Article

A hydrogeological model for groundwater management under climate change of a shallow low-lying coastal aquifer in southern Finland

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Abstract: A shallow low-lying coastal sand aquifer in southern Finland is vulnerable to the climate change and human activities. Under future climate change, a rise in sea-level would cause some parts of the aquifer and the water intake well to be under seawater. This, together with the predicted increase in precipitation, would enhance groundwater recharge and raise the water table, consequently contributing to the potential deterioration of groundwater quality or potential flooding in the low-lying aquifer area. An information on geological and hydrogeological characteristics of the aquifer for the climate change adaptation plan including the possible new locations of water intake wells was needed. This study aimed to construct a three-dimensional geological model and evaluate heterogeneity of the aquifer to provide a geological framework for groundwater flow model and the assessment of groundwater vulnerability. The methods used consist of a stochastic-geostatistical approach incorporated with groundwater flow model to predict the distributions of the superficial layers of a heterogeneous aquifer and to identify the distributions of the aquifer medias (sand and gravel) as well as groundwater flow system. In addition, the LiDAR-based digital elevation model was utilized to define the flood prone areas under the climate change scenarios. The three-dimensional geological model provides a better characterization of the heterogeneity of the aquifer and improved reliability of subsequent groundwater flow model and vulnerability assessment in the aquifer area. The proposed new locations of water intake wells and the results of the study provided useful information for local authorities for groundwater management in future.

Keywords: Groundwater management; Groundwater modelling; Climate change; Geostatistic; Coastal aquifer; Finland

PACS: J0101

1. Introduction

A shallow permeable low-lying coastal sand aquifer in southern Finland surrounded by the Baltic Sea is vulnerable to the climate change, sea-level rise and human activities [1]. Under future climate change, a rise in sea-level would cause some parts of the aquifer and the water intake well to be under seawater. Together with the predicted increase in precipitation, would enhance groundwater recharge and raise the water table, consequently contributing to the potential deterioration of groundwater quality or potential flooding in the low-lying aquifer area [2-3]. The study area is located in the shallow aquifer in Santala, southern Finland (Figure 1). The aquifer area is part of the First Salpausselkä ice-marginal formation, deposited during the Weichselian and Holocene deglaciation of the Scandinavian Ice Sheet [4]. It is an important drinking water resource and the main production of water supply to the town Hanko and local industries. The total yield of the aquifer in Santala area is 7000 m^3/d [5]. However, the aquifer area is highly vulnerable to the contamination and the climate change. The aquifer area has been treated by many groundwater risk sources (e.g. industry contaminants, gravel extraction, de-icing road salt). Groundwater levels have rapidly responded to recharge from the spring snowmelt and rainfall and in many places groundwater table is close to ground surface. The aquifer extends to sea shore and the water pumping was often below sea water level [2,6]. Under climate change scenarios A1B and sea-level rise A1B (highly regionalized), the mean sea level is predicted to reach +0.51 m a.s.l. and the potential storm surges would reach 1.75 m a.s.l. by the end of the 21st century [2]. At this level, the areas below +0.51 m a.s.l. would be under seawater, and the areas below 1.75 m a.s.l., including the water intake well, will be vulnerable to coastal flooding. An information on geological and hydrogeological characteristics of the aquifer for the climate change adaptation plan including the possible new locations of water intake wells and the flood prone area was needed for the local authorities, land users and land-use managers to support the groundwater resources management, and land-use planning and management in the study area.

The objective of this study was to construct a three-dimensional (3D) geological model and evaluate heterogeneity of the shallow aquifer in Santala, to provide a geological framework for groundwater flow model and the assessment of groundwater vulnerability, as well as to provide the data to support the water supply protection and groundwater management plan in the future. The methods used consisted of the deterministic and stochastic-geostatistical methods in order to identify the distribution of the aquifer medias based on the sediment descriptions from from drilled wells. In addition, an aerial light detection and ranging (LiDAR)-derived digital elevation model (LiDAR DEM) with the pixel size of 2 m × 2 m and vertical resolution 0.3 m from the National Land Survey of Finland was utilised to to identify the potential flood prone area in in the low-lying coastal aquifer area.

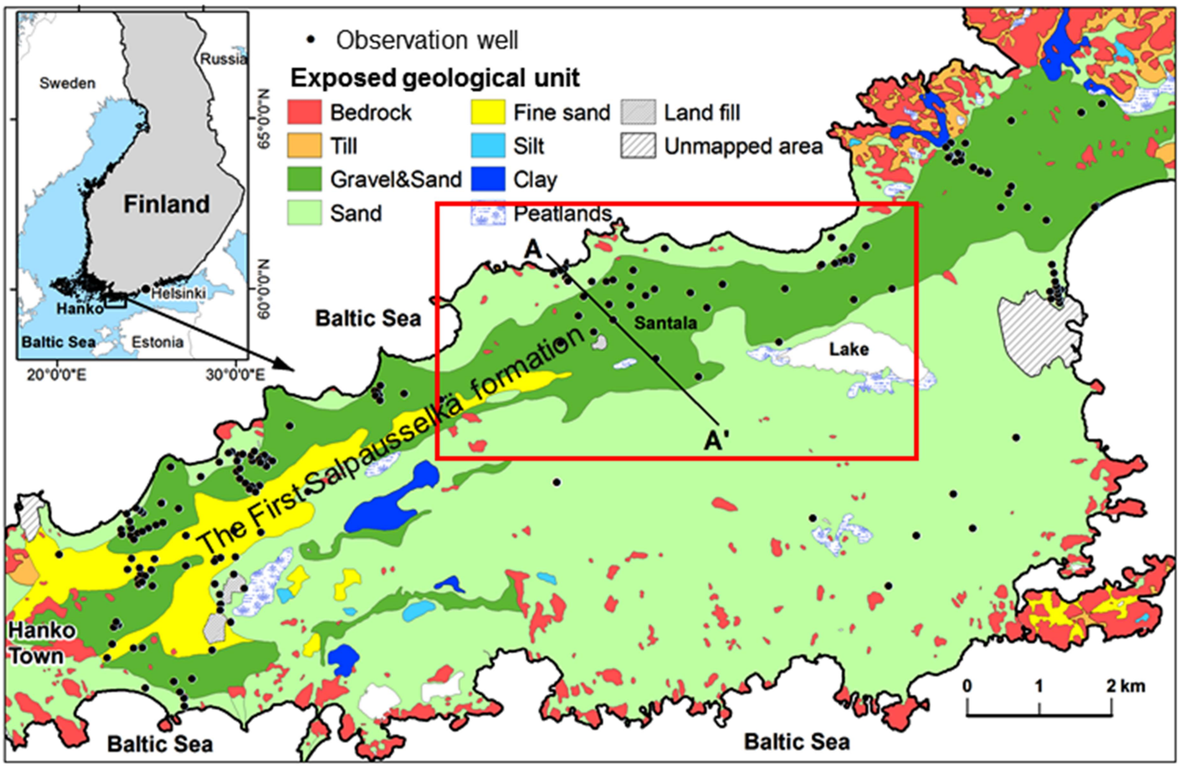

Figure 1. Location and Quaternary geological deposit map of the study area in Santala, south Finland.

2. Results

2.1. Three-dimensional (3D) geologcial model

Figure 2 presents the 3D visualisation of bedrock surface, groundwater table and drilled wells in Santala, presented with the four main soil types: gravel, sand, silt & clay. A thickness map of the Quaternary deposit is presented in Figure 3. The Quaternary deposit represents all unconsolidated sediments deposit between the bedrock surface and the topographic surface (LiDAR DEM). Once the bedrock surface is identified, the thickness of the Quaternary deposit is determined by subtracting the interpolated bedrock surface from the topographic surface. The bedrock surface shows highly undulated with low terrain bedrock in the east (zero to10 m a.s.l. in average) and a buried bedrock valley in the NE-SW direction conforms the first Salpausselkä formation (-5 to < -25 m a.s.l. in average). This causes the variations in thickness of the Quaternary deposit which vary between less than one meter and up to 75 m thick, with the mean thickness of 21 m (Figure 3). The 3D visualisation of the bedrock surface and the main depositional units in Santala - Hanko aquifer area: 1) the primary deposit – sand and gravel; 2) silt and clay layer; and 3) the littoral sand and gravel deposits, is presented in Figure 4. A cross-section along West-East direction (line A-A′, Figure 1), presenting the spatial distribution of aquifer materials in Santala generated by transition probability (T-PROGS) / Markov geostatistical approach [7, 8] is showed in Figure 5.

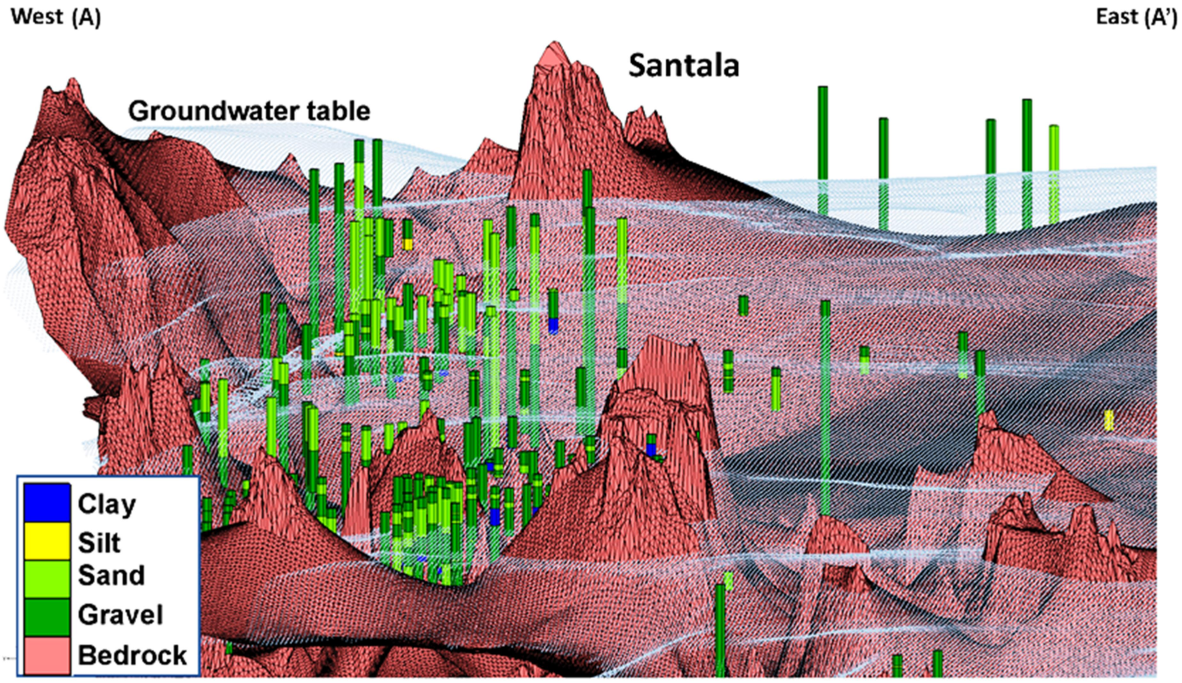

Figure 2. The 3D visualisation of drilled wells in Santala, presented with the four main soil types: gravel, sand, silt & clay.

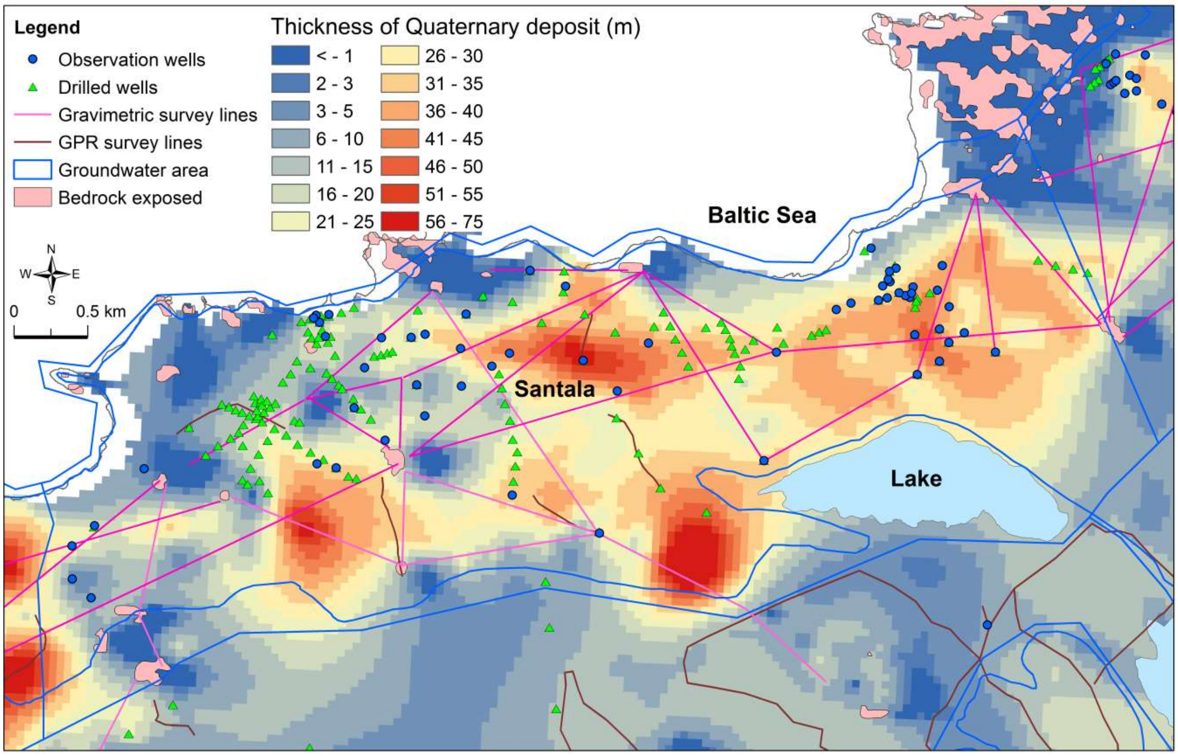

Figure 3. A thickness map of the Quaternary deposit. (Groundwater area © SYKE)

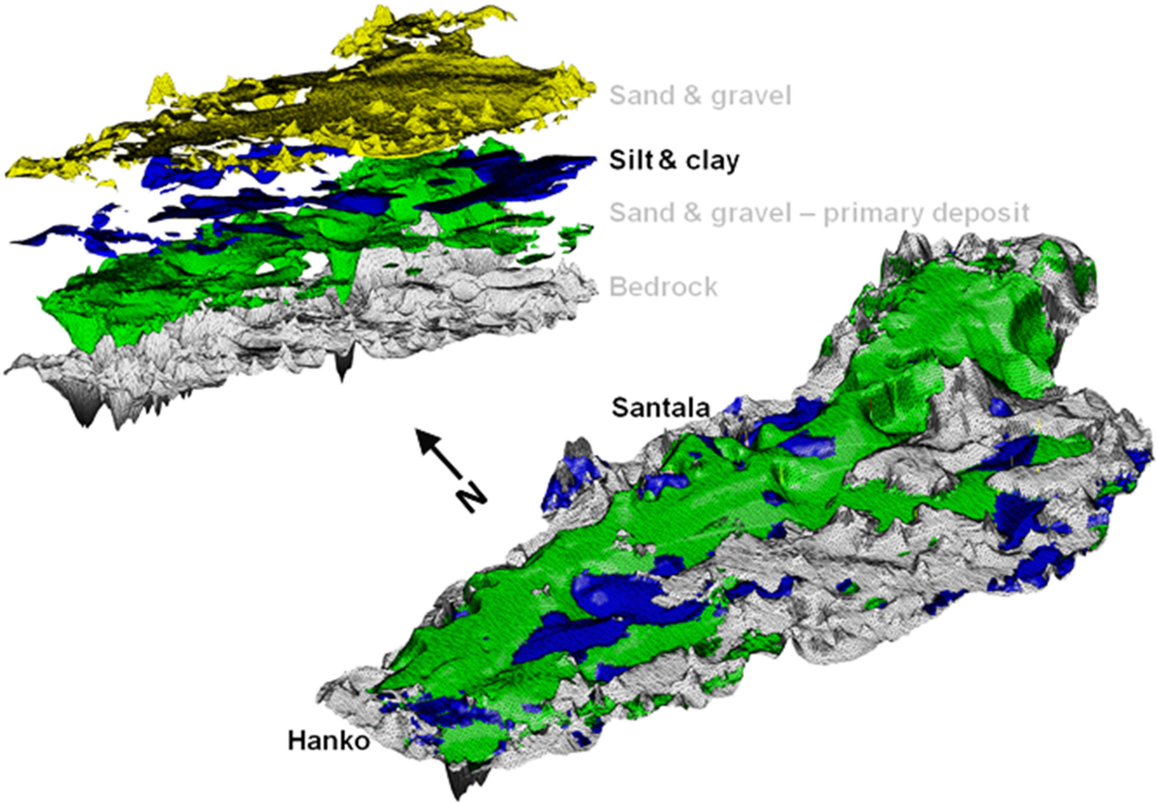

Figure 4. The 3D visualisation of the bedrock surface and the main depositional units in Santala - Hanko aquifer area: 1) the primary deposit – sand and gravel; 2) silt and clay layer; and 3) the littoral sand and gravel deposits.

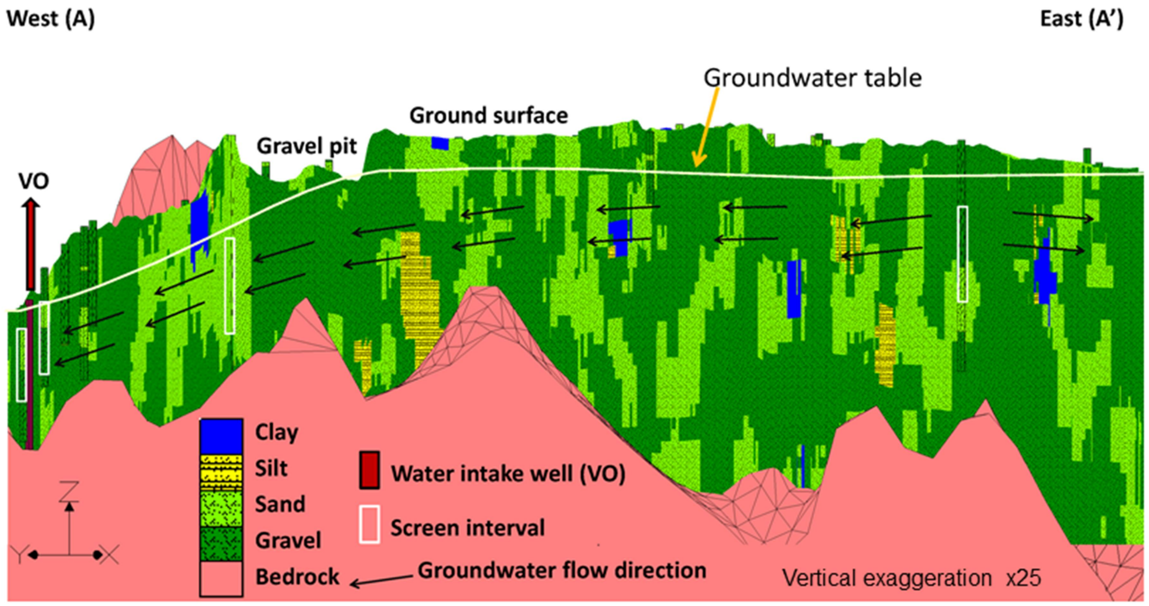

Figure 5. A cross-section along West-East direction (line A-A', Figure 1), presenting the spatial distribution of aquifer materials generated by transition probability (T-PROGS) / Markov geostatistical approach.

2.2. *The coastal flood prone area*

The study area has experienced the highest sea-level rise at +1.24 m a.s.l. during the storm surge on 9.01.2005 base on data from 1887. Possible maximum sea-level rise due to storm surge by the end of the 21st century could reach 1.75 m a.s.l. [2]. The area below the 1.75 m a.s.l. contour line was defined as a coastal flood prone area due to the sea-level rise and storm surge (Figure 6). This includs the current water intake well location, which is located approximately 60 m from the coastline.

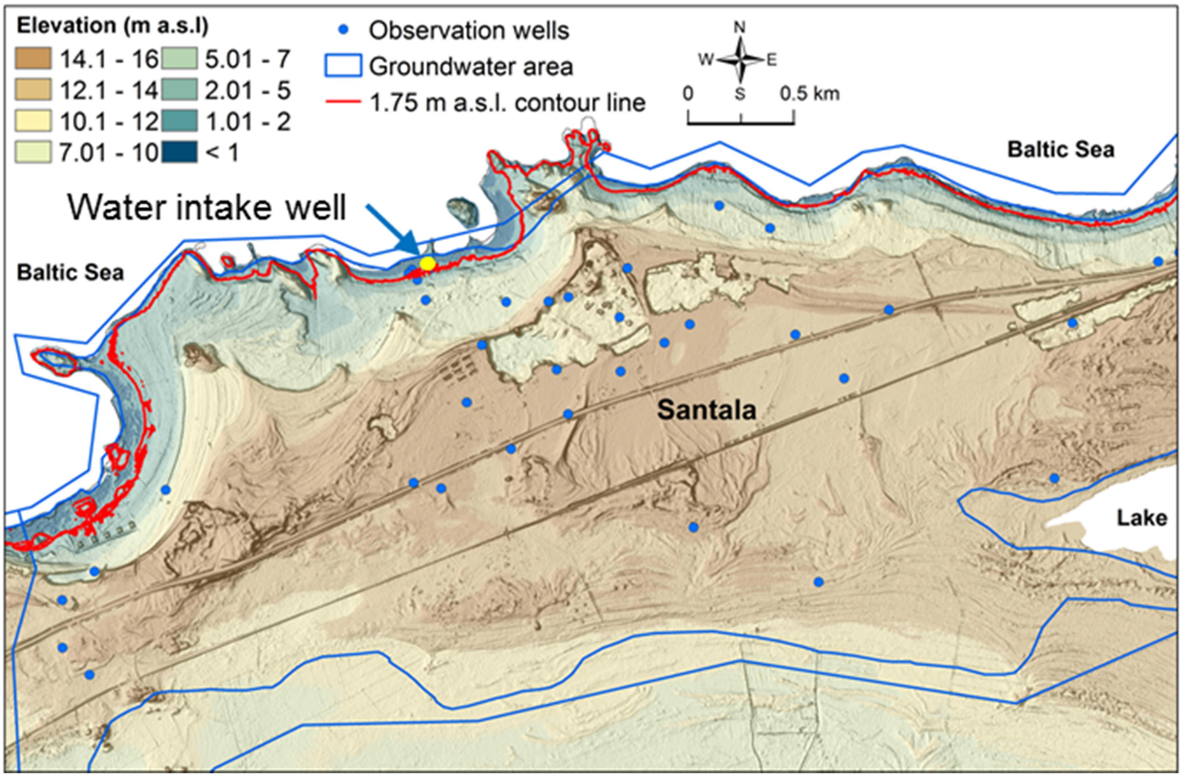

Figure 6. The elevation (LiDAR DEM) map of Santala area. The red contour line indicates a possible maximum sea-level rise at 1.75 m a.s.l due to storm surge by the end of 2100. (Topographic LiDAR DEM Database © National Land Survey of Finland 2016; Groundwater area © SYKE)

3. Discussion and conclusions

The characterisation of the shallow aquifer from the First Salpausselkä formaton in Santala is significant for the groundwater resources and land use management and planning. The deterministic approach was useful information to identify the aquifer boundary and the distributions of the major depositional units in the aquifer. However, in the complex aquifer area the 3D geological model showing the distributions of different soil types constructed by the transition probability (T-PROGS) geostatistical approach provides a better characterization of the heterogeneity of the aquifer and improved reliability of subsequent groundwater flow model and vulnerability assessment in the aquifer area. The LiDAR DEM data provide more accurately details of the ground surface and identification of the flood prone areas, especially in the low-lying area than the previous version of the DEM data.

Under future climate change scenarios, the major changes in the water supply does not need to be conducted if the water consumption of the municipality and the industry will be reduced and the pumping efficiency is improved. However, location of the water intake well in Santala shoreline is at risk due to the future sea-level rise and the storm surge. To secure the future water supplies in Santala, two proposed new locations of water intake wells, based on the integration of the hydrogeological data with the groundwater risk areas, were provided to the local authorities for groundwater management in future (Figure 7): Location 1- the water intake well is recommended to move further inland above the flood prone area; Location 2- to the eastern part of the aquifer area, where the aquifer body consist of a large part of permeable sand and gravel.

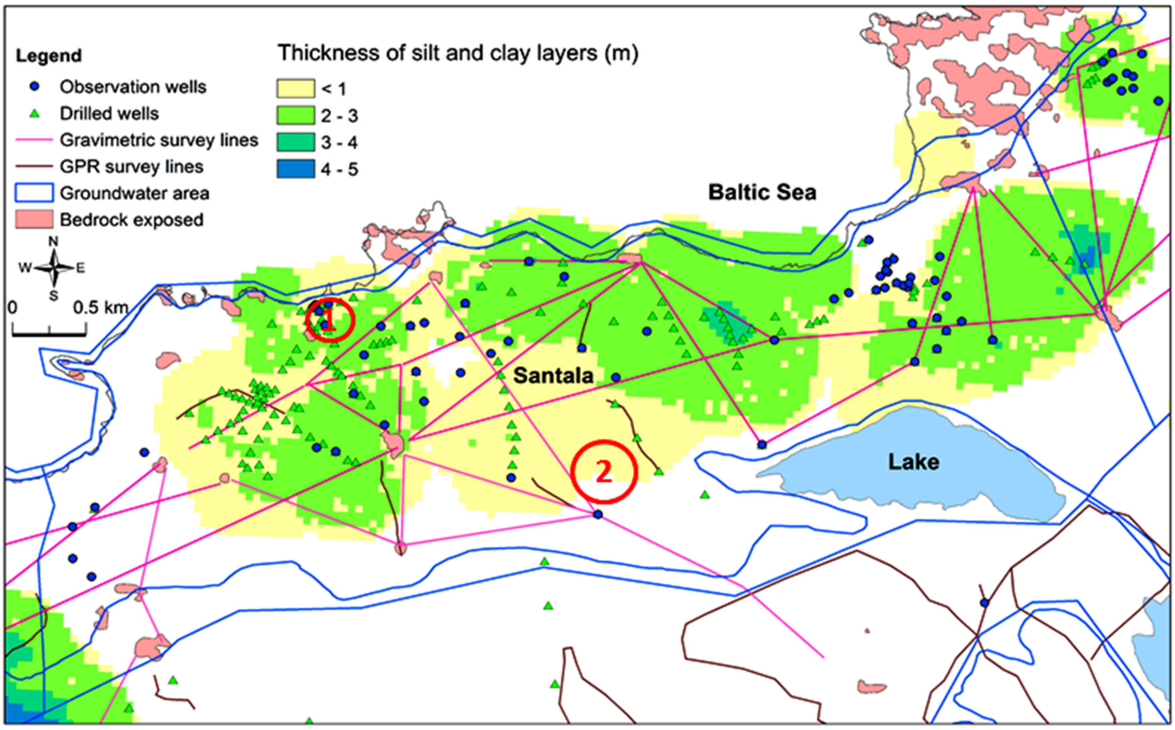

Figure 7. A thickness map of silt and clay layers presenting the proposed new locations of water intake wells. (Groundwater area © SYKE)

4. Materials and Methods

The methods used in this study consist of the deterministic and stochastic-geostatistical approaches [7,8] incorporated with groundwater flow model to predict the distributions of the superficial layers of a heterogeneous aquifer and to identify the distributions of the aquifer medias (sand and gravel) as well as groundwater flow system. This study applied the results of Luoma and Okkonen [2] on the groundwater flow model and the impact of climate change on groundwater resources in this area. In addition, the LiDAR-based digital elevation model (LiDAR-DEM) from the National Land Survey of Finland was utilized to define the flood prone areas under climate change scenarios.

The deterministic approach consist of the bedrock surface interpretation and the Quaternary deposit characterizations. Same like the other parts of Finland, shallow aquifer is found in the Quaternary sediments deposit above the crystalline Precambrian formation. The contrast between the crystalline Precambrian bedrock and the unconsolidated Quaternary sediments are large, gravimetric survey normally provides good indication of the bedrock surface. Bedrock surface topography was interpreted by utilizing all available geological and geophysical data that contain the top depth bedrock data. Figure 8 presents the data used in this study. All available top depth bedrock data were interpolated by using ArcGIS/ArcMap (version 9.3) by using kriging and inverse distance weight (IDW) interpolation methods. The bedrock surface data were then transferred into Groundwater Modeling Software (GMS) (version 9.2) for the 3D geologic modelling and visualization. The Quaternary deposit represents all unconsolidated sediments deposit between the bedrock surface and the topographic surface. Once the bedrock surface is identified, the Quaternary thickness is determined by subtracting the interpolated bedrock surface from the topographic surface (LiDAR DEM). In the bedrock exposed area, the thickness of unconsolidated sediment is zero. A 3D geological modelling was constructed for the bedrock surface and the main depositional units in Santala - Hanko aquifer area: 1) the primary deposit – sand and gravel; 2) silt and clay layer; and 3) the littoral sand and gravel deposits.

In the stochastic-geostatistical approaches, the distribution of the aquifer medias based on the soil descriptions from 149 drilled holes was simulated by utilising the transition probability geostatistics (T-PROGS) software run under the computer graphic of GMS (version 9.2). Figure 9 presents the Markov chain analysis of vertical-direction transitions based on the information of soil types from those drilled holes. The Markov chains analysis in the strike and dip directions was simulated based on the information depositional environment of the First Salpausselkä formation.

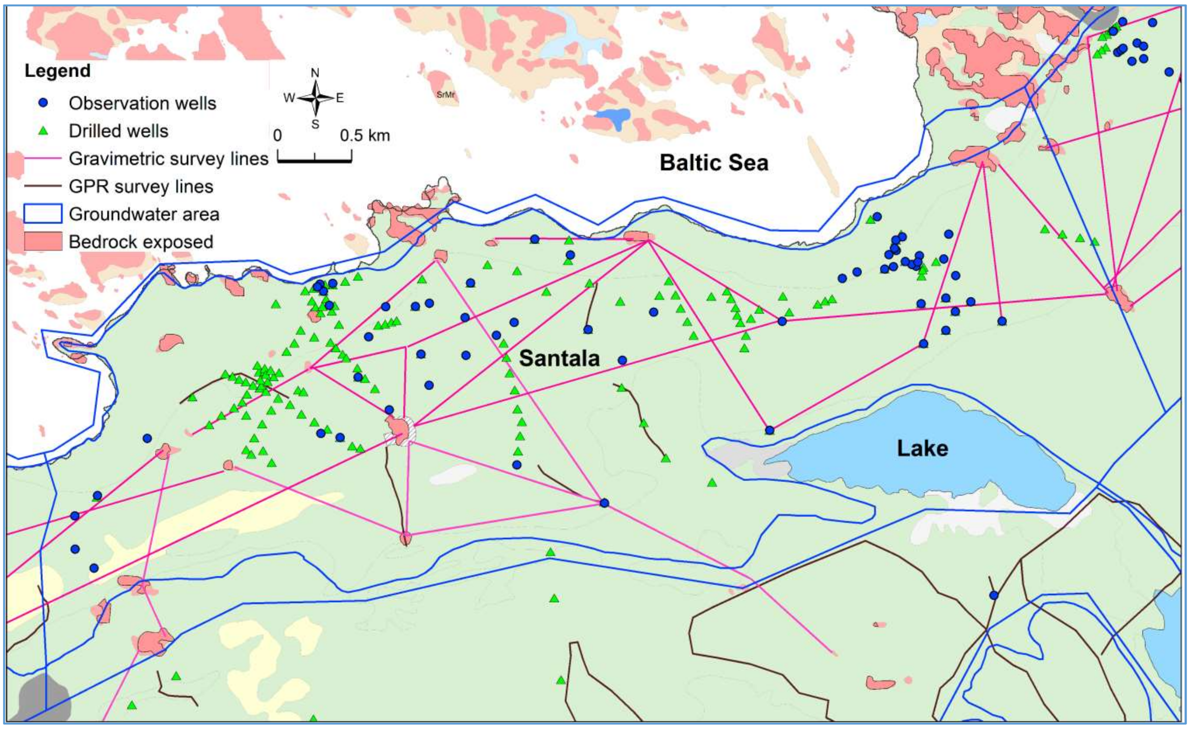

Figure 8. A map presenting the data used in this study. (Groundwater area © SYKE)

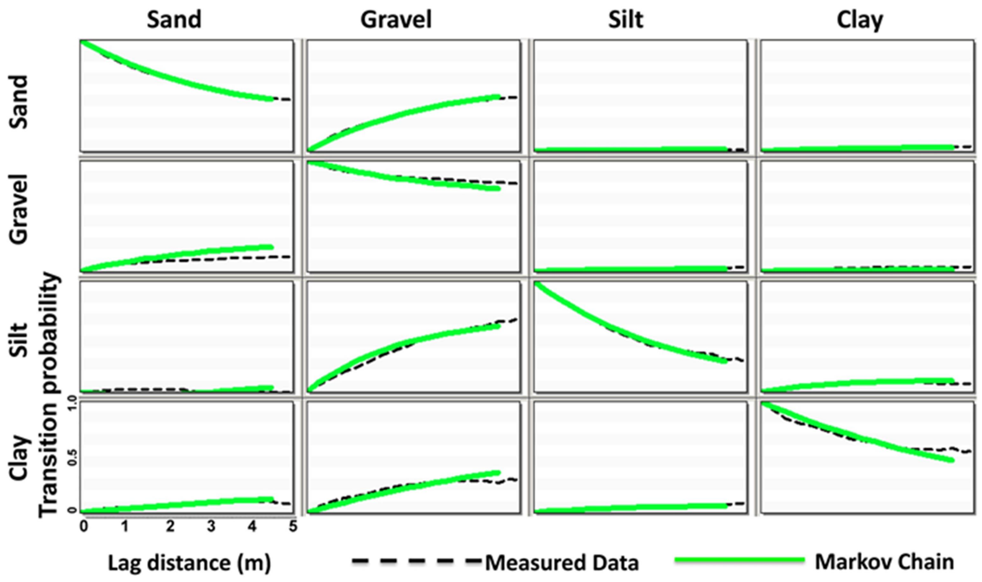

Figure 9. Matrix of vertical (z)-direction transition probabilities showing measured data from drilled wells (dash lines) and the Markov chain model (solid lines). The diagonal elements represent auto-transition probabilities within a category, and the off-diagonal elements represent cross-transition probabilities between categories.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Luoma, S.; Okkonen, J.; Korkka-Niemi, K. Comparison of the AVI, modified SINTACS and GALDIT vulnerability methods under future climate-change scenarios for a shallow low-lying coastal aquifer in southern Finland. J. Hydrogeology, 2016, doi:10.1007/s10040-016-1471-2. Available on: http://link.springer.com/article/10.1007/s10040-016-1471-2 (accessed on 10 November 2016).
2. Luoma, S.; Okkonen, J. Impacts of Future Climate Change and Baltic Sea Level Rise on Groundwater Recharge, Groundwater Levels, and Surface Leakage in the Hanko Aquifer in Southern Finland. Water 2014, 6(12), 3671–3700, doi:10.3390/w6123671. Available online: http://www.mdpi.com/2073-4441/6/12/3671 (accessed on 10 November 2016).
3. Luoma, S.; Okkonen, J.; Korkka-Niemi, K.; Hendriksson, N.; Backman, B. Confronting the vicinity of the surface water and sea shore in a shallow glaciogenic aquifer in southern Finland. Hydrol. Earth Syst. Sci. 2015, 19, 1353–1370, doi:10.5194/hess-19-1353-2015. Available on: http://www.hydrol-earth-syst-sci.net/19/1353/2015/ (accessed on 10 November 2016).
4. Fyfe, G. J. The morphology and sedimentology of the Salpausselkä I Moraine in southwest Finland. PhD Thesis, Cambridge University: Fitzwilliam College. 1991.
5. FCG Suunnittelu ja Tekniikka Oy. Hangon pohjavesialueiden suojelusuunnitelman päivittäminen. Hangon kaupunki, Hangon vesi- ja viemärilaitos and Uudenmaan ELY-Keskus. 2013. (in Finnish)
6. Luoma, S.; Klein, J.; Backman, B. Climate change and groundwater: Impacts and Adaptation in shallow coastal aquifer in Hanko, south Finland. In Climate Change Adaptation in Practice—From Strategy Development to Implementation; Schmidt-Thomé, P., Klein, J., Eds.; Wiley-Blackwell:Chichester, UK, 2013; pp. 137–155.
7. Carle, S.F. T-PROGS: Transition Probability Geostatistical Software. Version 2.1. University of California, Davis, 1999.
8. Weissmann, G.S.; Carle, S.F.; Fogg, G.E. Three-dimensional hydrofacies modeling based on soil surveys and transition probability geostatistics. Water Resources Research 1999, 35(6) 1761-1770. Available on: http://onlinelibrary.wiley.com/doi/10.1029/1999WR900048/epdf (accessed on 10 November 2016).