. 10 Calibrated groundwater recharge of the model 1.

5.2 Model 2

Fig. 11 presents a correlation between observed and simulated groundwater levels for the 77 observation wells in model 2 with the correlation coefficient (R^2) of 0.94. Fifty-five (55) of total 77 observation wells has the residual less than one meter. Twenty-two (22) of total has the residual between 1.01 and 2.44 m. Fig. 12 presents a map of simulated groundwater level, flow paths and flow directions of model 2. Groundwater discharge toward the low-lying area in the east and the coastline. In the perched-groundwater area in the western side, the flow direction was limited by the presence of fine-grained sediments and the topography of the fine-grained layer, where the flow from the south and southeast northwards to the coastline. The calibrated K values range between 0.2 and 13.0 m/d (Fig. 13). The calibrated recharges range between zero and 0.00123 m/d (the maximum recharge set for the simulation) (Fig. 14). The water budget of model 2 is presented in Table 2. The change of water balance between inflow and outflow was less than 0.01%. The total inflow of the model domain is 4324.50 m^3/d, which consists of the recharge from the perched groundwater area of 1572.33 m^3/d and the recharge from the main groundwater area of 2752.17 m^3/d.

Calibration of the observation wells in the Hopearanta has a better fit in model 1 (the residual is less than 1 m) than in model 2. This could support the interpretation that groundwater level in this area should belong to the main groundwater rather than the perched water. Groundwater levels in the Furunäs area are highly variable and the calibration did not fit with one groundwater levels (the residual is greater than 1 m). The sediments in this area is high heterogeneous, a multi-layer model could reduce this uncertainty.

Table 2 Simulated groundwater budget of model 2.

Model 2	All Model 2 area		Perched groundwater		Main groundwater	
Sources/Sinks	Flow-in (m^3/d)	Flow-out (m^3/d)	Flow-in (m^3/d)	Flow-out (m^3/d)	Flow-in (m^3/d)	Flow-out (m^3/d)
Specific head	0.00	-3982.00	0.00	-1527.45	0.00	-2454.54
Wells	0.00	-30.00	0.00	0.00	0.00	-30.00
Drains	0.00	-312.95	0.00	-45.31	0.00	-267.65
Recharge	4324.50	0.00	1572.33	0.00	2752.17	0.00
Total	4324.50	-4324.95	1572.33	-1572.76	2752.17	-2752.19

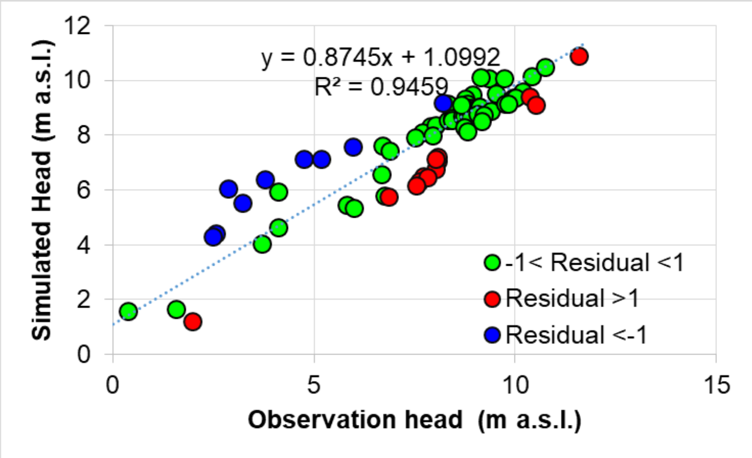

Fig. 11 Comparisons between observed and simulated groundwater levels for the 77 observation wells in model 2 with the least-square fit, R^2 value of 0.94.

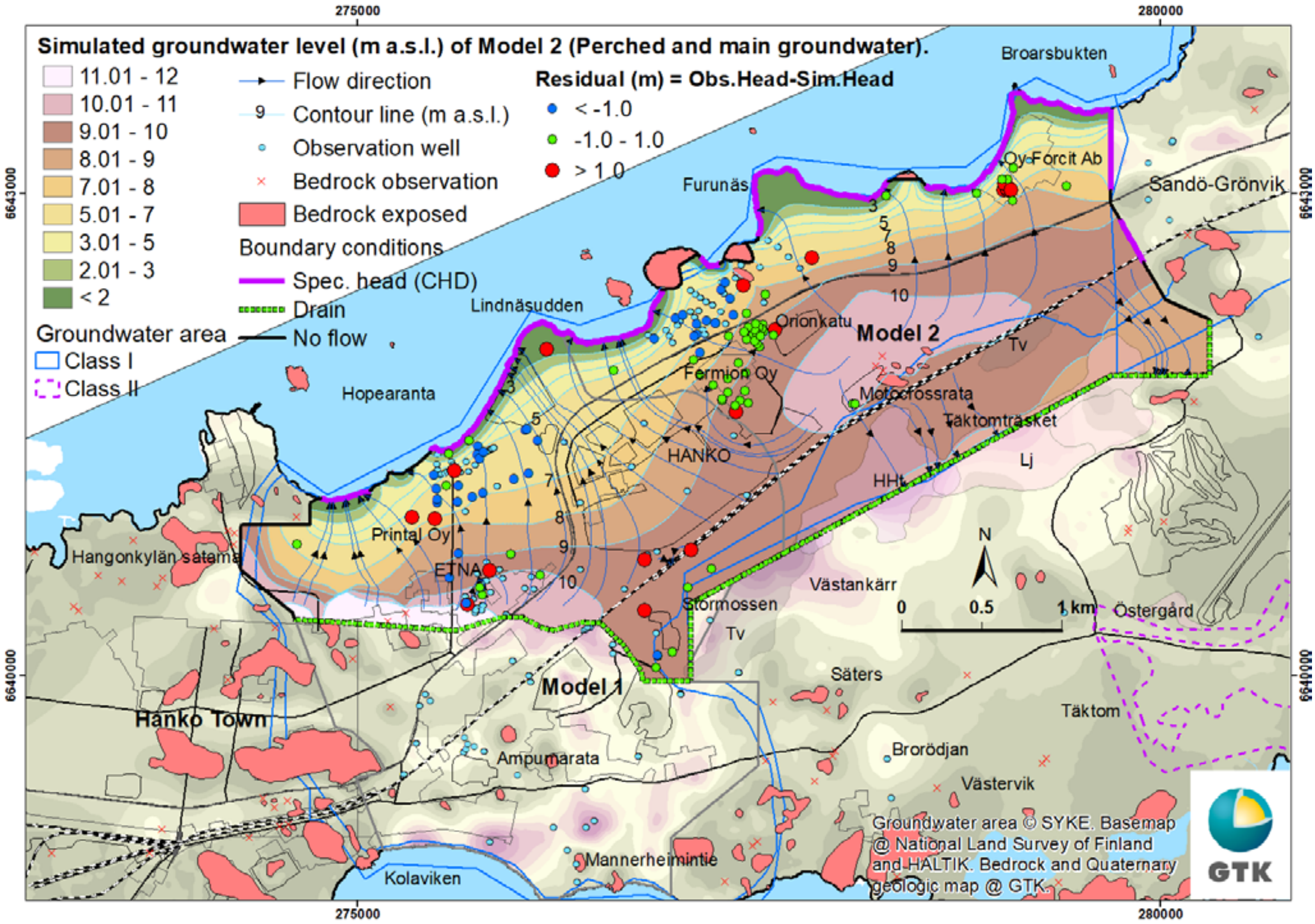

Fig. 12 Spatial distribution map of the calibrated simulation head with the residuals (differences between observed and simulated heads) from 77 observation wells in model 2.

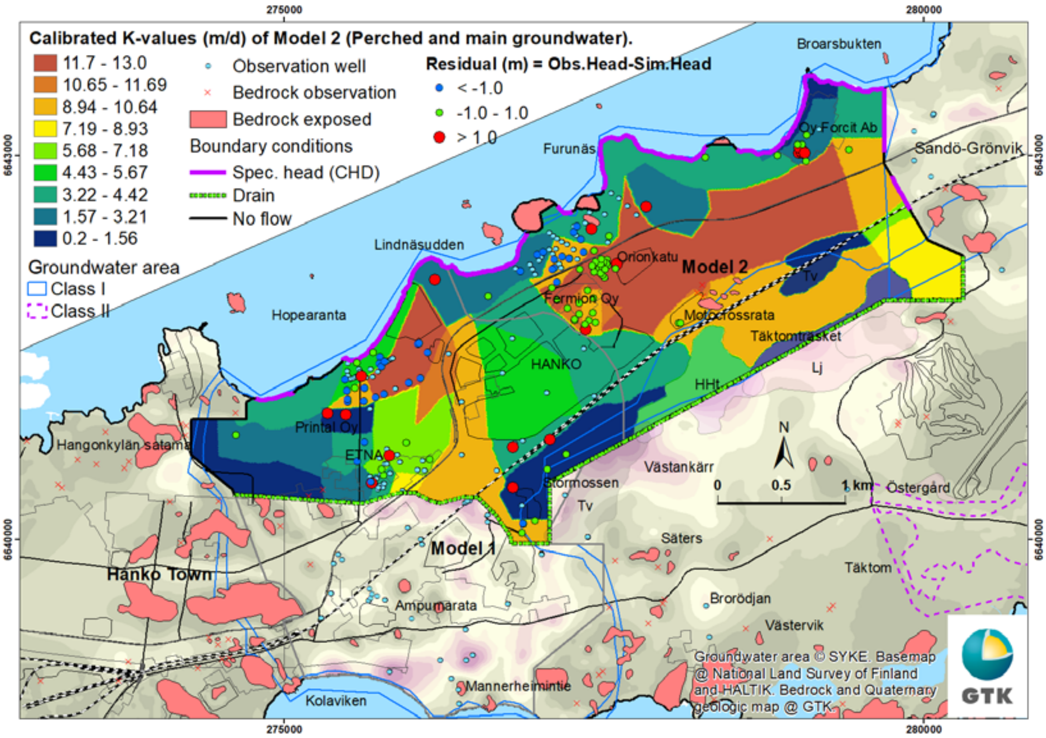

Fig. 13 Calibrated hydraulic conductivities (K values) of the model 2.

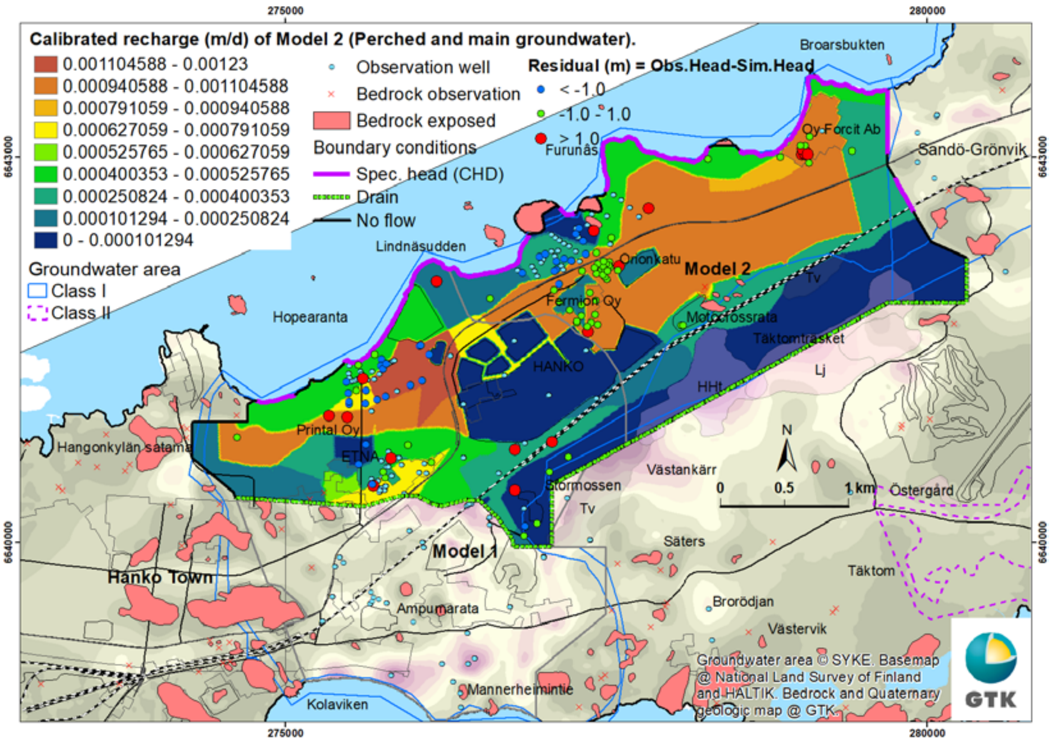

Fig. 14 Calibrated groundwater recharge of the model 2.

6 MODEL LIMITATIONS

The elevated bedrock topography causes thin bed to many areas of the model domain, especially the area around the Hanko town in the western of model 1. This causes the simulated groundwater level is higher than the other areas. The simulated groundwater levels obtained from the best fit of the calibrations based on the conditions of input parameters for one layer model. A multi-layer model or a local model for the specific area could provide a better fit. Geochemistry of groundwater could support the interpretation of groundwater flow and flow direction.

7 CONCLUSIONS AND RECOMMENDATIONS

Based on the geological and hydrogeological information, the Hanko groundwater area is divided into two aquifers by a thick fine-grained (silt & clay) unit that extends across the groundwater area in the NW-SE direction, covers the areas from Lindnäsudden in the Baltic Sea coast to south and south-east of Fermion Oy, and south of Motocross-rata. Two steady-state groundwater flow models were constructed for the shallow aquifer in the Hanko groundwater areas: model 1 for the area in the western side of the fine-grained unit between Hopearanta, Printal Oy, ETNA and Hanko town; model 2, in the eastern side of the fine-grained unit, covers the areas between Furunäs, Fermion Oy, Motocross-rata and Forcit Oy. The main findings for both models are summarised below:

Model 1 is a semi-confined aquifer of the main (lower) groundwater which is partly bounded by the fine-grained unit. In the fine-grained area, the RIV package from MODFLOW was utilized to estimate recharge from the leakage of perched water through the fine-grained bed. The calibration between the simulated and observed groundwater levels from 88 observation wells shown a good calibration with the correlation coefficient (R^2) of 0.94. The total inflow of the area was estimated at 4134.65 m^3/d, which consists of 1365.97 m^3/d from the leakage of the fine-grained unit, 2499.51 m^3/d from the groundwater recharge, and 269.18 m^3/d from the inflow of sea-water at the shoreline in the Hopearanta water intake area. This indicates a sufficient water budget for the total current pumping rate of 1808.00 m^3/d. However, the high pumping rate from the water intake wells along the coastline could lower down the groundwater level and induce more sea-water into the aquifer.

Model 2 is an unconfined aquifer and consists of the perched groundwater (the upper groundwater level of model 1) and the main groundwater of the aquifer in the east. The model was calibrated with the groundwater levels from 77 observation wells and shown a good calibration with the correlation coefficient (R^2) of 0.94. However, the poor calibrations with the residual greater than 1 m were observed in the finer-grained aquifer areas such as in Furunäs. Lack of the calibration points such as in the southern of Oy Forcit Ab area, causes high uncertainty of the simulation in this area. The simulated water balance shown the total inflow of the model domain of 4324.50 m^3/d, which obtained from the recharge from the perched groundwater area of 1572.33 m^3/d and from the main groundwater area of 2752.17 m^3/d.

The calibrations and the residuals from both models clarified the groundwater zones and also the uncertainty areas. A multi-layer model or a local model for the specific area could provide better calibrations. The models are needed to be validated with the variations of the input parameters and also in the transient state, which could clarify more the groundwater flow system under the different seasonal variations and future sea levels and climate conditions.

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Appendix 1.

APPENDIX 1. LEAKAGE CALCULATION USING THE RIVER PACKAGE

In the simulation of the interaction between surface water and groundwater, the River Package (RIV) in the MODFLOW (Harbaugh et al. 2000) (Fig. A1), represents the head-dependent flux boundary as same as the other packages such as the Drain, the Lake, the Stream or the General-Head boundary packages. It can be used as a tool to evaluate the interaction between surface water and groundwater in an aquifer, where the river can act as groundwater discharge (gaining river) or recharge (losing river), depends on the simulated groundwater level is above or below the river stage. The RIV requires three types of input data: river stage, riverbed conductance and riverbed bottom elevation. The model 1 of the Hanko groundwater area, contains two groundwater levels; the perched groundwater in the upper level, and the main groundwater in the lower level. Both groundwater levels are separated by a fine-grained unit (Fig. A2). To simulate the interaction and leakage between perched groundwater and the main groundwater, the RIV Package in the MODFLOW was utilized. The perched water level was assigned as the river stage elevation, the bottom of the fine-grained layer was set as the river bed elevation, and the riverbed conductance was calculated from the fine-grained material.

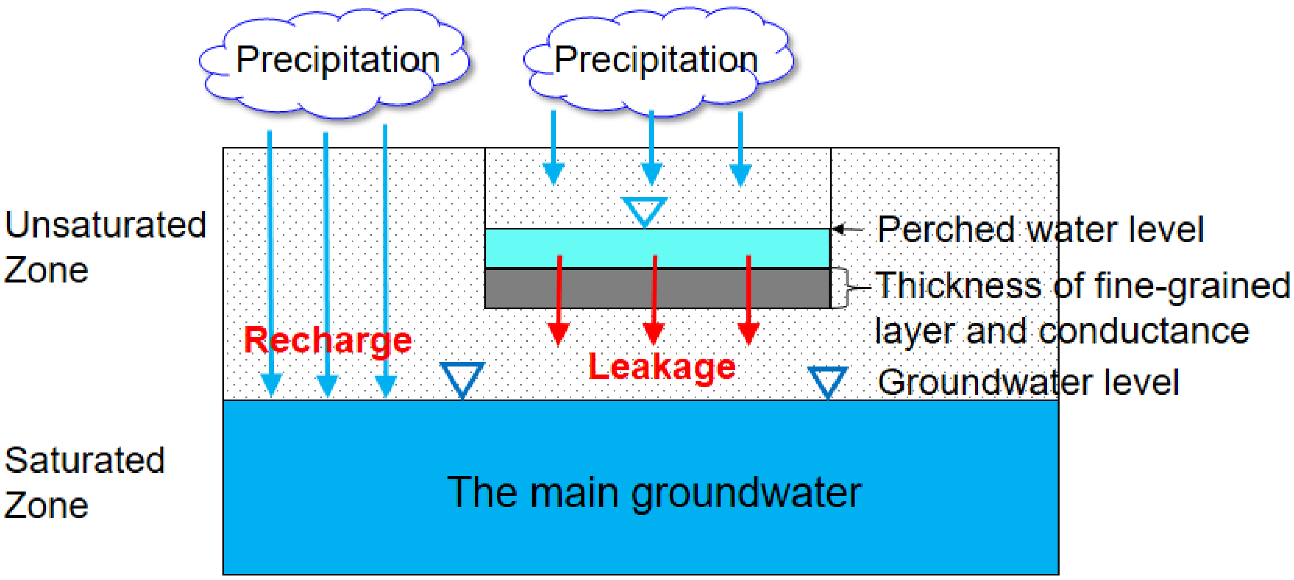

Fig. A1 Cross section showing the relation between the perched groundwater and the main groundwater. In the fine-grained area, groundwater recharge obtained from the vertical leakage of the perched water through the fine-grained bed.

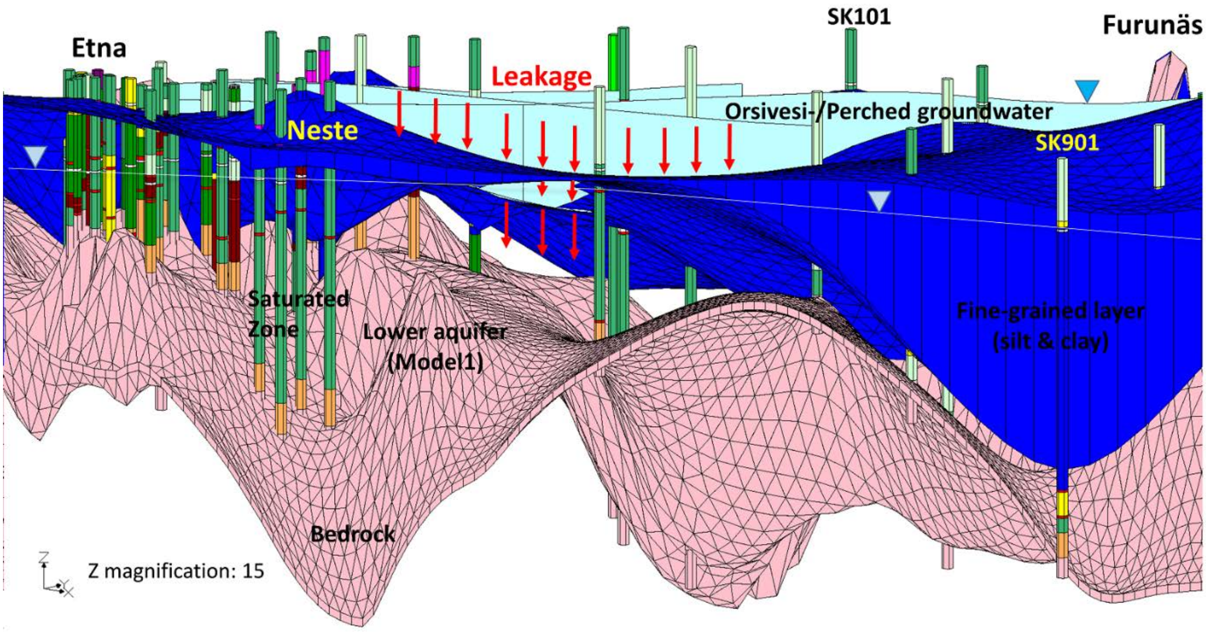

Fig.A2 A 3D cross section showing the relation between the perched groundwater and the main groundwater of the aquifer in model 1 area in the Hanko groundwater area. In the fine-grained area, groundwater recharge obtained from the vertical leakage of the perched water through the fine-grained bed.

The conductance of the fine-grained layer is calculated by the following equation:

$$CRIV = (KLW)/T \qquad (1)$$

Where

CRIV riverbed conductance, in this case, conductance of fine-grained material (m^2/d)

K hydraulic conductivity of fine-grain material (silt & clay) (m/d)

L, W, T length, width and thickness (m) of fine-grained layer.

Leakage, the amount of infiltration (m/d) is calculated by the following equation:

Leakage = Conductance (m^2/d) * Head Difference (m)

= (CRIV)*(Perched water level – Bottom elevation of fine-grained layer) (2)

In the Hanko groundwater area, there is no K-value of fine-grained (silt & clay) materials available, the initial input data was used from the literature and finalized by calibrating with the trail-and-error method until the simulation head and observation heads of the main aquifer are in a good matched. The maximum leakage was set to 0.00123 m/d, which is the maximum estimated groundwater recharge applied in this area. Fig. A3 presents the interpolated thickness of the fine-grained unit, Fig. A4 the calibrated conductance of the fine-grained material, and Fig. A5 the estimated leakage of the perched groundwater. In the area that does not encountered the fine-grained layer, groundwater recharge was estimated as the net recharge, the amount of infiltration that arrived at the groundwater table. The total groundwater recharge (Fig. A6) is a combination of the groundwater recharge and the leakage from perched water.

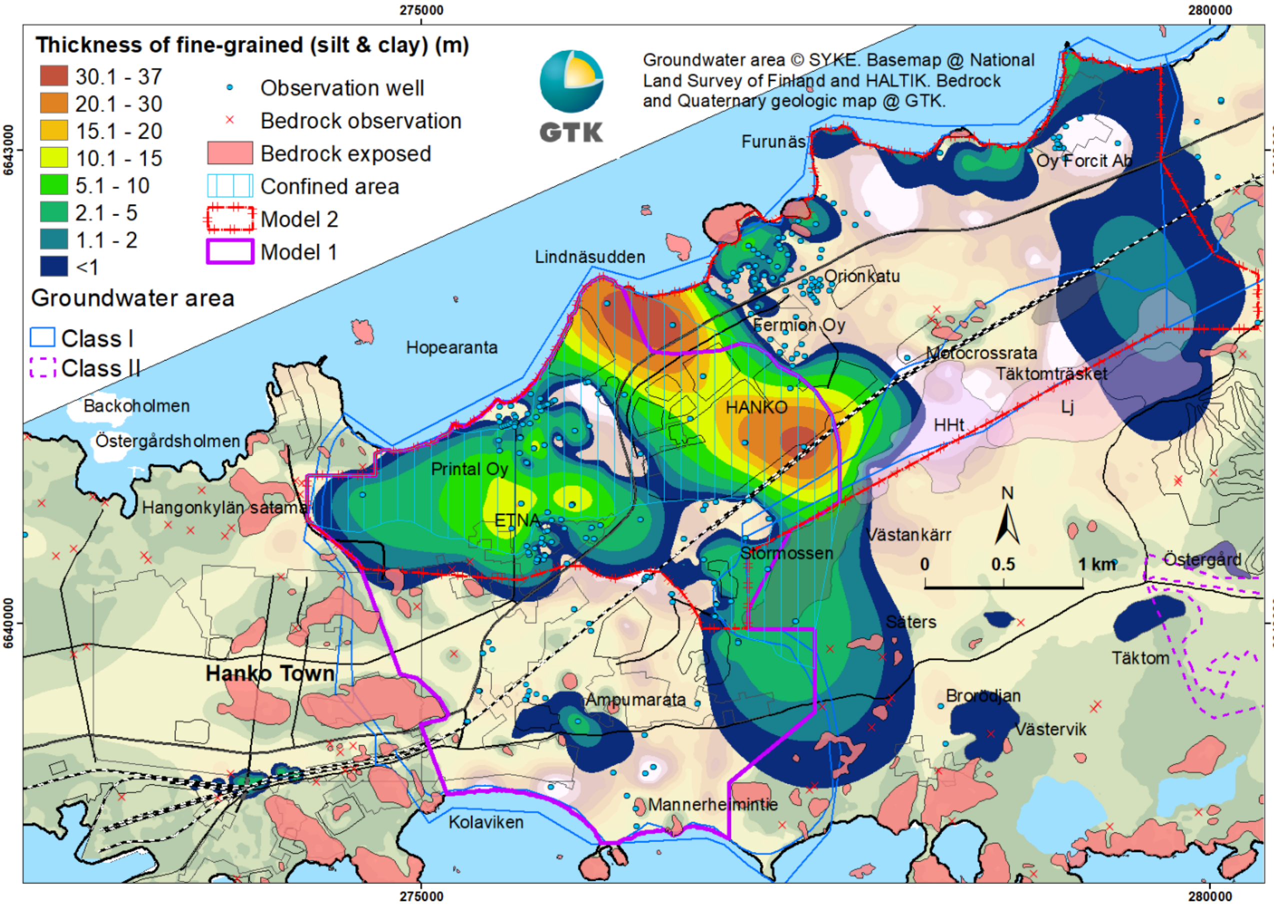

Fig. A3 Interpolated thickness map of the fine-grained unit and the model area 1 and 2.

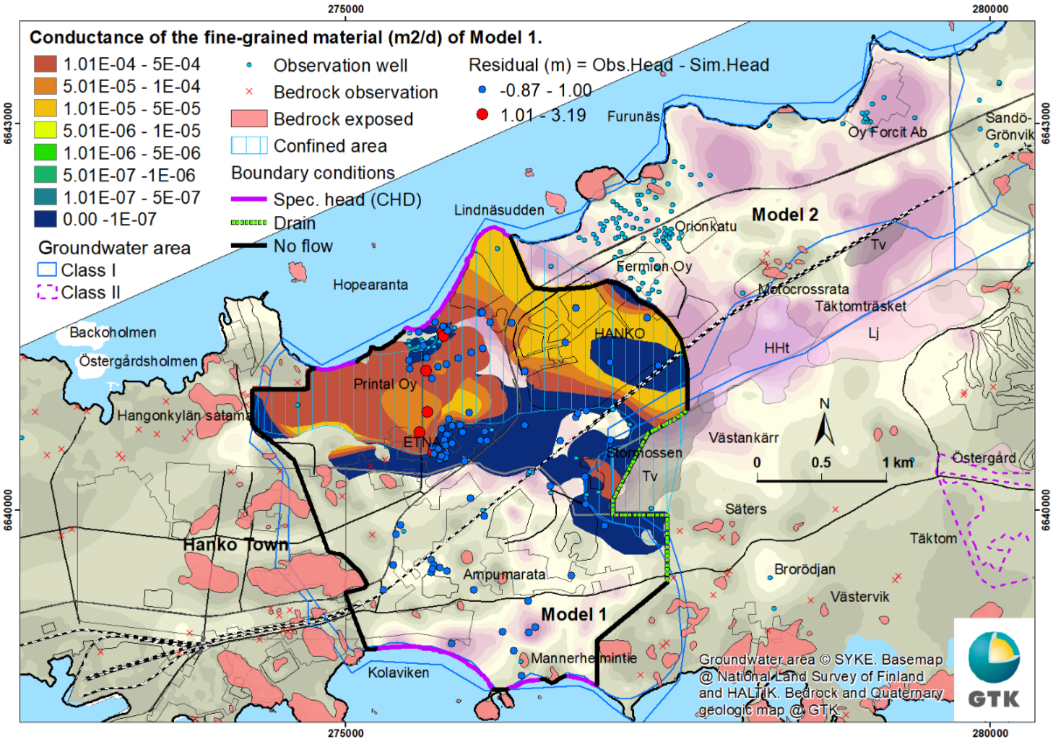

Fig. A4 The calibrated conductance of the fine-grained material.

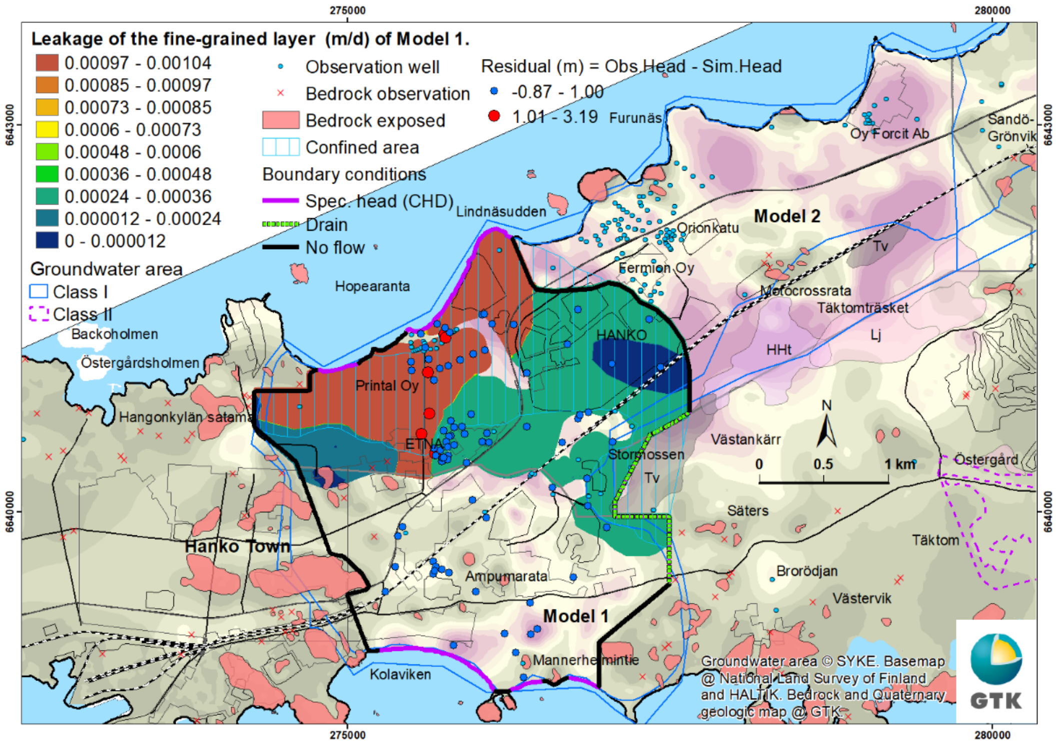

Fig. A5 The leakage of the fine-grained layer.

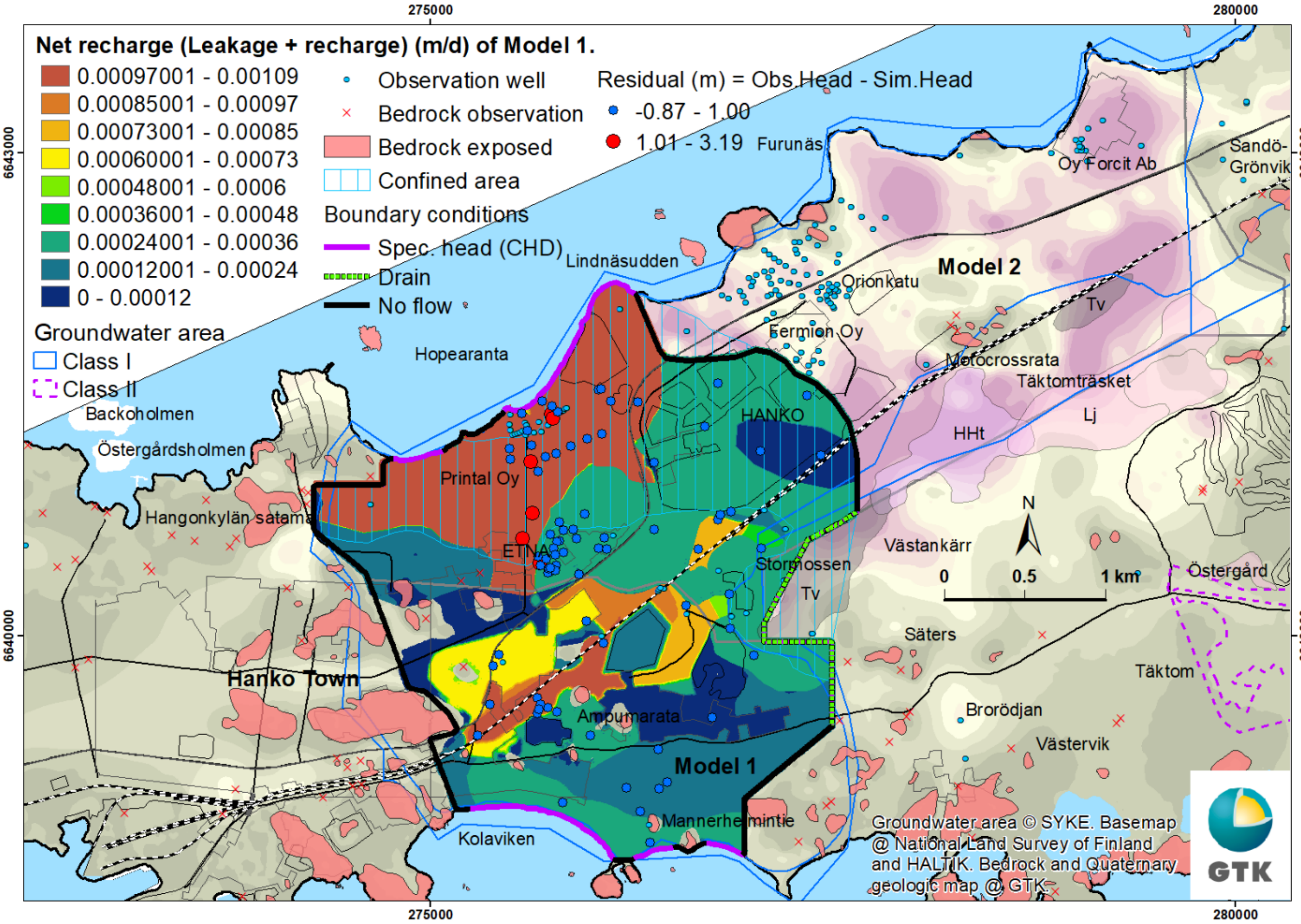

Fig. A6 The total groundwater recharge of the main aquifer in model 1 in the Hanko groundwater area.