# Hydrostratigraphy and 3D Modelling of a Bank Storage Affected Aquifer in a mineral exploration area in Sodankylä, Northern Finland

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**Abstract** 3D geological modelling and flow modelling were used to investigate groundwater flow patterns near Kersilö, Sodankylä, close to a Cu-Ni-PGE discovery named Sakatti. A MODFLOW-NWT model was generated to simulate the groundwater table. Alternating sorted sediment and till units were observed within the study area, indicating complex aquifer conditions. The hydrological settings were examined to understand the changes driven by the regulation of the River Kitinen. The results of flow modelling indicate groundwater movement towards the river. The artificial rise in the river stage has caused wetting of the mire area near Matarakoski.

**Key words** groundwater, surface water, modelling, surficial deposits, mire hydrology, mining environment

## Introduction

A prominent Cu-Ni-PGE mineralization named Sakatti has been discovered close to the River Kitinen in Sodankylä, Northern Finland (Brownscombe et al. 2015). The deposit is located below the Natura 2000 protected Viiankiaapa mire (fig. 1). In Northern Finland, the sedimentary package is often a complex combination of deposits from alternating glacial and ice-free events, as demonstrated in previous studies (e.g. Hirvas 1991). Therefore, aquifers are usually small and scattered (Lahermo 1973) and inadequately studied. It is vital to understand the hydrostratigraphy of surficial deposits and the surface water–groundwater interactions in order to conduct exploration activities in a sustainable way.

The River Kitinen has been regulated by hydroelectric power plants constructed by Kemijoki Oy since the 1960s (Marttunen et al. 2004). In its pristine state, the river was known to be subject to extensive spring flooding, which affected the hydrology of the Viiankiaapa mire and the local flow patterns of surface and groundwater. The regulation of the river ended the major flooding events and was hypothesised to change the surface and groundwater flow patterns.

The aim of this study was to utilize geological 3D modelling and flow modelling as tools to understand the flow patterns of surface water and groundwater and examine how the regulation of the river has affected the hydrological settings of the study area.

## Materials and methods

All available information on surficial deposits (e.g. Gustavsson et al. 1979), stratigraphic sites (Hirvas 1991), groundwater monitoring wells and bedrock topography was collected into a GIS database called the Kersilö database (Åberg et al. 2017) within the area X: 482

000–500 000, Y: 7 500 000–7 480 000 (EUREF-FIN TM35 coordinate system). A 3D model of surficial deposits and the bedrock surface was generated near Sakatti covering an area of 3.0 x 3.5 km (fig. 1). In addition to the Kersilö database, ground penetrating radar (GPR) profiles from two field campaigns in April and August 2015 were used as input data for the 3D modelling (fig. 1) and groundwater table interpretations. The 3D model was generated with Leapfrog Geo®. It consisted of seven sediments units, a peat layer, the River Kitinen, weathered bedrock and bedrock surface (fig. 2, tab. 1).

A simplified version of the 3D model (see tab. 1) was converted into a groundwater flow model. MODFLOW-NWT (Niswonger et al. 2011) was chosen as the modelling code due its suitability for unconfined and highly heterogeneous aquifer conditions. The flow model consisted of eight layers with varying hydraulic conductivity zones defined by the 3D model (see tab. 1). The hydraulic conductivities of the hydrostratigraphic units were then calculated from the geometric means of calculated hydraulic conductivity values based on previous grain-size analyses and slug tests. The flow model was manually calibrated with UCODE_2014 (Hill and Tiedeman 2007) by adjusting the hydraulic conductivities to obtain a better fit between the observed and simulated groundwater table. The yearly variation in the groundwater table was also studied from recordings of the 17 monitoring wells (fig. 1).

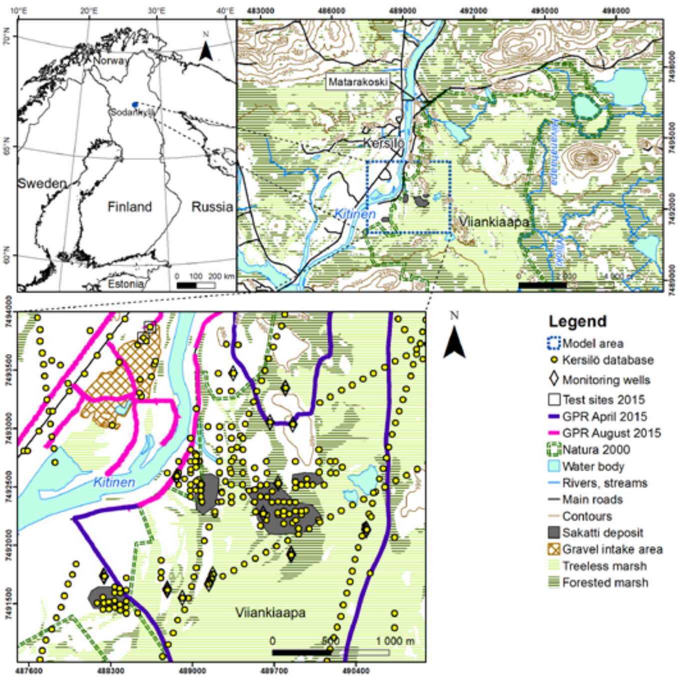


*__Figure 1__ Location of the study area around the River Kitinen in Northern Finland (above). The Kersilö database and ground penetrating radar (GPR) profiles were used as input data for the 3D model (below). The Kersilö database indicates the locations of available surficial deposit and bedrock surface observations. Terrain polygons © National Land Survey of Finland, Sakatti deposit modified after Brownscombe (2015).*

The surface water flow direction was estimated in the Viiankiaapa area by using ortho images, a two-metre-resolution LiDAR DEM and existing flow directions from maps. Changes in the hydrological settings of the River Kitinen were examined from different maps and unpublished discharge and river stage data obtained from Kemijoki Oy.

## Results

***Table 1*** *The geological units of the 3D model and flow model. The unit of hydraulic conductivities is m s-1. HK = horizontal hydraulic conductivity. VK = vertical hydraulic conductivity.*

| Modelled unit | 3D model | Flow model | Original HK parameter* | Calibrated HK parameter | VK multiplier¤ |
|---|---|---|---|---|---|
| River Kitinen | x | x | 1.0E-01 | 1.0E-01 | 1 |
| Peat | x | x | 8.5E-06 | 1.0E-03 | 0.001 |
| Top deposits | x | x | 2.3E-05 | 2.3E-05 | 0.1 |
| Upper till | x | x | 4.1E-06 | 4.1E-06 | 0.1 |
| Middle sorted deposits | x | x | 6.9E-04 | 7.3E-06 | 0.1 |
| Middle till | x | | | | |
| Lower sorted deposits | x | | | | |
| Lower till assemblage | x | x | 1.6E-05 | 1.6E-05 | 0.1 |
| Lowest sands and gravels | x | x | 1.5E-04 | 1.5E-04 | 0.1 |
| Weathered bedrock | x | | | | |
| Bedrock | x | x | 9.4E-06 | 9.4E-06 | 1 |

*Geometric mean of the calculated hydraulic conductivities
¤The multiplier of vertical hydraulic conductivity that was used in the calibrated model

According to the 3D model, the volume of surficial deposits is 0.096 km$^3$, of which 59% is till, 32% is sorted deposits and 9% is peat. The average thickness of surficial deposits is 9.1 m and the thickness varies from 0 to 41 m. The altitude of the bedrock topography varies between 148–190 m. The aquifer systems are complex and scattered due to alternating sorted and unsorted deposits. The low hydraulic conductivity of till units conceals perched groundwater conditions.

The flow model indicates that groundwater mainly flows towards the River Kitinen (fig. 3). At monitoring wells close to the River Kitinen, higher annual variation in the groundwater table was recorded during 2012–2015, indicating a possible bank storage situation.

Surface water flows towards the River Kitinen on the eastern side of the river and towards the smaller rivers Hiivanahaapa and Ylijoki (fig. 1) on the western side. The construction of

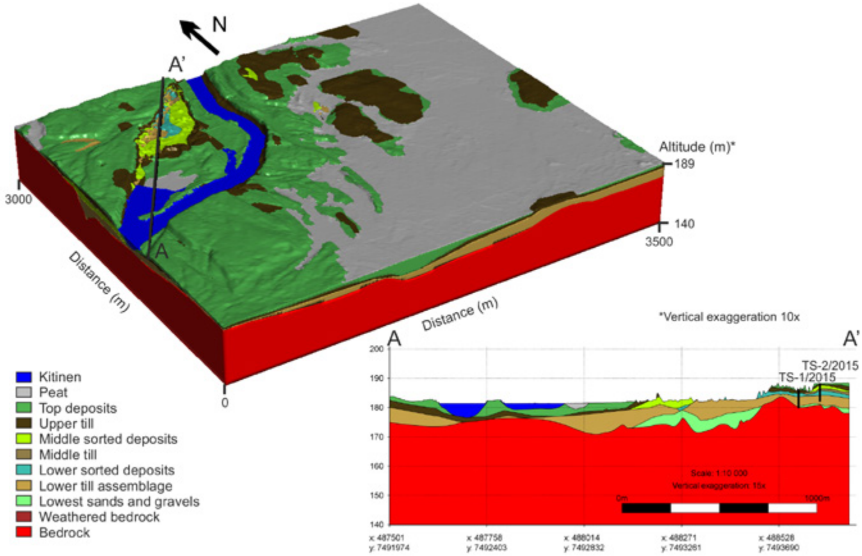


***Figure 2*** *3D model of unconsolidated sediments and bedrock topography near Kersilö village (above) and cross-section A-A' of the 3D model (below). The location of the 3D model is presented in fig. 1. The sediment structure is tentatively based on the interpretation of the test sites TS-1/2015 and TS-2/2015.*

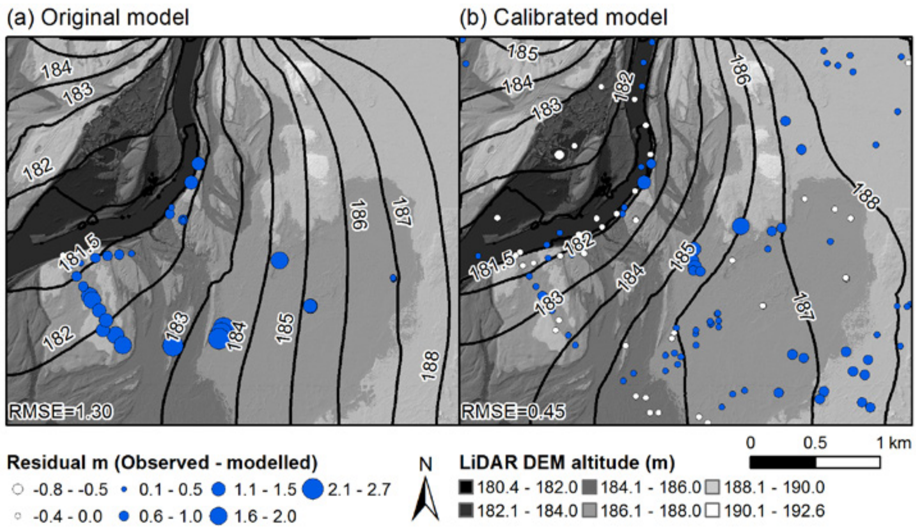


***Figure 3*** *Groundwater flow modelling results with groundwater table observations interpreted from GPR profiles, groundwater monitoring wells and surface water bodies (rivers, flarks etc.). (a) The first version of the model with the original parameters calculated from the geometric means of hydraulic conductivities. (b) Manual calibration of the model with surface water body points included. The surface water points were added to achieve better calibration results in the mire area. LiDAR DEM © National Land Survey of Finland.*

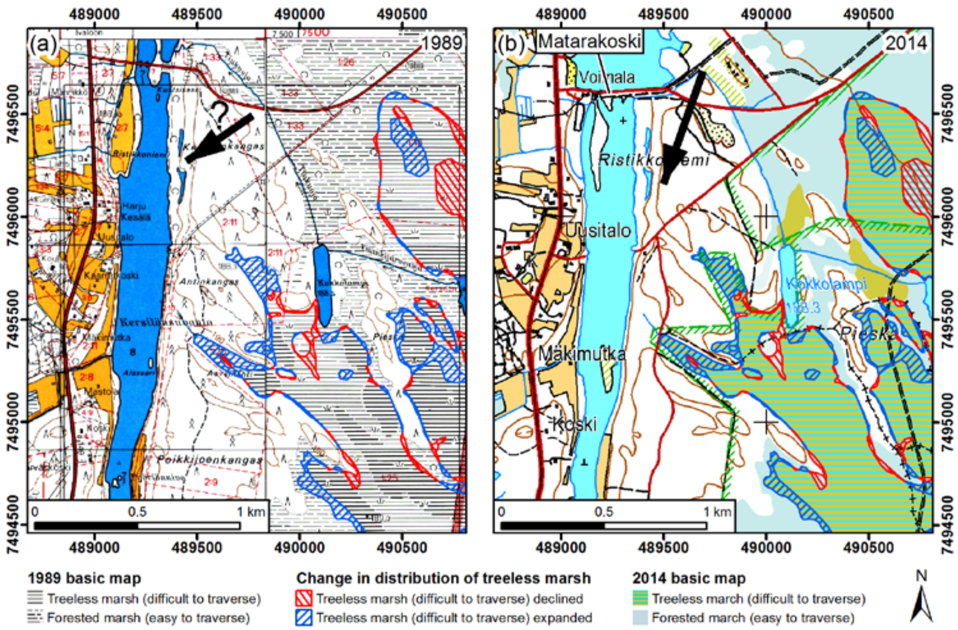


***Figure 4*** *The change in the distribution of treeless marsh in the Kokkolampi area near Matarakoski hydroelectric power plant. (a) The situation in 1989 before the construction of the Matarakoski hydroelectric power plant; (b) the present situation. The treeless marsh area increased near Kokkolampi from 1989 to 2014. The black arrows indicate the estimated groundwater flow directions near Matarakoski. Basic maps (2014, 1989) © National Land Survey of Finland.*

the Matarakoski hydroelectric power plant in 1995 has caused a rise of several metres in the river stage in the Matarakoski area and a reduction in flooding of the river. At the same time, the mire area near Kokkolampi has become wetter (fig. 4), which is an indication of a rise in the groundwater table in the area due the elevated river stage.

## Discussion

MODFLOW-NWT was suitable for the heterogeneous and unconfined aquifers systems of the study area. The flow model results were highly dependent on the hydraulic conductivities of the sediments and their distributions. Parameter estimation with UCODE_2014 (Hill and Tiedeman 2007) was also tested. However, the manual calibration resulted in a more reliable fit and convergence due to the low sensitivities of most parameters according to sensitivity analysis. The RMSE of the calibrated model was 0.45, indicating a fairly good fit. The poor fit in the south eastern corner (fig. 3) of the model area was due the peat layer modelled in the area being too thin. The observations in the middle of the study area indicate perched groundwater, which would explain the underestimation of the groundwater table. The uncertainties of the groundwater flow model are highly dependent on the uncertainties of the 3D model. Thus, reconstruction of the 3D model, especially the peat unit, and parameter estimation with UCODE_2014 will be carried out. Due to the simplicity of MODFLOW, the open-source flow-modelling software ParFlow (Kollet and Maxwell 2006) will be used for more detailed modelling of groundwater recharge.

The construction of the Matarakoski power plant has changed the hydrological settings. The rise in the river stage has probably affected the groundwater table, causing the wetting of the mire area near Kokkolampi. Changes in the groundwater flow patterns may also affect the biodiversity of the mire. According to Karplund (1990), the regulation of the river has caused a decline in the distribution of many endangered flood-dependent species in the area.

3D modelling of surficial deposits can be applied to estimate the volume and the distribution of the groundwater reservoirs. In addition, it can be applied into infrastructure planning and evaluation of siting of the mining facilities. Groundwater model may also facilitate how the change in flow patterns affects distribution of groundwater dependent plants.

## Conclusions

Groundwater flow modelling and interpretations of surface water flow direction both indicated flow towards the River Kitinen. Groundwater modelling is an effective tool to estimate the continuity of geological units in study areas with scarce data. However, the actual uncertainty of the flow model is difficult to evaluate due to uncertainties in the structure of the 3D model. Further calibration or reconstruction of the flow model is needed to obtain a better fit.

The construction of power plants has considerably changed the hydrological system of the river and the mire area due to reduced flooding. The rise in the river stage has affected the groundwater flow near Matarakoski, changing a possible bank storage situation, as indicated by the yearly groundwater table variations at the monitoring wells. To gain a better understanding of the system, more groundwater observations near the dam are needed.

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