Managed Aquifer Recharge and Sedimentological Characterization Within The Complex Esker Deposits in Pälkäne, Finland

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Abstract: It is proposed to construct a Managed Aquifer Recharge (MAR) plant (capacity of 70 000 m^3/d) to provide potable water for over 300 000 inhabitants in Tampere and Valkeakoski region in Southern Finland. The plant includes the infiltration of surface water in a Quaternary glaciofluvial ridge (esker) with subsequent withdrawal of the water from downstream wells. We present the sedimentological characterization and rearranged MAR design of the 3 km long unconfined esker aquifer in Pälkäne (capacity of 20 000 m^3/d) that were needed to overcome the effect of discontinuities in the hydraulic connections along the Taustiala bedrock threshold as implied by a non-operational preliminary 1 –layer groundwater flow model. A more detailed sedimentological characterization was obtained by ground penetrating radar (GPR) and a tracer test indicating flow paths and residence times of the infiltrated water. Four main hydrogeological units were distinguished. The bedrock threshold divides the groundwater flow into two preferred flow paths. The sedimentological interpretation was applied to determine the variation of hydraulic conductivities for the new 7 –layer groundwater flow modeling. Sedimentological information together with hydrogeological studies were used in designing the sites and capacities for infiltration and withdrawal.

Keywords: Managed Aquifer Recharge; Esker; Aquifer; Sedimentology; Ground Penetrating Radar; Depositional model; Hydrogeology; Groundwater flow model

1. Introduction

Finnish lakes are typically humic, containing natural organic matter (NOM) derived from the decay of vegetation in the forests and peatlands of the catchment areas. NOM can be detrimental in drinking water as it is a possible source for bacterial growth. The removal of NOM is one of the main tasks in producing drinking water from surface waters in Finland. As an alternative for chemical water treatment, managed aquifer recharge (MAR) can be used for drinking water production.

There are currently 26 MAR plants in Finland (Jokela and Kallio 2015). During MAR, NOM is removed by physical, chemical, and microbial processes (Kortelainen and Karhu 2006; Kolehmainen et al. 2007; Kolehmainen 2008). A typical Finnish MAR plant includes infiltration of lake or river water in an esker and withdrawal of water from wells a few hundred meters down-gradient. The infiltrated water should have a residence time of at least one month before withdrawal to provide time for processes needed to lower NOM concentrations by break down or remove NOM as evidenced by the operational results from several MAR plants (Helmisaari et al. 2005; Jokela et al. 2017).

42   Eskers in Finland are glaciofluvial formations which were commonly deposited by streams in
43   tunnels beneath the ice during the final deglaciation of the Scandinavian ice sheet. Typically, an esker
44   consists of 20 to 50 meters of gravel and sand that is covered by a thin humic soil layer (< 10 cm).
45   Generally, eskers are preferred areas for potable water MAR treatment. However, they can also be
46   centers of population, are considered recreational or nature conservation sites or they can be sources
47   for extraction of gravel. When MAR plants are being planned, these interests may be conflicting.
48   Public participation is an important feature of MAR planning in Finland (Jokela and Valtonen 2010;
49   Kurki et al. 2013). Site selection and the actual planning for the exact locations for infiltration and
50   abstraction areas should be based on sound research and modeling to ensure reliable MAR operation.
51   Tavase Ltd. is a wholesale company owned by six municipalities located in southern Finland.
52   The company aims to construct a MAR plant east of Tampere to provide potable water for the
53   municipalities of Tampere and Valkeakoski region. The number of people living in the region exceeds
54   300,000. The location and design for the MAR plant has been under extensive research. The MAR
55   plant will consist of three MAR sites in separate esker aquifers, two of which are located in the
56   municipality of Kangasala and one in the neighbouring municipality of Pälkäne. The capacities of the
57   aquifers are 22 000, 28 000 and 20 000 m^3/d, respectively, and thus the total capacity of the MAR plant
58   will be 70,000 m^3/d. Raw water will be taken from Lake Roine in Kangasala and pumped to the
59   infiltration areas located 1 km (Kangasala) to 7 km (Pälkäne) from the lake. Three infiltration methods
60   will be used: basin infiltration will be applied for approximately one third of the total capacity (in
61   one of the Kangasala aquifers), whereas parallel well infiltration and sprinkling infiltration systems
62   will be constructed for infiltration of the rest. Sprinkling infiltration comprises aboveground pipe
63   network (infiltration rakes) through which water is distributed on top of natural forest soil. Well
64   infiltration will be the primary infiltration method, but sprinkling infiltration can be used when
65   necessary. No pretreatment will be needed for basin and sprinkling infiltration. However, an optional
66   drum sieving was designed for well infiltration (Jokela et al. 2017). Before distribution to the trunk
67   mains of the distribution networks, water will be disinfected by ultraviolet (UV) radiation,
68   chlorination or both, and the alkalinity and hardness will be adjusted at the shareholder
69   municipalities´ waterworks.
70   Glaciofluvial aquifers often show complex internal structure and related variation in hydraulic
71   properties that are difficult to predict for groundwater flow modeling purposes and MAR designs.
72   This is due to the overlapping mosaic of deposits by changing depositional environments associated
73   with rapidly changing processes and intense deformation at short distances at the ice margin, where
74   most of the deposition takes place (Mäkinen 2003a). Moreover, those areas that have experienced
75   intense erosion and redeposition by shore processes during the glacio-isostatic land uplift provide
76   difficulties for the interpretation of glaciofluvial sedimentation (Mäkinen and Räsänen 2003).
77   Therefore, the aquifer characterization in glaciofluvial landforms should always be based on the
78   depositional model that includes the understanding of the depositional stages (Sharpe et al. 2002).
79   This understanding is then used to predict sediment distribution and related hydraulic properties in
80   areas with sparse data, and to define main hydrogeological units that enable data input straight into
81   groundwater flow models (Sharpe et al. 2002; Artimo et al. 2003).
82   The sedimentological understanding can be achieved by applying ground penetrating radar
83   (GPR) sedimentology that enables synthesis of the existing data (Artimo et al. 2010). GPR surveys are
84   fast and cost-effective, and provide continuous profile data over wide areas with possibilities for
85   pseudo 3-D interpretation (Bridge and Hyndman 2004; Artimo et al. 2010). The limited penetration
86   in thick deposits can usually be compensated by the understanding of the depositional environments
87   and stages enabling integration of universal facies models.
88   The important step in connecting the sedimentological information with groundwater flow
89   modeling (grid size) is scaling, which emphasizes the delineation of major depositional units and
90   architecture instead of detailed sedimentary facies distribution. In the case of esker deposits and
91   associated landforms, the most crucial task is to determine the location and dimensions of the high
92   conductivity esker core and its relation to bedrock topography and groundwater table. Finally, the
93   sound basis for groundwater flow modeling and MAR design is through integration of

sedimentological understanding and infiltration/tracer test results that are applied to verify hydraulic properties as well as the scaling procedure (Artimo et al. 2010).

The aim of this paper is to transfer geological data of a complex depositional system to a reliable groundwater flow model for MAR feasibility assessment. We focus on sedimentological characterization that was needed after the preliminary one–layer groundwater flow model (MODFLOW code) failed to adequately simulate MAR operation due to an excessive 3 m drop in groundwater level between the infiltration area and the pumping wells. Instead, a 7-layer groundwater flow model with 25 x 25 m cell size was constructed in order to better represent the hydrogeological environment and groundwater flow conditions. The new flow model should form the basis for MAR design and be able to simulate MAR operation for capacity of 20 000 m^3/d. The sedimentological characterization and determination of hydraulic conductivity values for the groundwater flow model relies on GPR-determined sedimentology that is used for the synthesis of the different geological data sets, and supplemented with infiltration and tracer test results.

2. Materials and Methods

2.1. MAR procedure

The study was conducted in the Quaternary Isokangas-Syrjänharju unconfined esker aquifer in the municipality of Pälkäne. The esker (glaciofluvial ridge) is part of a long interlobate esker chain that was deposited between two differently behaving ice masses during the last deglaciation phase of the Scandinavian ice sheet. The Syrjänharju esker in the SE end of the study area forms a distinct ridge, whereas the Isokangas esker in the NW part of the area exhibits more widespread deltaic landforms within generally higher lying bedrock topography. The ice margin terminated in the Yoldia Sea phase of the ancient Baltic Sea with the highest shore around 155 m a.s.l. (above sea level) as indicated by the delta levels (Eronen and Haila 1990). During the rapid glacio-isostatic land uplift, the esker became subjected to powerful shore processes that have markedly modified the original morphology of the esker, especially the distal parts of the esker deltas.

The planned production capacity for the area is 20 000 m^3/d. Information from gravimetric measurements, boreholes, groundwater observations and from an earlier infiltration study were used for planning the proposed infiltration and abstraction locations. Infiltration of lake water using infiltration wells IK1, IK2 and IK3 (Fig. 1) was planned in the NW part of the study area. Abstraction wells divided into two well-fields on both sides of the esker core (K3 and K4 in Figure 1) were located 1600 m downstream in the SE part of the study area. A more detailed description of the infiltration test set-up has been presented elsewhere (Jokela and Kallio 2015). The positions of the wells K3 and K4 were chosen before the GPR surveys and were guided by the practical constraints like a nature conservation area located between the two wells and well depth. Based on the preliminary groundwater model (MODFLOW), the retention time for the recharged water in the soil was two months.

2.2. Groundwater observations and monitoring wells

The study area has 67 observation wells and most of them has been drilled down to the bedrock. Groundwater (natural) head (Figure 1) has been extensively monitored for many years. Before the infiltration and tracer test, 15 groundwater elevation automatic measuring devices were installed in selected wells (Figure 1). Measurement data was transferred via GSM system to Insta Ltd server from where it was available for monitoring purposes. Manual groundwater level measurements were also carried out daily/weekly according to the monitoring programme. Several natural springs by the lake (Figure 1), revealed by the colder water spots, form an important groundwater discharge area included in the model domain. Thus, the groundwater observations were supplemented with gyro-stabilized and computer controlled Flir infrared camera survey (resolution 320 x 240 pixels and temperature resolution of 0,08 C) using helicopter with 70 and 100 m flight altitudes.

141   *2.3. Borehole data and gravimetric surveys*

142   Mapped bedrock exposures, borehole data, and gravimetric measurements were already used
143   to interpolate the bedrock topography (Figure 2) and to define the thickness of the deposits as well
144   as the main characteristics of the material distribution. The bedrock interpolation and the material
145   distribution were further improved by the interpretation of GPR surveys. In addition, the gravimetric
146   data was evaluated against the esker core positions from the GPR data, because based on our
147   experience, gravimetrics tend to treat the boulder-rich cores as bedrock highs with an error of about
148   5-15 m.

149   *2.4. Ground Penetrating Radar sedimentology*

150   The continuously moving ground penetrating radar (GPR) survey provides information from
151   the geological structures and groundwater levels (Bridge and Hyndman 2004; Artimo et al. 2010).
152   The sedimentological interpretation of GPR profiles is supported with areal reference from
153   geomorphological interpretation and local lithological reference from the borehole logs.
154   In this study, 3 GPR surveys with total length of 36 km were completed after preliminary
155   groundwater modelling and at different stages by using GSSI SIR-3000 georadar by Geo-Work Ltd.
156   The use of 100 MHz antenna (19 km) provided detailed image of the main sedimentary structures
157   with penetration depth of about 15-25 m and forms the framework for the recognition of the
158   depositional stages during the deglaciation.
159   The penetration depth was improved to 30-40 m in good ground conditions by using 40 MHz
160   DUAL antenna (17 km) in order to better detect sediment stratigraphy and bedrock topography,
161   especially within the Taustiala bedrock threshold. However, the increased penetration means poorer
162   definition of the sedimentary structures so that only the large-scale features can be determined. Thus,
163   the survey also focused on the delineation of the esker cores and adjacent hidden kettle holes within
164   the thicker sediments in the SE part of the system including the pumping well sites K3 and K4. The
165   kettle holes were formed by melting of buried ice and related collapse of glaciofluvial sediment. They
166   were later levelled and partly filled by the ancient shore processes so that they now appear only as
167   hidden structures. Finally, the GPR sedimentology forms a geological framework for synthesis of all
168   data sets including groundwater observations as well as infiltration and tracer tests.

169   *2.5. Combined infiltration and tracer test*

170   The combined infiltration and tracer test in the Isokangas esker in Pälkäne was carried out as a
171   recirculating test, in which groundwater was recirculated from the downstream pumping wells to
172   the infiltration area. Pumping and infiltration was done for 9 months with maximum rate of 7000
173   m^3/d. Infiltration was done with deep wells in combination with sprinkler infiltration at the surface.
174   In the tracer investigation, 11 mg/l a water-soluble tracer (NaI) was added to the infiltrated water
175   when steady state conditions were achieved. Sodium iodide was chosen as tracer, because it is very
176   soluble, has negligible retardation in mineral soil, is easily detectable and is harmless to man and pets
177   even in relatively high concentrations. Tracer was injected to the infiltration wells. Tracer
178   concentration was monitored in 45 observation wells (cf. Figure 1) along the expected flow paths
179   between infiltration and the two production wells, K3 and K4. In addition, other wells and springs
180   were monitored and the total number of observation points was 100. The highest monitoring
181   frequency was every second day. The tracer investigation was supervised by Geosigma Ltd, Sweden.

182   *2.6. Groundwater flow modeling*

183   The preliminary one-layer groundwater flow model (MODFLOW code and the Visual
184   MODFLOW Pro 4.2 interface) proved to be unsuitable for the modeling purposes and indicated that
185   there is a marked change in groundwater flow conditions with a steepening flow gradient between
186   the infiltration and the pumping sites. In order to overcome the modelling problem and to adequately
187   describe water conductivity in the esker deposits, the sedimentological characterization was needed

188   to compile a numerical 7-layer groundwater flow model (MODFLOW and PMWIN). The model layer
189   thickness varies from 0.1 m (the lowest layer) to over 45 m. The number and shape of the layers were
190   selected so that the most important hydrogeological structures controlling the groundwater flow
191   could be described as detailed as possible. Moreover, several layers were needed to keep the model
192   saturated so that it could be used also in those areas where simulations were bounded by dry cells.
193   These dry cells turn to inactive cells and are excluded from the calculations. The flow model covers
194   an area of 6.2 x 4.9 km with a 25 x 25 m grid size (Figure 3). In the East, South and West the model
195   was bounded by lakes. In the North, Southwest, and Northwest the model area is delineated by
196   bedrock thresholds and groundwater divides (Figure 2).
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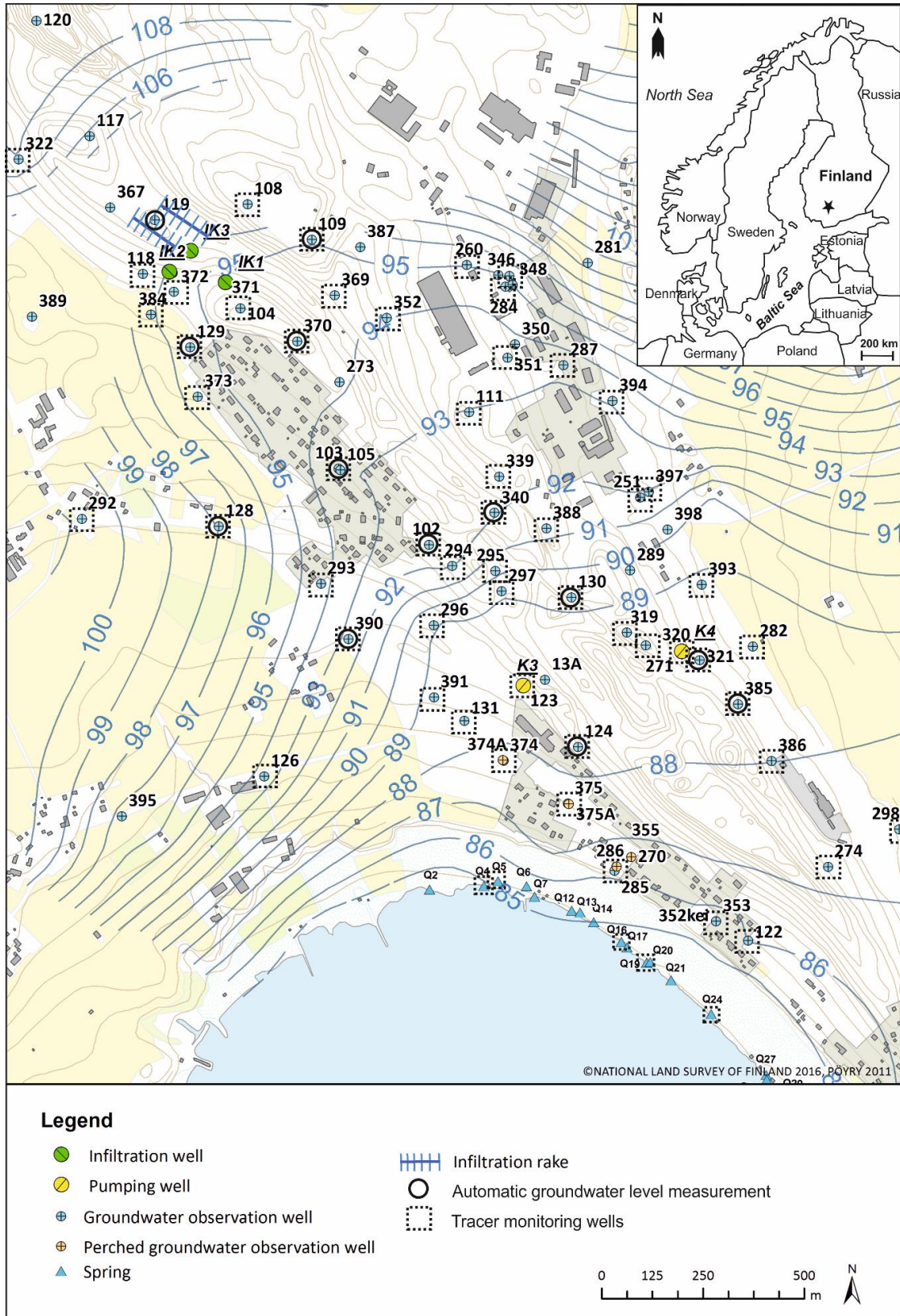
Figure 1. Groundwater (natural) head with locations of groundwater observation wells. Esker ridge in the middle fringed by cultivated fine-grained plains (yellow areas). Groundwater information on the map by Pöyry Ltd. 2011 (modified).

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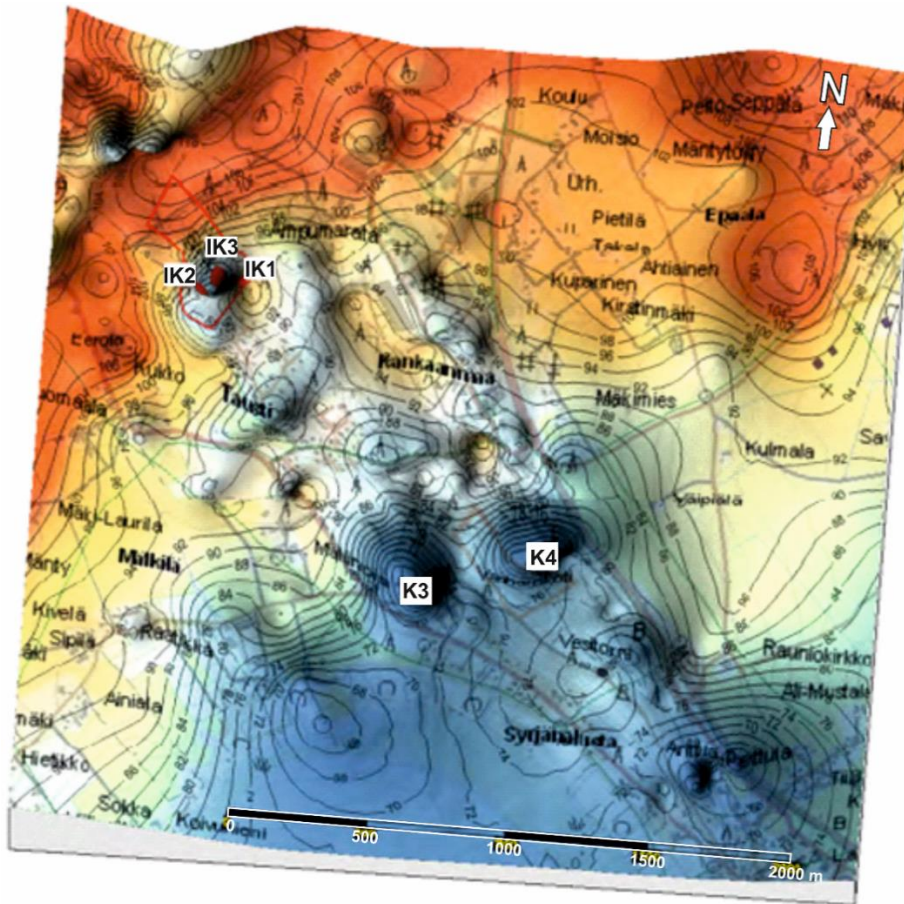
Figure 2. Bedrock topography of the study area based on outcrops, borehole data and gravimetric measurements. Note location of infiltration (IK1, IK2, IK3) and pumping sites (K3, K4) separated by the Taustiala bedrock threshold. The bedrock threshold and groundwater divide to the NW of the infiltration area (IK1-IK3) directs the groundwater flow along the esker towards the SE. Figure by Pöyry Ltd. 2011 (modified).

The distribution of the hydraulic conductivities was predicted by the depositional model based on the sedimentological interpretation of the area (Figure 3) supported by grain-size changes from GPR profiles and borehole data, and conductivity tests. Esker core with boulder gravel has the highest hydraulic conductivity values whereas the esker margins as well as delta structures show lateral fining of sediments. The flow model was calibrated to natural groundwater head measurements and validated with infiltration tests, drawdown near the pumping wells and groundwater mound around the infiltration area. The groundwater flow modeling was done by Artimo et al. 2011.

Figure 3. The groundwater flow model area with K-values of layer 6 ranging between 0.5-800 m/d based
on the borehole data and the sedimentological interpretation. Pumping wells K3 and K4 are indicated.
The main preferential flow path is between the wells along the main esker core (dark green zone). Figure
based on Artimo et al. 2011 (modified).

3. Sedimentological characterization

3.1. *Sedimentological interpretation*

The geological structure of the esker complex can be divided into 4 main depositional units
influenced by rapid variation in bedrock topography (Figure 4). The division is based on the
sedimentological interpretation of GPR data that combines all other geological and hydrological data
sets.

3.1.1. *The subglacial esker core and related crevasse deposits*

The bouldery esker core forms the preferential groundwater flow path within the esker complex
(Figure 4). The core formed in a subglacial tunnel and became later covered by ice-marginal crevasse
deposits. The single core follows the centerline of the esker ridge, but just before the Taustiala bedrock
threshold the core is divided into two parallel cores, that continue until the SE end of the area, where
two parallel boulder-rich esker ridges join the Syrjänharju ice-marginal delta. The cores are separated
by kettle holes and hidden kettle holes. Further towards the SE from the delta, the esker core was
formed in a single tunnel (Figures 4 and 5a). The esker core is about 150 m wide and 20-40 m high.
Borehole data shows even 20 m thick diamictons (borehole 340) that actually represent the variously

236 sorted esker core sediments.

237   In general, the esker core is covered by relatively dry and homogeneous sand or gravel that
238 shows less reflections in GPR profiles (Figure 6). These deposits were formed in crevasses at the ice
239 margin when the subglacial tunnel collapsed and the ice margin ended in a proglacial water body.
240 These deposits typically reveal large cross-bedded sets and channel-structures. Large meltwater
241 channel structures have also been found in GPR profiles between the esker cores to the North of
242 pumping site K3, which indicate higher hydraulic conductivities in this area. In places, the top of the
243 crevasse deposits is covered by more fine-grained sediments that were formed by more quiescent last
244 stage glaciofluvial flow during the deglaciation.

245 *3.1.2. Kettle holes and hidden kettle holes*

246   The esker core is well delineated by large kettle holes or hidden kettle holes (also known as
247 MUKH –structures) (Figure 4) (Mäkinen 2003b). Kettle holes are also found between the esker ridge
248 and the proximal deltas. They were formed after the sediment-buried ice blocks were melted (Figure
249 5b). Hidden kettle holes do not reveal the original hole-topography because of the intense reworking
250 by the shoreline processes during the rapidly continued glacio-isostatic land uplift. However, the
251 deformed and relatively steeply dipping margins of these structures are usually well depicted by
252 GPR (Figures 6 and 8). Hidden kettle holes are mostly associated with the SW side of the esker core
253 which was more subjected to powerful shore erosion. The material in kettle holes is often
254 heterogeneous with fine-grained walls due to collapse structures and deformation/faulting, and
255 related debris flows. Therefore, the kettle holes influence the groundwater flow pattern around the
256 core (Artimo et al. 2010). Moreover, these features are usually important for planning the location of
257 infiltration and pumping sites.
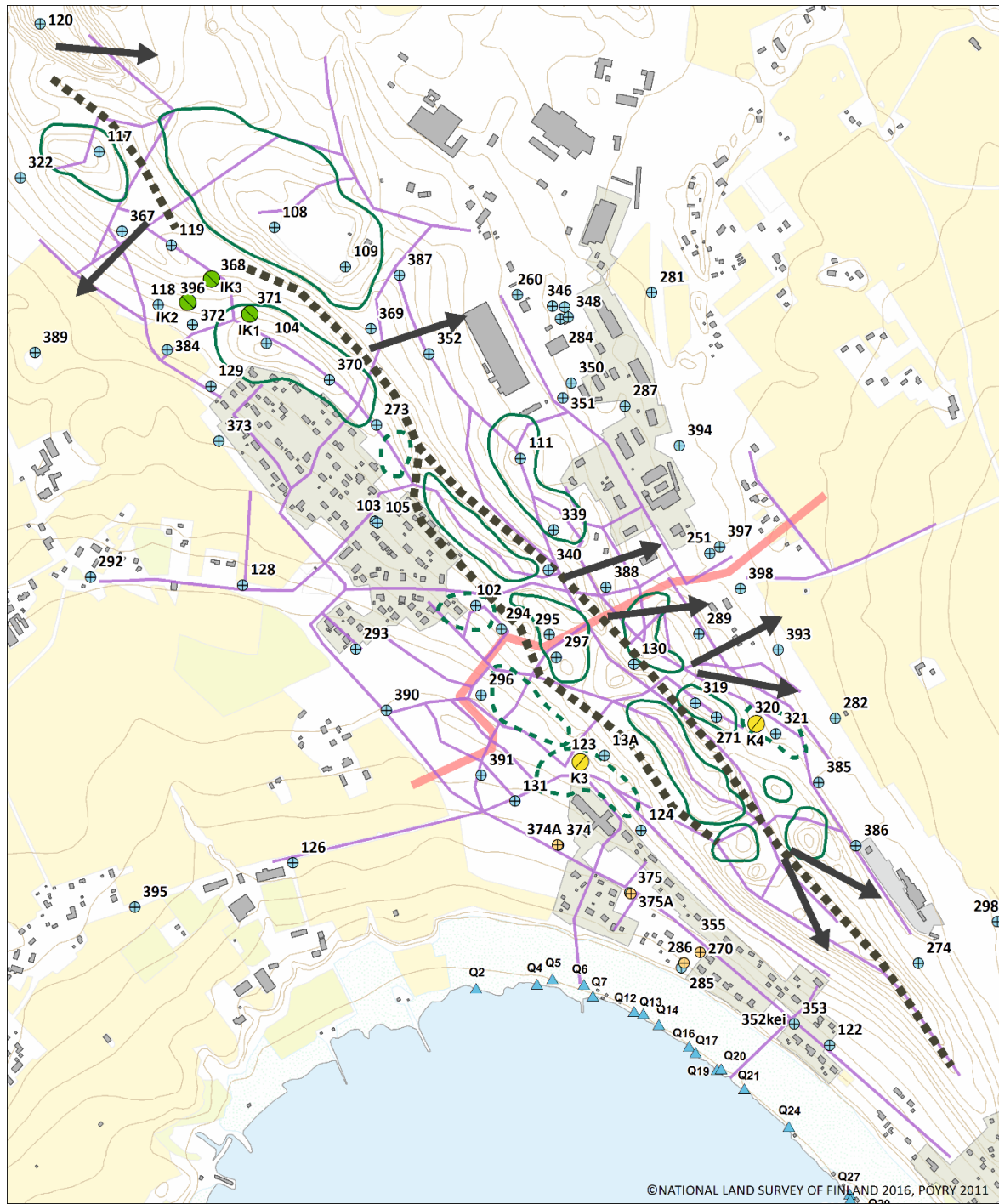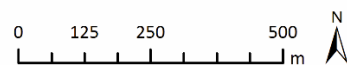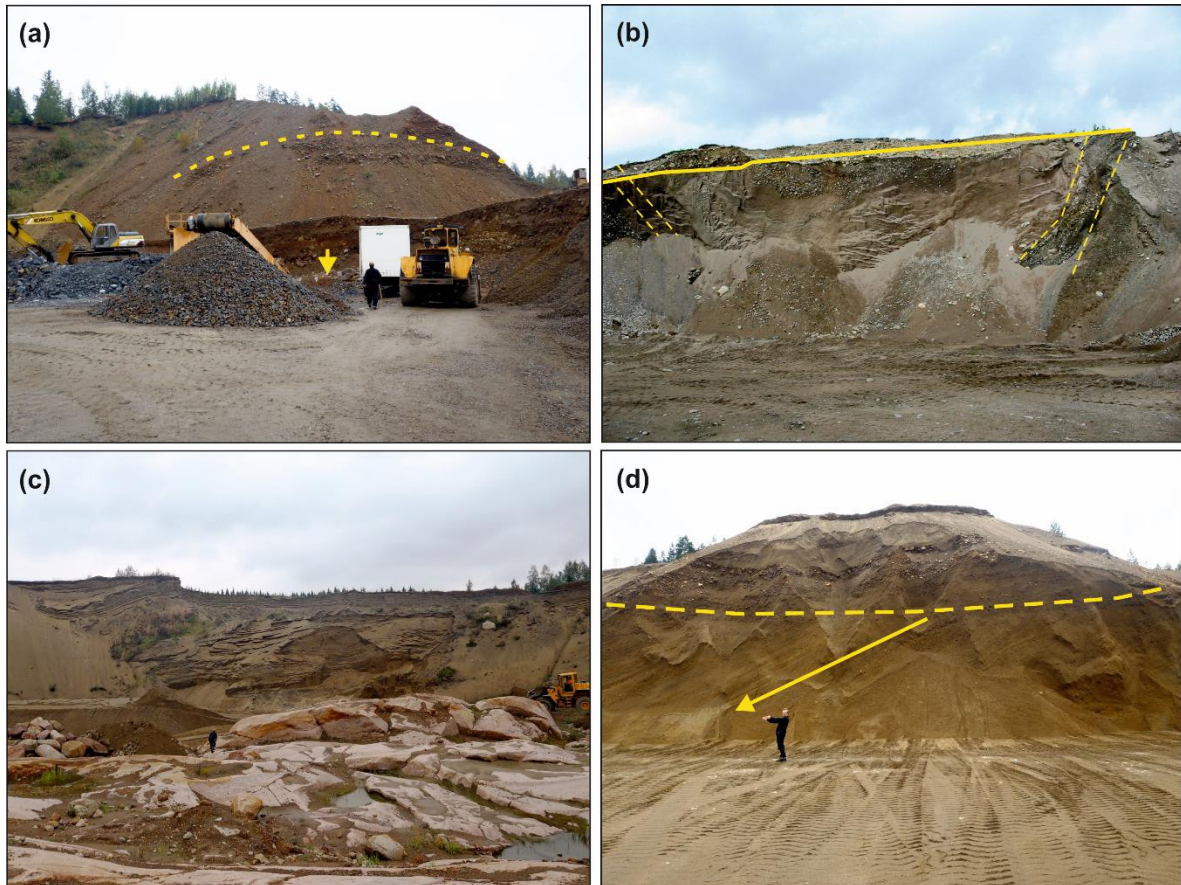
Figure 4. The sedimentological interpretation showing the main depositional and hydrogeological units, the Taustiala bedrock threshold and the GPR (100 MHz + 40 MHz) survey lines (36 km). Groundwater information on the map by Pöyry Ltd. 2011 (modified).

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Figure 5. Pit exposures of the depositional units within the Isokangas – Pälkäne esker system: (**a**) Exposed esker core (dashed line) on bedrock (arrow) to the SE of the study area; (**b**) hidden kettle hole with steep margins and numerous faults in the middle (shore erosion limit by solid line); (**c**) deltaic sediments over exposed basement rocks to the NW of the study area; (**d**) delta foresets (arrow) and horizontal topsets (dashed line). Photographs by E. Ahokangas.

3.1.3. Esker deltas or deltaic enlargements

The esker core is connected with 7 repeated ice-marginal deltas or deltaic enlargements with spacing of about 500 m (Figures 4 and 5c). These deltas exhibit the changing position of the ice margin during the deglaciation and the main palaeoflow direction is indicated by large-scale foresets (Figure 5d). The level of the deltas indicate the highest shore of the area at 150-155 m a.s.l (Eronen and Haila 1990). The delta margins are heavily eroded by shore processes.

The proximal part of the deltas close to the esker core contain coarser material than the distal side and thus locally widen the zone of higher hydraulic conductivities. The proximal side is also associated with thicker esker deposits due to enlarged ice-marginal tunnels. The eastward directed deltaic enlargements on the NE side of the esker at 125-135 m a.s.l. contain till-like deposits several metres thick that probably represent debris flows associated with coarse-grained deltas. The deltaic deposits are also largely eroded by shore processes as indicated by the adjacent kettle holes filled with extensive shore deposits that are well visible in GPR data (Figure 8).

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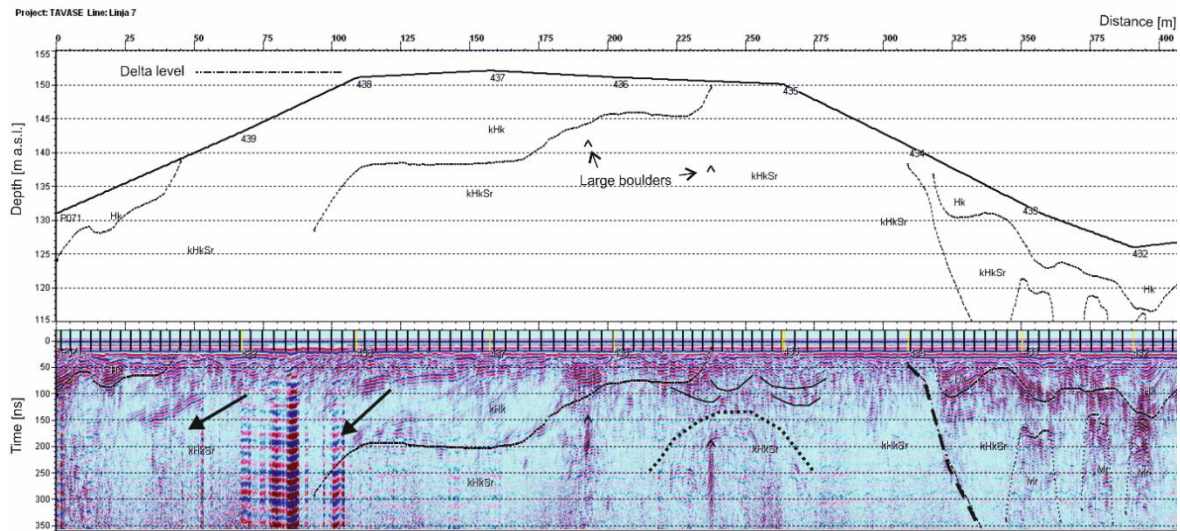
Figure 6. GPR profile transverse to the esker system within the infiltration rake area. Note the esker delta deposits with foresets (arrows) to the SW, the esker core (pointed line) overlain by crevasse deposits (trough-shaped sets by solid lines) in the middle, and the steeply dipping (dashed line), deformed beds of the kettle hole at right (NE side). The profile image is corrected for topography in the line drawing above the image. GPR image by Geo-Work Ltd.

3.1.4. Fine-grained sediments of esker margins

The margins of the esker (areas outside the outermost kettle holes) and related deltas are fringed with fine sand to silt and clay deposits that were deposited in proglacial water. These fine-grained deposits are located closer to the esker on the western side of the complex, whereas in the eastern side they are further away from the esker ridge due to the mostly eastward deposited deltas. The western side also has clay-silt layers close to the land surface and are holding perched groundwater. These sediments weaken the radar impulse and restrict penetration depths at the margins of the esker system, but are not a relevant factor for the groundwater modeling.

3.2. Hydrogeological properties

Groundwater levels were monitored both in the infiltration and recovery areas. The maximum drawdown in the recovery area was 1.5 m in the observation wells at 30 - 50 meters distance from the pumping well K3. The increase of groundwater level in the recharge area was 2–3 m. The maximum increase of 3 m was monitored in the close vicinity of infiltration well IK1. Stable groundwater levels were achieved with different infiltration rates in the recharge area. Generally, the changes in groundwater levels were slightly smaller than were anticipated. Examination [Geosigma Ltd., unpublished] of the results from the various observation wells showed that tracer transport seems to occur about as expected along about 2/3 of the distance between the infiltration area and the pumping wells, as indicated by breakthrough data (not shown) from observation wells 104, 370, 273 and 340.

Both groundwater head monitoring data and the tracer test results were used in combination with sedimentological studies to evaluate the hydrogeological properties of the esker. The esker complex is divided into 2 main hydrogeological subareas by the Taustiala underground bedrock threshold transverse to the esker trend (Figures 4 and 9). Towards the NW bedrock is widely over 90 m a.s.l., whereas to the SE bedrock surface drops to 60-80 m level. Groundwater flows over the threshold with a 2-3 m drop in groundwater levels. Preferential flow path is along the main esker core towards the SE until the bedrock threshold, where groundwater observation well 340 (Figure 1) showed a complex behavior during the tracer test. This might be explained by the contribution of the parallel groundwater flow in the adjacent secondary esker core. The bedrock topography seems to direct this secondary flow path towards the main core. As supported by the tracer test results (see

318 examples in Figure 7), the bedrock threshold divides the groundwater flow into 2 preferential flow
319 paths:

320   1.   Main flow along the esker cores between Boreholes 297-295-340-388-130 (Figure 1).

321   2.   Secondary flow first towards the NE between boreholes 339-340 and then towards the East
322   via Borehole 251 (Figure 1). After the bedrock threshold there is a flow connection from
323   borehole 251 through the eastern margin esker deltas to boreholes 398-393-385-386-274
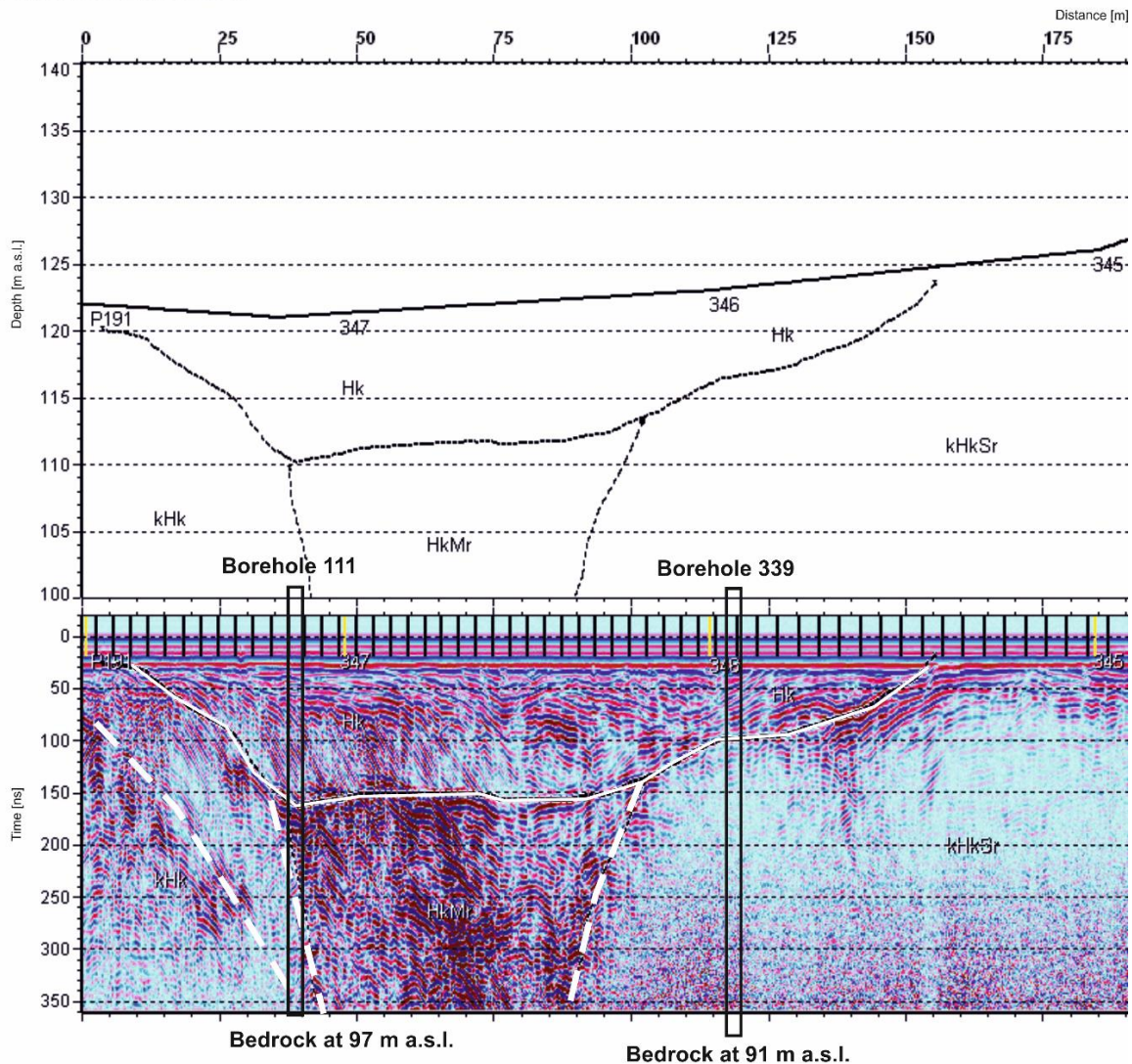324   (Figure 1).
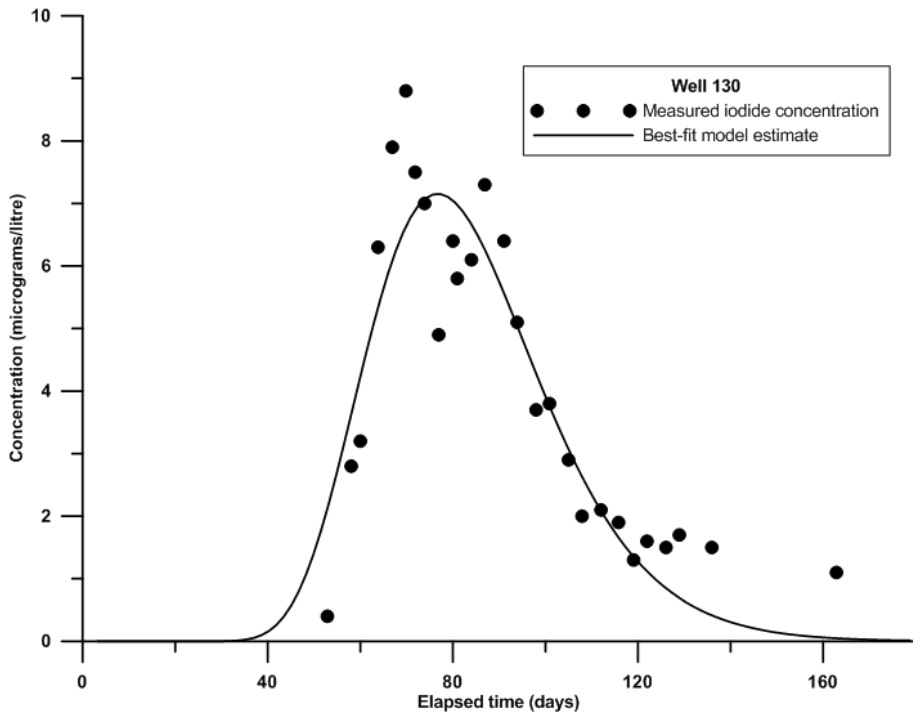
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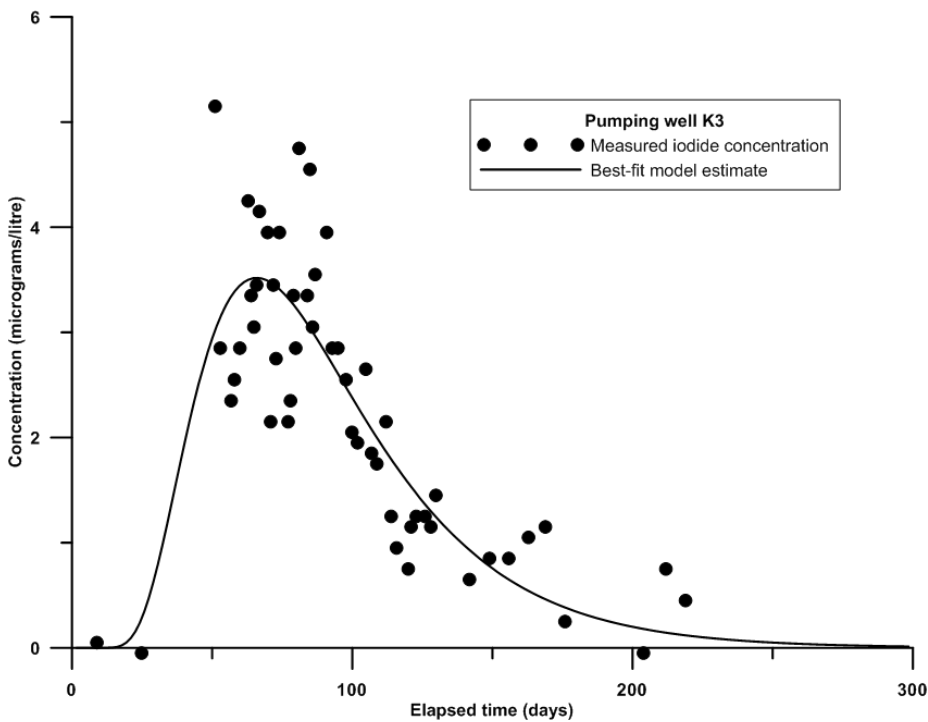
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327   **Figure 7.** Examples of tracer breakthrough curves from observation well 130 and pumping well K3.
328   Curves by Geosigma Ltd.

Figure 8. GPR profile across a large kettle hole from NW to SE. Note shore infill with cross-beds
(above solid white line) and the deformed sediments with steeply dipping margins outlined by
dashed lines. Borehole 111 ends in bedrock at the bottom of the profile. GPR image by Geo-Work Ltd.

Average residence time for groundwater flow from the infiltration area to the Taustiala bedrock
threshold along the esker core was 47 days based on borehole 340. The hydraulic conductivity of the
core is 700 – 800 m/d (8×10^{-3}...9×10^{-3} m/s). Pumping of the infiltrated water was from wells K3 and K4.
Both wells showed good specific yields (well K4 approximately 6000 m^3/d with 1 m drawdown, data
not shown), but only 4-5 % of the tracer was recovered. This indicates that the esker core is the main
aquifer and that the large kettle holes (with wells K3 and K4 in them) markedly influence and slow
down the lateral groundwater flow.

Average residence times for the wells K3 and K4 were 84 days and 104 days, respectively. Well
K4 is located within the complex esker delta and kettle hole area on the eastern side of the core,
whereas well K3 is located within more uniform sediment conditions closer to the coarse-grained
core along the groundwater flow direction. Taking into account the high specific yield of the well K4,
the lowering of the groundwater level at the beginning of the test was higher than expected. It seems
that the kettle holes restrict the flow to some extent. This is also verified by the tracer test results
indicating 23 days longer residence time and minor recovery for the well K4. Later, the well started
more effectively to collect the infiltrated water. However, at this stage most of the tracer was already
passed along the high-conductivity esker cores as observed in downstream boreholes.
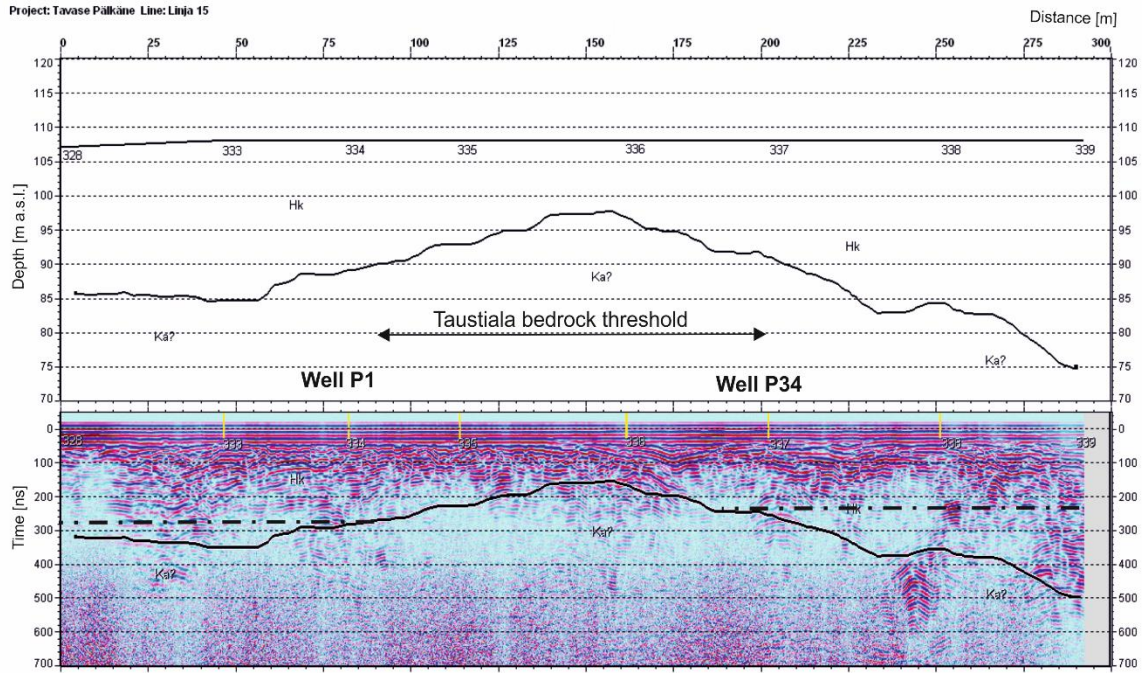
Figure 9. GPR profile over the Taustiala bedrock threshold in the eastern side of the esker system with two private wells P1 and P34 showing 3 m difference in the groundwater levels (dashed lines) along about 100 m distance. Bedrock surface by solid line. GPR image by Geo-Work Ltd.

Based on the hydraulic conductivity measurements (Packer test), the conductivity decreases relatively fast outside the esker core as indicated by the well K3 with value of 300 m/d (3.5×10^{-3} m/s). Near the margins of the esker system (boreholes 128, 131 and 293), the conductivities drop to 10 - 15 m/d (1.1×10^{-4} m/s - 1.7×10^{-4} m/s). The synthesis of the sedimentological and hydrogeological data imply that the groundwater discharges to the south of well K3 towards the lake with several marginal springs as implied by the tracer test results while the main flow is towards the Syrjänharju delta, where the two parallel esker cores join the delta system.

3.3. Groundwater flow model

The 7-layer groundwater flow model is able to reproduce natural groundwater levels, flow paths and residence times. However, the modeling has uncertainties in some parts of the margins of the model area due to lack of detailed data coverage. Several water production simulations were run with the model and the results prove its functionality during the infiltration conditions.

4. Discussion

The sedimentological characterization and the more accurate data on the influence of the Taustiala bedrock threshold are well in accordance with the infiltration and tracer test results, and enabled the definition of the main hydrogeological units and hydraulic properties for the groundwater flow modeling. A similar sedimentological approach has been successfully applied for the glaciofluvial Virttaankangas MAR plant that has a capacity for 100 000 m³/d and provides drinking water for the Turku city district with 300 000 inhabitants (Artimo et al. 2003; Mäkinen 2003b; Artimo et al. 2010).

The main findings of the research are:

1. The NW bedrock threshold and the associated groundwater divide proved to persist during the highest infiltration volumes.

376   2.   The Taustiala bedrock threshold in the middle of the area divides the area into 2
377   hydrogeological parts and shows a complex groundwater flow over it. Therefore, the MAR
378   design had to be rearranged based on the groundwater flow model simulations.

379   3.   The pumping wells K3 and K4 are located in kettle hole structures on both sides of the
380   esker core (high hydraulic conductivity) and they markedly restrict the groundwater flow
381   lateral to the core. On the other hand, this enables longer residence times (Artimo et al.
382   2010).

383   4.   The discharge along the esker core out from the MAR plant area and lake marginal spring
384   discharges can be controlled by the infiltration and pumping adjustments based on
385   groundwater flow model simulations.

386
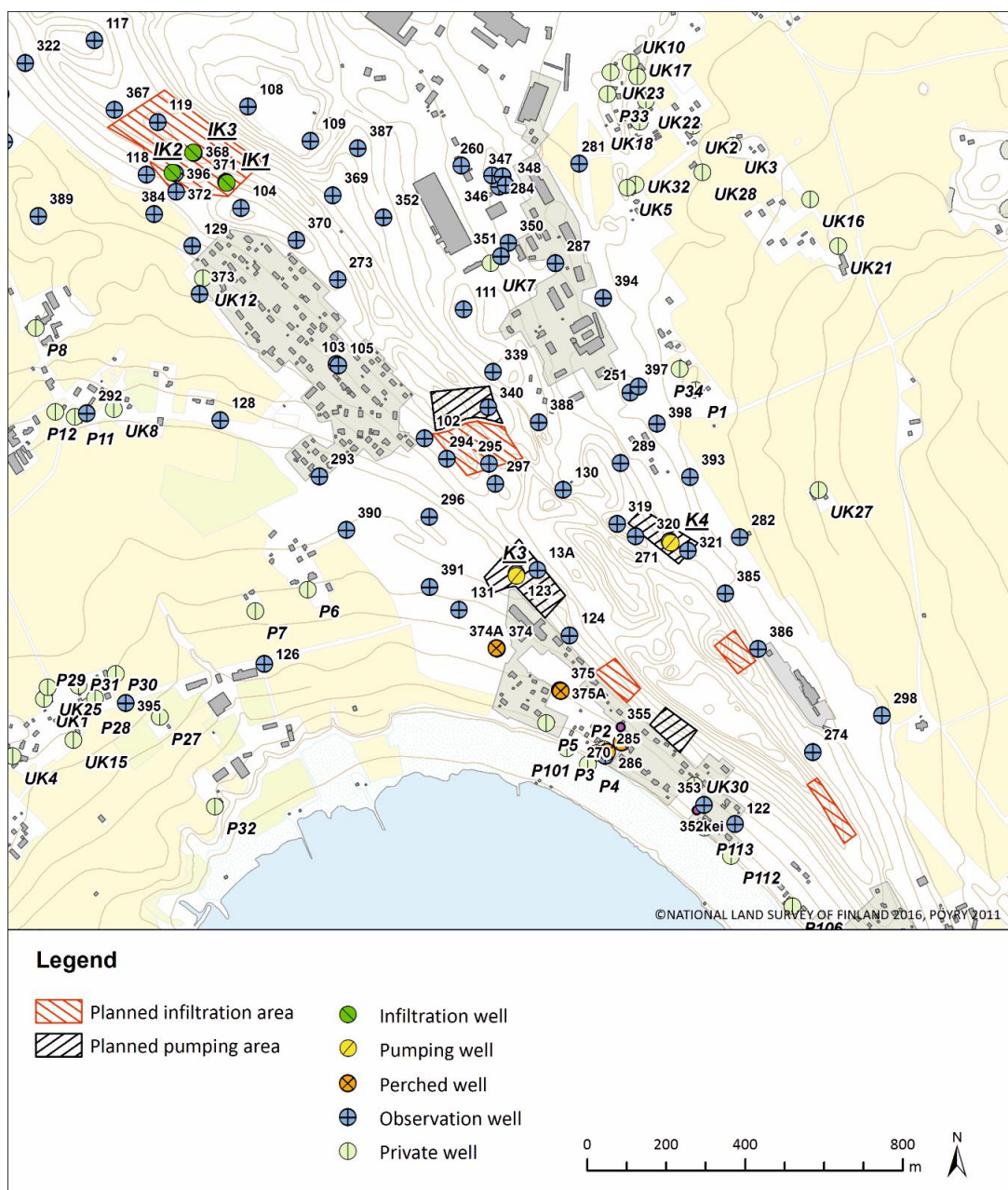
387

388   **Figure 10.** Final MAR design based on the research results and groundwater flow modeling.
389   Groundwater information on the map by Pöyry Ltd. 2011 (modified).

390   The research results indicate that the preliminary MAR design with infiltration only to the North
391   of the Taustiala bedrock threshold and pumping to the South of it, is not possible for the planned
392   capacity of 20 000 m^3/d. The simulations by the groundwater flow model show that the threshold and
393   the area towards SE of it must have additional infiltration. Otherwise the groundwater level will sink
394   too much immediately to the SE of the bedrock threshold. Furthermore, the volume of the original
395   infiltration site can be reduced, which also further ensures that the northern bedrock threshold is not
396   overflowing during the full MAR capacity. The preliminary infiltration and pumping sites are
397   preserved, but new sites are needed for the SE side of the Taustiala bedrock threshold.
398   The new MAR design is planned to consist of infiltration and pumping sites that are lined in the
399   direction of the groundwater flow (Figure 10). This arrangement using new downflow-side
400   infiltration areas enables creation of inverse gradients for the area to the SE of the pumping wells K3
401   and K4. It also provides longer residence times and higher discharges within the same area. The
402   residence times, calculated and visualized by model simulations (MODFLOW, PM-PATH), will be
403   around 6-10 weeks with some variation between the pumping sites. The area close to well K3 holds
404   better possibilities for groundwater production for there the groundwater discharges are first
405   directed towards the SW. The last infiltration site should be located further SE from the Syrjänharju
406   delta in order to prevent the groundwater flow along the esker core towards the town of Pälkäne.
407   The final MAR design (Figure 10) eliminates the effect of discontinuities in the hydraulic
408   connections along the Taustiala bedrock threshold and gives better possibilities to regulate
409   groundwater levels and discharges towards the large lake in the South. The 7-layer numerical
410   groundwater flow model reliably explains the observations made during the research. It is applicable
411   in infiltration conditions and can be used for MAR simulations.

412   **5. Conclusions**

413   The sedimentological characterization using GPR as a key method was able to describe the complex
414   structure and related groundwater flow paths over the bedrock threshold as well as to explain the
415   poor recovery of the NaI during the tracer test. It also managed to estimate the distribution of
416   hydraulic conductivities for the groundwater flow model that is applicable for reproducing the
417   observed groundwater levels and discharges during the natural conditions as well as during the
418   infiltration test. The 7-layer groundwater flow model indicates that preliminary MAR design should
419   be rearranged and that the flow model is able to simulate MAR operation for planned volume of 20
420   000 m^3/d.

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