OÜ Inseneribüroo STEIGER

Hydrogeological studies and groundwater modeling for the Paldiski 500 MW Pumped Hydro Energy Storage Project in the Republic of Estonia

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1. INTRODUCTION

Energiasalv Pakri OÜ (hereinafter EP) (address: Regati puiestee 1, Tallinn, 11911 Harju county, register code: 14107173) wishes to obtain the building right for the construction of the planned Pumped-Hydro Energy Storage (PHES) in the city of Paldiski. Permit applicant ordered from Engineering Bureau STEIGER (STEIGER), address: Männiku tee 104, 11216 Tallinn, register code 11206437 hydrogeological studies with a hydrogeological model (hereinafter investigations) to describe the baseline situation and assess the effects of shaft construction on groundwater levels.

EP plans to build a 500 MW PHES on the Pallase 16 and 18 properties and to build a 2.6 ha artificial island and water intake in Paldiski Bay to supply the station with water per the solution proposed by detailed planning. Reservoirs, water intake inflow channel, turbine room, entrance shaft, ventilation, and cable shafts and access tunnels shall be planned underground, approximately at the depth of 500-750 m from the ground surface inside the rocks of crystalline basement. During the construction of shafts, the excavation works intersect through sedimentary bedrock where three: Silurian-Ordovician (S-O), Ordovician-Cambrian (O-Ca) and Cambrian-Vendian (Ca-V) aquifer systems can be distinguished. O-Ca and Ca-V aquifer systems provide water supply for the PHES neighboring households and industries. The public water supply of the city is mainly based on the Ca-V aquifer system. Therefore, the possible impact of construction work on local water supply, including groundwater level and quality needs to be assessed with special diligence.

Hydrogeological model and the conclusions based on the model, analyze the potential impacts of the proposed activity on the groundwater level in different construction scenarios. In connection with the planned activity, hydrogeological and geophysical studies were performed, and the groundwater model was built.

The report is based on the hydrogeological site works conducted by STEIGER, correspondence with EP, public databases and information sources, which are presented in the text of the report under the chapter “Used literature” with corresponding references.

2. GENERAL DESCRIPTION

2.1. Location

The area of the investigations is situated on the Estonian northern shore on the limestone plateau between Paldiski and Lahepera gulf, on the southwestern side of Pakri Peninsula (Figure 1).

The planned PHES underground structures will be located at an average distance of 900 m from the western shore of the peninsula (the western boundary of the Pallase territory is approx. 700 m and the eastern boundary approx. 1200 m). An intake structure in the Baltic Sea will be located on an artificial island approximately 150 m to northwest from the Paldiski harbor and a few dozen meters from shore. The location of the planned pumped hydroelectric power plant-related infrastructure is shown in Figure 1 marked with a red line. To the west, the area is bordered by the railway, to the north by the Paldiski logistics park and private houses, to the east by private houses, and to the south by the territory of the Estonian Defense Forces.

Figure 1. Paldiski Peninsula with the location of the planned PHES (marked in red) (Estonian Land Board Geoportal)

2.2. Landscape and landforms

The Pakri Peninsula is about 12 km in length, the average width is 5 km and the area of the peninsula is about 40 km^2. Absolute elevation of the ground surface on Pakri Peninsula is 31 m at its highest point. The bedrock cliff curves over a large part of the peninsula, being steeper between the city of Paldiski and Cape Pakri, partly buried and more terraced on the beach of Leetse (Tõnisson and Sivadi, 2008).

On the northern coast of the Pakri Peninsula cliff with a height of 24 - 25 m is prominent and at some points descends directly into the sea. Heading southeast, the cliff moves inland from the shoreline and provides space for a few meters of a wide rubble slope with

a bank forest and a stepped beach strip. Kersalu cliff is buried under the sand completely (Arold, 2005).

The special feature of the landscape is created primarily by the proximity of the sub-horizontal carbonate bedrock to the ground and therefore the dominated by limestone plains with hop vegetation cover moraine plains with grit, arable land and deciduous forests in the landscape structure. The landscape is articulated by hills, limestone hillocks covered with alvars, and wet areas in the carved hollows. In the higher parts of the limestone plains (alvars) near the cliff with very thin limestone-based soils, dry out in the summer and are therefore stunted but species-rich (Arold, 2005). Based on Estonian Land Board Geoportal, most dominating soil types on the planning area are peat soils, calcareous loam soils, and patches of lowland soils.

As the thickness of the Quaternary sediments is very small, the modern topography reflects the relief of the bedrock in quite good detail. The latter is a limestone plateau that descends to the southeast. The elevation of the bedrock surface decreases from 22 - 25 m at the top of the peninsula to 10 - 12 m in Kersalu. In the middle of the peninsula, the bedrock rises to 25 m above sea level, forming an elongated hillock in the northwest to the southeast direction (Figure 2), which is bounded on the northeast partially also on the north by a terrace. This is caused by the contact of relatively soft Kukruse and hardened carbonate rocks of the Idavere Stage (Kink, et al., 1996ab). To the west of this hillock on a plain, the construction of the PHES is planned. The area of the proposed activity and under-ground facilities is relatively flat, with a slight slope to the west (seaward). The height of the ground above sea level is between 13 - 20 m.

Figure 2. Topographical map of the peninsula with PHES area marked with red lines (Estonian Land Board Geoportal)

3. SURFACE WATER

Surface water as the most mobile part of the landscape best reflects its condition. Across the Pakri Peninsula, the interaction between groundwater, surface, and soil water is very similar, as the unconfined aquifers are mostly weakly protected or unprotected. When groundwater levels fall, surface water infiltrates from the streams and ponds into the groundwater, and surface water bodies dry up. Only in front of the Paldiski cliff, the seeping groundwater feeds the surface water. The peculiarity of the Pakri Peninsula is that most of the surface water runoff is not groundwater, but so-called vadose water (Perens and Häelm, 2011).

The Pakri Peninsula is "cut off" from the mainland by the Vasalemma River flowing into Pakri Bay, Klooga Lakes, and the Otu (Tuulna) Stream, which flows into Lahepere Bay (Figure 3). Therefore, no rivers or springs are flowing through the peninsula, and the surface water consists only of rainwater (Kink, 1996).

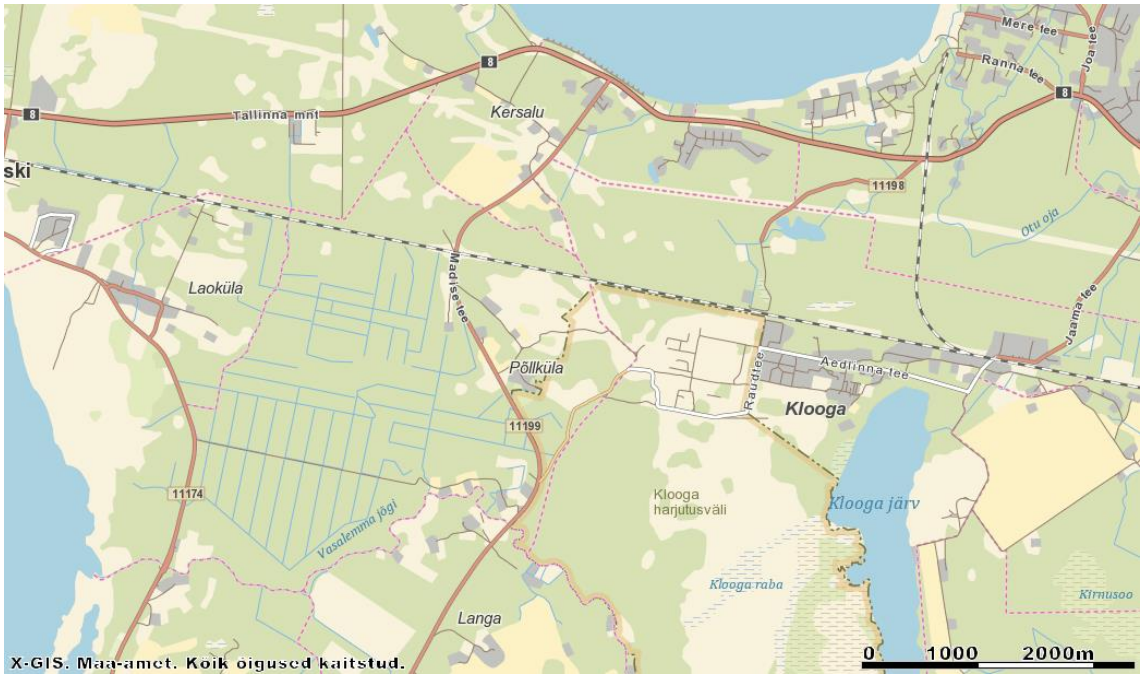

Figure 3. River, lake and stream network at the base of the peninsula (Estonian Land Board Geoportal)

There are few lakes/ponds on the plateau (Arold, 2005). Most of the ponds are man-made and on private land (Figure 4).

The surface water flow network consists of short streams and ditches of 1 - 2 km long, with a small catchment area. The density of the water network is low – 0.2 - 6.0 km/km^2 (Kink, 1996). The low density of the water network is due to the karst and fissure systems of the carbonate rocks that form the upper part of the bedrock. Rainwater infiltrates quickly into groundwater. Human activities have also contributed to quick infiltration such as quarrying, trenching, and various excavations (Kink, 1996).

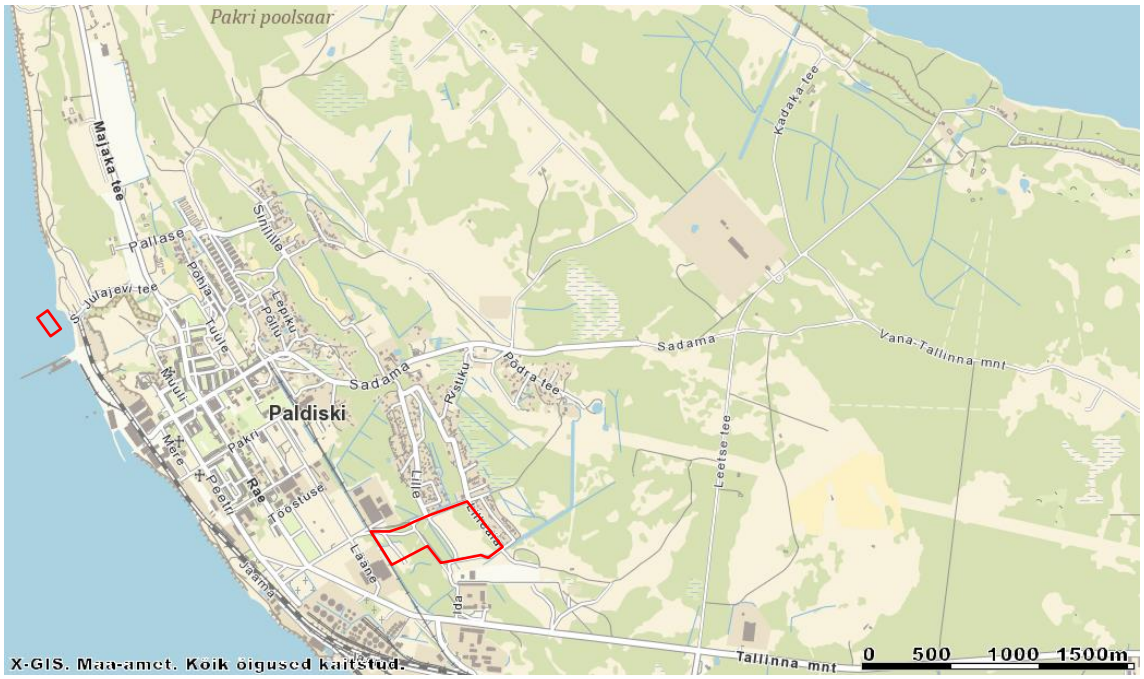

Figure 4. The surface water and water flow network of Pakri Peninsula (Estonian Land Board Geoportal)

The northwest to southeast water drainage divides the peninsula into three drainage basins (Figure 5) as follows: Lahepere, Laoküla, and Paldiski Bay drainage basins (Kink, 1996).

The area of the Paldiski Bay catchment area is 16.59 km^2. This catchment area includes the coast of Paldiski Bay from Pakri Lighthouse to Laoküla ditch. Groundwater protection in this area is variable. The catchment area is covered with forest and shrub, alternating with alvar pastures. In some places, rapidly infiltrated precipitation water opens at the foot of the cliff as small springs. There are no significant natural surface water bodies in the Paldiski Bay drainage basins (Kink, 1996). The main watercourses in the Paldiski Bay catchment area are drainage ditches, some of which also act as sources of groundwater supply. In most cases, the depth of the ditches is 0.5 - 1.0 m.

The area of the Lahepere Bay catchment area is 10.58 km^2. The catchment area includes the coast of Lahepere Bay from Pakri lighthouse to Kersalu village. The catchment area is covered with scattered bush and forest vegetation. Most of the area is a meadow. The groundwater in the whole catchment area is unprotected (alvars, quarries). The bedrock is covered with 1 - 2 m thick sand or loam (Kink, 1996).

The area of the Laoküla catchment area is 6 km^2. Surface waters flow into Paldiski Bay through the Laoküla ditch (Kink, 1996).

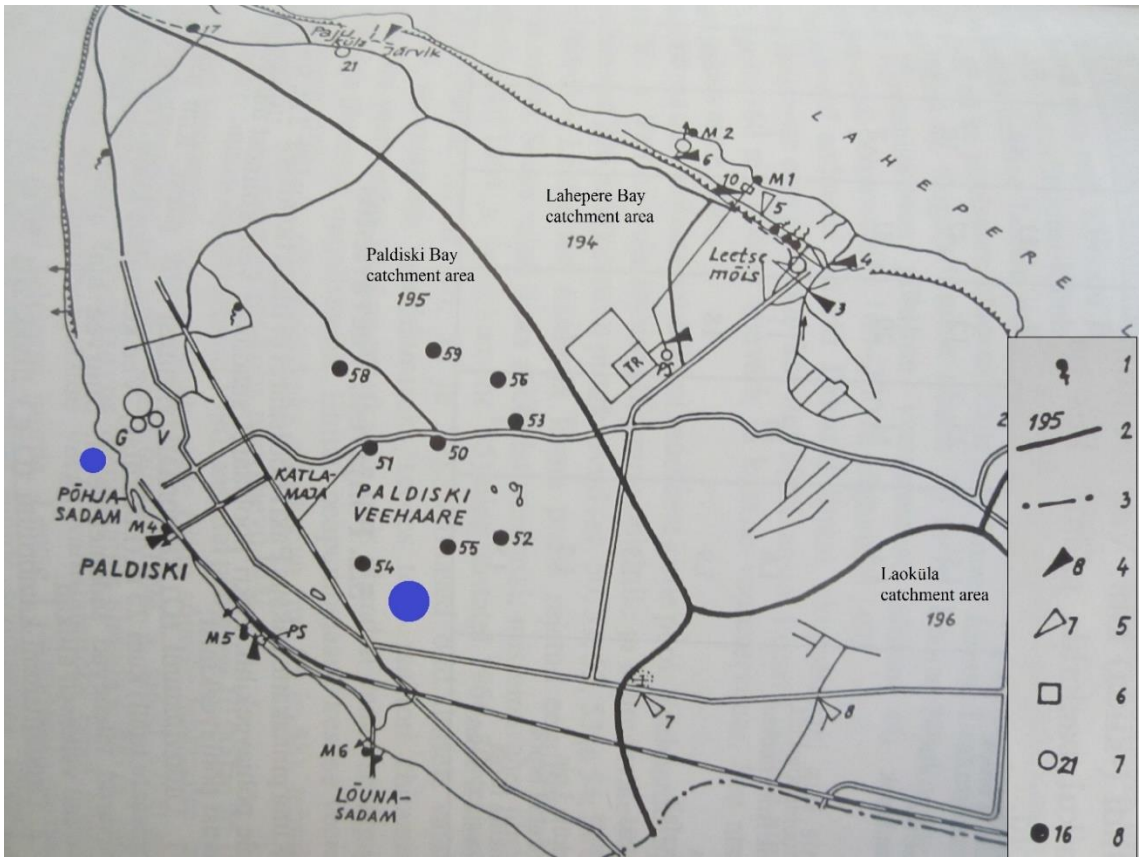

Figure 5. Drainage divide of Pakri peninsula. 1 - spring; 2 - number and border of drainage divide; 3 - the boundary of the territory of the former army; 4 - surface water monitoring point; 5 - surface water measuring point; 6 - bucket well; 7 - O-Ca borehole; 8 - Ca-V borehole (Kink, 1996). Big blue dots represent the PHES area.

The Pakri Peninsula has less than half of the catchment area between the Laoküla ditch and the Vasalemma River. The catchment area on the peninsula has only the upper reaches of the Laoküla ditch, which has practically no water. Thus, it is impossible to monitor the drainage and water composition there. In the catchment area, groundwater is unprotected or poorly protected (Perens and Häelm, 2011).

4. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

To describe the extent of the aquifers/aquitards and to obtain geological layering input for the model, the following wells and boreholes were used:

- For the Ordovician layer, O-Ca and Ca-V well No. 542, 541, 52342, 1118, 1144, 534, 540, 547, 586, 1603, 1636, 19885, 11372, 55707, 51759, 50694, 1190, 55798, 50594, 55064, 19885 and boreholes PAL-Well_1, PAL-Well_2, and PAL-1 drilled by STEIGER as part of the project were used (Figure 6).
- For Ordovician-Cambrian aquifer system, O-Ca wells No. 542, 541, 52342, 1118, 1144, 534, 540, 547, 586, 1603, 1636, 19885, 11372, 55707, 51759, 50694, 1190, 55798, 50594, 55064, boreholes PAL-Well_1, PAL-Well_2, and PAL-1 and an O-Ca well No. 545 extending into the Lontova claystone were used (Figure 6).
- For Cambrian-Vendian, wells No. 542, 541, 52342, 1118, 1144, 534, 540, 547, 586, 1603, 1636, 19885, boreholes PAL-Well_1, PAL-Well_2, and PAL-1 and an O-Ca well No. 545 extending into the Lontova claystone were used (Figure 6).

The use of other historic wells was hampered by vague geological boundaries defined in the well log records or misinterpretations that may have resulted from the used non-coring drilling method.

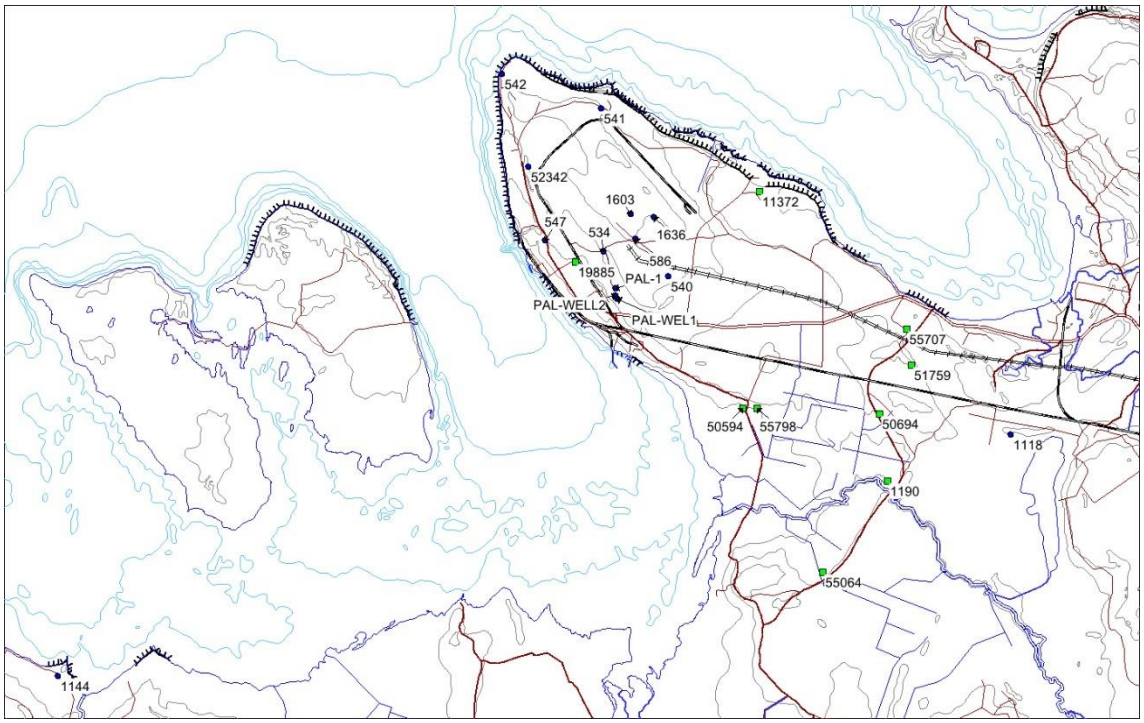

Figure 6. Location of wells that were used to obtain data for geological input

Vertical placement and thicknesses of the aquifers and aquitards based on PAL-1 core logging and geophysical downhole logging results is presented in Figure 7. More detailed geological log of PAL-1 is presented in Appendix 1.

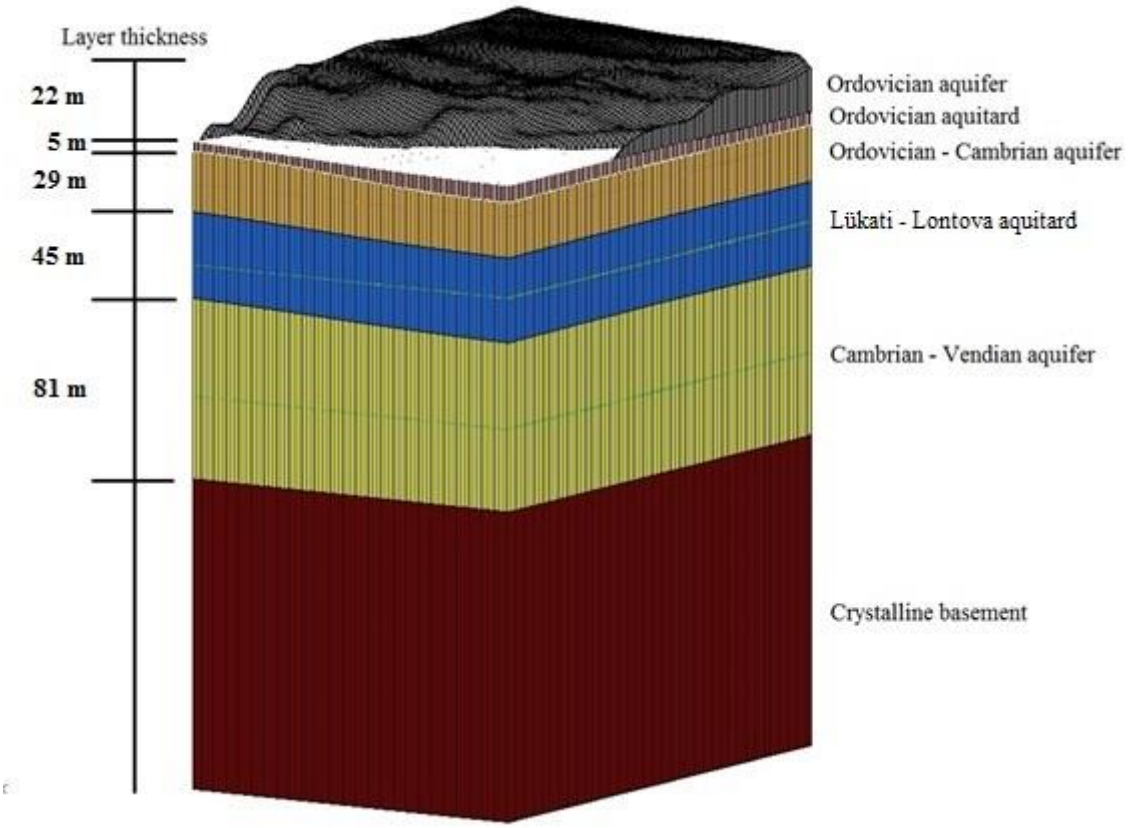

Figure 7. Hydrogeological cross-section of Paldiski including layer thicknesses based on PAL-1 core logging (Appendix 1) and geophysical studies done by STEIGER

4.1. Water in the Quaternary Cover

The biggest disadvantage of the Quaternary deposits is its low groundwater pollution tolerance. The Quaternary sediments are a regulator for infiltrating precipitation for the deeper Ordovician and Ordovician-Cambrian aquifer systems. Most of the aquifers described below have no significant groundwater supply (Suuroja et al., 2010).

The Technogeneous deposits (tQIV) layer is primarily related to the military construction of the Pakri Peninsula. Soil piles up to a few meters thick are usually waterless (Suuroja et al., 2010).

The marine deposits (mQIV) without significant groundwater supply spread sporadically. The hydraulic conductivity of the sands is less than 10 m/d (Suuroja et al., 2010).

The glaciofluvial deposits (fQIII) are not used for water supply. The hydraulic conductivity of layered textured sands is 2 - 5 m/d, reaching tens of m/d for gravel sands. The thickness of the water layer is mostly 1.5 - 2 m (Suuroja et al., 2010).

Glacial deposits (gQIII) that are sporadically water-bearing, are practically not used for water supply. Groundwater in glacial deposits is usually pressurized. The moraines are usually water-poor, and the hydraulic conductivity of the moraine is 0.05 - 0.5 m/d. In the area in front of the cliff, the moraine can be considered as a relative (weak) aquitard as

the sediments have very low permeability. Hydraulic conductivity reaches 10^{-3} m/d in sandy loam moraines (Suuroja et al., 2010).

The PHES area of the Pallase area 16 and 18 properties is covered by a 0.3 - 2.5 m thick layer of Quaternary gravel. Gravel has a predominant particle diameter of 2 to 64 mm with a finer and/or coarser fraction <50% of the sediment volume (Aaresild, 2013).

In the hydrogeological model, the Quaternary cover is not considered separately and is included in the Ordovician aquifer system due to the small thickness of the layer.

4.2. Ordovician aquifer system

In the Ordovician aquifer, the distinction between aquitards and aquifers has been abandoned because the water content of these carbonate rocks depends mainly on fissures and not on their lithology, so Ordovician aquifers are considered to be as one unit. Both fissures and the karst cavities are sporadically presented in Ordovician carbonate rocks. (Suuroja et al., 2010) The thickness of the weathering zone at the contact with the Quaternary sediments is thin, usually between 1 - 3 m (Perens and Häelm, 2011).

The first stage from the ground is the limestone of the Lasnamäe Stage that is characterized as light gray, small, and fine-crystalline, mostly medium-layered and flat. The limestone of the Lasnamäe Stage, as well as the Aseri and Kunda Stages, containing iron ooids, is suitable to produce gravel. Volkhov Stage consists of green calcareous sandstone and glauconite sandstone, and the underlying Latorp stage consists of laminated clay (Appendix 2) (Viru et al., 2009).

The aquifer is practically unconfined everywhere. The water level is predominantly 1 - 2 m from the ground. The thickness of the unsaturated zone often exceeds 1 m and, in some cases, reaches 6 m in the southern part of the peninsula. The specific capacity rate for boreholes, based on existing wells, varies between 0.015 and 2 l/s×m, with predominant values of up to 0.5 l/s×m. The average lateral hydraulic conductivity of the aquifer forming carbonate rocks is 8.1 m/d (Perens and Vallner, 1997) and the transverse hydraulic conductivity is 5 times lower. In most of Estonia, the total transmissivity of the Silurian-Ordovician aquifer system usually varies between 100 - 500 m^2/d, depending essentially on the distribution of zones of tectonic disturbances (Perens and Vallner, 1997).

4.3. Ordovician Aquitard

The Ordovician regional aquitard consists of limestones, marls, siltstones, glauconite sandstone, claystone, and argillite of the Latorp Stage (Toila Formation and Leetse Formation), Varangu Formation and Pakerort Stage (Türisalu Formation). The limestone and sandstone of the Latorp Stage, the micro-layered claystone of the Varangu Formation, and the dark brown argillite of the Pakerort Stage form a firm aquitard between the unconfined Ordovician aquifer and the Ordovician-Cambrian aquifer below (Perens and Häelm, 2011). The Türisalu Formation, with a thickness of 3 - 4 m, has the best sealing properties. Hydraulic conductivity of the rocks is very variable: the lateral conductivity changes between 0.001-1 m/d, the transversal conductivity ranges from 10^{-7} to 10^{-5} m/d. (Perens and Vallner, 1997).

4.4. Ordovician-Cambrian aquifer system

The Ordovician-Cambrian aquifer system (O-Ca) spreads in most of the area, being the first unconfined aquifer from the ground only in front of the cliff. The aquifer consists of fine-grained sandstone and siltstone of the Lower Ordovician Kallavere Formation and the Lower Cambrian Tiskre Formation. The thickness of the aquifer system is 20 - 60 m (Perens and Vallner, 1997). Groundwater recharge takes place on limestone highlands through openings in the Ordovician aquitard. The aquifer is confined, being unconfined only in the opening area and near the cliff (Suuroja et al., 2010).

The water level is predominantly 13 - 26 m from the ground. Filtration properties of the aquifer forming rocks are consistent: lateral hydraulic conductivity is 1 - 5 m/d (Suuroja et al., 2010), in some studies also 1 - 3 m/d and transverse hydraulic conductivity is 5 times lower (Perens and Vallner, 1997). The specific capacity of the wells is between 0.1 - 0.3 l/s per 1 m lowering of the water table. The median value of the specific capacity of 21 O-Ca historic boreholes in Pakri Peninsula is 0.124 l/s × m. In northern Estonia, the total transmissivity of the Ordovician-Cambrian forming sandstone usually varies between 25 - 50 m^2/d (Perens and Vallner, 1997).

4.5. Lükati-Lontova aquitard

The Lükati-Lontova regional aquitard spreads over the whole area and is represented by siltstones and claystone of the Lükati and Lontova formations (sandy interlayers in the lower part of the Sämi Member of the Lontova Formation can be considered as belonging to the Cambrian-Vendian aquifer system). Aquitard consists (from bottom-up) of the upper part of Sämi Member, Kestla Member of the Lontova Formation (thickness 15 - 20 m), the Tammneeme Member (thickness 10 - 15 m) and the Lükati Formation with a thickness of 18 m. Thus, the thickness of the aquitard is a maximum of 53 m, with a very high insulation capacity. The lateral hydraulic conductivity of the aquitard forming clayey sediments is 2×10^{-6} - 2×10^{-7} m/d and the transverse hydraulic conductivity is usually 10^{-7}-10^{-5} m/d (Perens and Vallner, 1997). Based on the cross-sections of the wells and boreholes in the area, the average thickness of the aquitard is 40 m, being 44.6 m in the PHES area (based on core logging and downhole geophysics).

4.6. Cambrian-Vendian aquifer system

The Cambrian-Vendian aquifer system (Ca-V) lies from the ground between 81 - 177 m and is separated from the overlying O-Ca aquifer by a layer of Lükati-Lontova aquitard consisting of blue claystone that is up to 45 m thick.

The Cambrian-Vendian aquifer system is represented by sandstones and siltstones. As the laminar claystone layer of the Kotlin Formation, which separates the Gdov and Voronka aquifers, wedge out in the western part of Estonia the Cambrian-Vendian aquifer system has been considered to be uniform (Suuroja et al., 2010).

Based on the lithological composition and filtration properties of the rocks, a distinction can be made between the upper Sämi Member belonging to the Lontova Formation and the lower 40 - 50 m thick Kroodi Member belonging to the Ediacaran sediments of the Vendian complex (Suuroja et al., 2010).

The water level is predominantly 13 - 43 m from the ground. The wells and boreholes opening the Voronka Formation (including the lower part of Sämi Member) generally have a smaller specific capacity, mostly 0.2 - 3.0 l/s × m. The median specific capacity is 0.5 l/s × m. The lateral hydraulic conductivity is 0.6-12.5 m/d with an average value of 2 - 6 m/d (Perens and Vallner, 1997) and the transverse hydraulic conductivity is 5 times lower. The specific capacity of the boreholes opening the Vendian Complex (Kroodi Member) is significantly higher - median 1.5 l/s × m (Suuroja et al., 2010). Hydraulic conductivity is 0.5 - 9.2 m/d, average 5 - 6 m/d (Perens and Vallner, 1997) and the transverse hydraulic conductivity is 5 times lower. In Northern Estonia, the total transmissivity of the Cambrian-Vendian forming sandstone usually varies between 100 - 350 m^2/d (Perens and Vallner, 1997).

5. GROUNDWATER USE AND MONITORING

5.1. Groundwater use in Paldiski

Groundwater is obtained from three bedrock aquifers: the Ordovician aquifer, the Ordovician-Cambrian aquifer, and the Cambrian-Vendian aquifer (Perens and Häelm, 2011).

In 1939, drinking and domestic water were consumed from the upper aquifer - Ordovician aquifer system. After the Second World War the main source of water supply for the Soviet army was Ca-V groundwater pumped from a depth of 160 - 200 m and for small consumers water from O-Ca aquifer was used (Kink, 1996).

Very first two Ca-V water supply wells, named G (Cat. No. 537) and V (Cat. No. 547), for civilian use were made in 1952 near the bastion of Peter (Figure 8) (Kink, 1996).

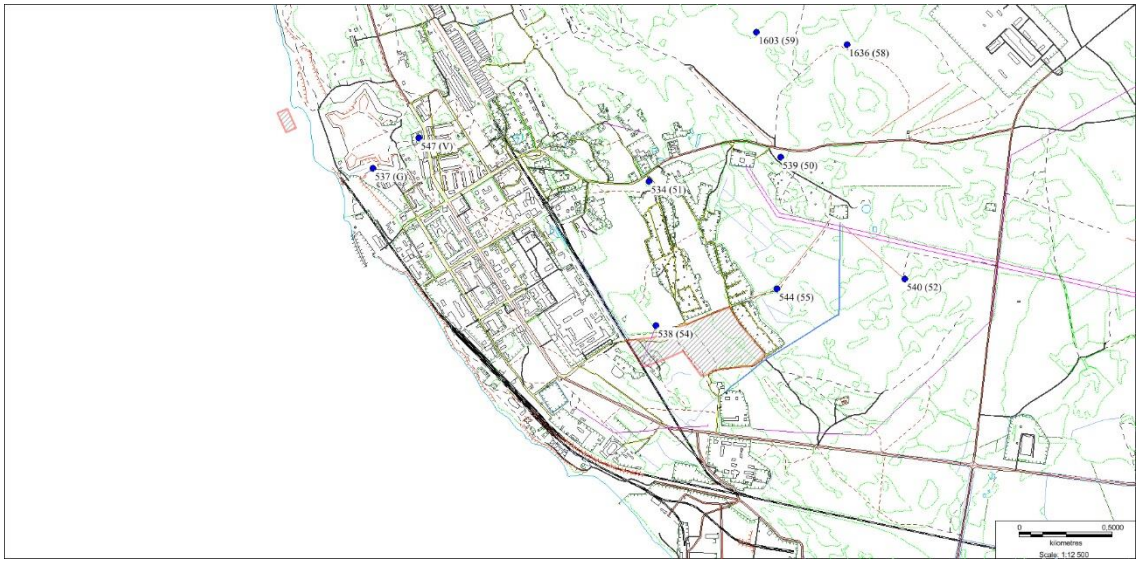

Figure 8. Paldiski city water supply boreholes that are in the modeled area (blue circles)

Today's Paldiski city public water supply wells are located to the east of the city center, 2 km northeast from the railway (Figure 8). The wells were drilled in 1963. Water was needed for the nuclear facility that was built and for the growing city of Paldiski (Kink, 1996).

The first 200 m deep wells No. 50 (Cat. No. 539), 51 (Cat. No. 534), 52 (Cat. No. 540), 53 and 54 (Cat. No. 538) were drilled running parallel to each other as one part of wells was drilled next to Paldiski - Leetse road and the parallel branch to the south from the Paldiski - Leetse road (Figure 8). Thus, two water mains were built in parallel and connected. The system was supplemented in 1964 with well no. 55 (cat. no. 544) and from 1966 to 1986 with 3 more well to the north (boreholes no. 56, 58 (cat. no. 1639) and 59 (cat. no. 1603). The latter was probably necessary to meet the water needs of the nuclear facility in connection with the construction of the second reactor. There was a total of 9 wells in the water supply system. By 1994 two wells were kept in reserve (No.

53 and 58), one was technically defective (No. 53) and six other wells were in operation (Kink, 1996).

To date, the maximum permitted amount of a total of 1575 m^3/d is permitted for the Paldiski water extraction from 7 wells (Ca-V aquifer) (OÜ Entec Eesti, 2015). The wells are No. 539 (No. 50), 534 (51), 540 (52), 538 (54), 544 (55), 547 (V), and 542 (Lighthouse).

Currently, 5 wells are in active use No. 538, 539, 540, 544, and 534. While well No. 547 is kept in reserve (OÜ Entec Eesti, 2015). Specifications about those wells are given in table 1 below.

Table 1. Data of Paldiski water supply active wells and water pumps. (OÜ Entec Eesti, 2015)

Cadaster number	Borehole number	Depth from ground level, m	Ground level, m	Allowed water extraction amount, m^3/h	Maximum flow of water pump m^3/h	Static water level, m	Dynamic water level, m
539	50	200	24.6	45-72	30	-6.4	-13.4
534	51	202	21.0	55-65	30	-7.0	-17.0
540	52	203	20.0	60-70	30	-8.0	-12.0
538	54	210	17.5	40	30	-7.5	-13.5
544	55	203	20.5	40	30	-3.5	-8.5

Water supply wells No. 1639 (58) and 1603 (59) have been preserved and are not in use, while borehole No. 537 was tamped in 1996 (OÜ Entec Eesti, 2015).

Water extraction records have been kept since 1975. The city of Paldiski and the nuclear facility consumed 6000 - 10,000 m^3/d of groundwater in the 1980s (Suuroja et al., 2010; OÜ Entec Eesti, 2015). Due to the shutdown of the reactor, the departure of the former Soviet army and the declining population, the city's water consumption in 1994 was dropped to only 3000 m^3/d. (Kink, 1996) By 2014 the extraction rate had fallen to 958 m^3/d, accounting for less than a tenth of Soviet time consumption (OÜ Entec Eesti, 2015).

According to Table 13 of the Water Management Plan chapter “1.7.2 Groundwater supply and extraction”, the groundwater consumption reserve for Ca-V wells in Paldiski has been approved at a total of 4000 m^3/day and the period of use until 2030 (OÜ Entec Eesti, 2015). The groundwater consumption reserve for O and O-Ca wells has not been assigned.

In addition to 5 working water supply wells, there are a total of 5 Ordovician, 24 Ordovician-Cambrian, and 12 Cambrian-Vendian wells near the PHES area and in the Paldiski Bay watershed, as shown in Figure 9 below.

Most important of them are the Cambrian-Vendian wells, especially the Paldiski city water supply wells considering that those are the closest to the PHES area.

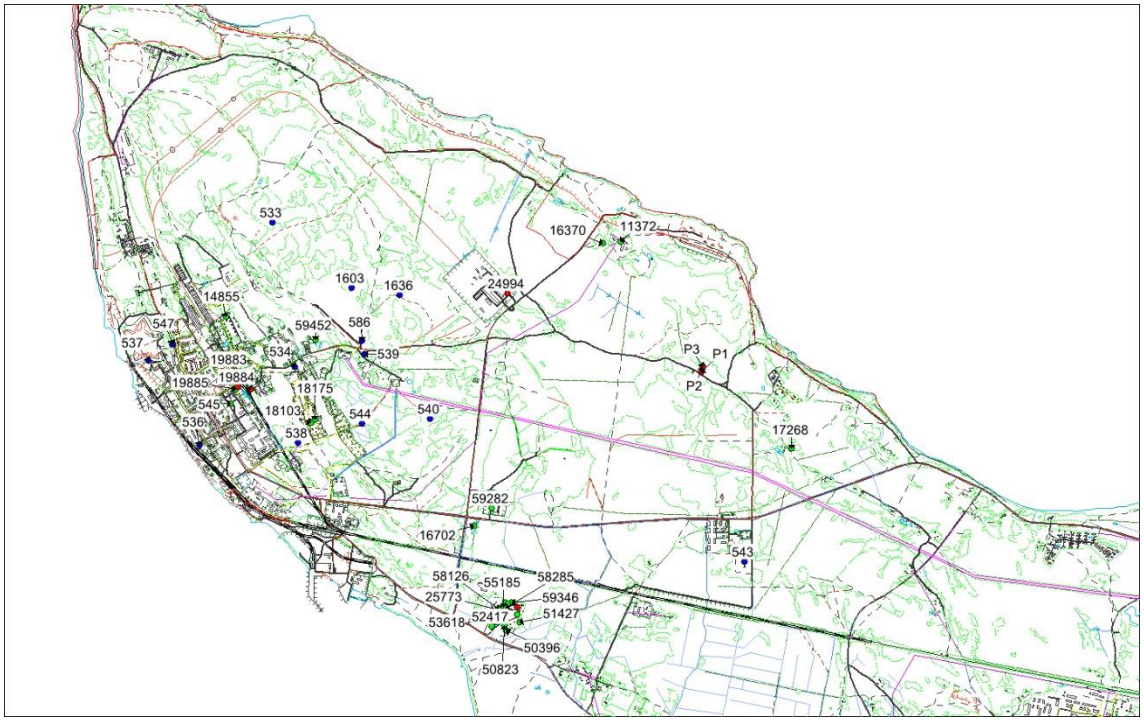

Figure 9. Ordovician (red circles), Ordovician-Cambrian (green circles) and Cambrian-Vendian (blue circles) wells located near PHES area

5.2. National groundwater monitoring network and groundwater level changes

As there are no major rivers or streams on the Pakri Peninsula, no water measuring posts were built there before World War II during the first independence. During the Soviet occupation, the peninsula was closed, and no field measurement data is available (Kink, 1996).

Out of three aquifers, only Cambrian-Vendian wells have been monitored. As previously mentioned, other aquifers are rarely and modestly used. Therefore, there is no data on Ordovician or Ordovician-Cambrian water level fluctuations.

Local water company Lahevesi AS (a company that is supplying Paldiski with water) has been monitoring water levels in public water supply wells but not for collecting data as a groundwater survey (measuring real water level) but as a need to protect submerged pumps from going dry when groundwater level would drop lower then pumps are.

The company has no knowledge of real groundwater levels nor how deep in the well are the sensors nor have they any barometric compensation done for the measured data. This results that the Lahevesi AS monitoring data can not be used as an input for the hydrogeological modeling and the model calibration.

That sums up all the groundwater level monitoring that has been done in the Paldiski peninsula.

6. METEOROLOGICAL OVERVIEW

6.1. Precipitation

The closest weather station (~ 5.5 km) to the PHES area, which collects precipitation data, is the Paldiski weather station. The station is situated at the northern tip of the Pakri peninsula, in the Pakrineeme cordon, where in addition to air temperature, humidity, and air pressure, precipitation measurements are also collected. The height of the observation point from the sea level is 23.12 m, which is roughly at the same height as the PHES in Pallase area. The nearest second weather station is Vihterpalu hydrometry station, which is located significantly farther away (~ 16 km). As such for the hydrogeological model, Paldiski weather station observation data has been used.

Table 2 presents the results of the observations (average, minimum and maximum precipitation) in 1970 - 2003 based on data from the State Weather Service.

Table 2. Results of Pakri precipitation observations in 1970 - 2003 (State Weather Service)

Average precipitation (mm) 1970 - 2003												
Jan.	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dets.**	**Year**
43.1	30.6	30.1	33.5	28.2	51.6	57.9	62.5	58.3	61.6	57.8	50.7	**560.7**
Minimum precipitation (mm) 1970 - 2003												
Jan.	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dets.**	**Year**
5.5	5.0	7.3	4.3	2.3	4.9	1.8	6.9	17.8	6.2	2.8	16.3	**397.0**
Maximum precipitation (mm) 1970 - 2003												
Jan.	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dets.**	**Year**
88.6	86.1	63.3	82.9	78.3	152.4	122.0	150.9	113.1	130.7	111.0	94.7	**732.8**

The previous table is good for describing precipitation of the area over a longer period, but it is also important and sometimes practical for the hydrogeological model to use more recent data. The longest recent observations of precipitation in Paldiski with continuous data are from the period 2011 - 2019, presented in Table 3. The 9-year average precipitation volume is 657 mm/y and the median mean is 577 mm/y. For the

hydrogeological model, the median value of 577 mm/y has been used, because it best represents both the long-term and the results of the last 9-year survey.

Table 3. Results of precipitation (mm) observations for 2011 - 2019 (State Weather Service)

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019
January	110.7	74.4	49.4	45.8	62.9	123	29.0	31.9	53.0
February	23.3	83.2	51.9	20.0	28.7	64.1	28.3	34.5	41.3
March	24.7	42.1	21.1	28.2	21.2	8.5	43.8	24.4	59.5
April	14.7	81.0	31.6	12.9	44.5	44.4	54.3	40.4	4.9
May	35.7	48.0	19.8	48.4	27.2	13.6	12.0	15.9	59.6
Jun	50.5	81.6	46.2	105.8	52.4	64.1	65.8	38.2	19.6
July	103.1	120.9	15.4	25.5	94.1	42.8	20.5	8.1	44.3
August	52.9	99.4	111.1	124.7	32.9	49.2	120.3	61.8	52.6
September	106.8	138.2	14.6	31.2	35.6	40.7	50.4	101.7	77.1
October	67.5	127.6	44.3	28.4	10.7	20.9	130	60.4	146.5
November	33.8	70.8	92.3	42.0	64.3	75.8	85.7	46.1	35.2
December	117.6	91.8	65.9	64.3	47.5	22.4	79.4	30.5	76.2
Total	741.3	1059.0	563.6	577.2	522.0	569.5	719.5	493.9	669.8

6.2. Evapotranspiration

Data from the nearest station, Tallinn, can be used to assess evapotranspiration. According to Tallinn station, evapotranspiration is 85% of the average of long-term precipitation. According to the water balance of the Estonian territory, evaporation makes up 63% of the precipitation (Рессурсы поверхностных вод СССР, 1972).

In the water balance calculations for the Vasalemma River, evaporation accounts for 60% of the average precipitation (Рессурсы поверхностных вод СССР, 1972). The volume of evaporation and transpiration in Estonia is at 457 mm/y (from 728 mm/y of precipitation), which consists of 63% of the total precipitation (Tšeban, 1975). As such for the hydrogeological model the 63% evapotranspiration and 37% infiltration value has been used.

7. PHES UNDERGROUND CONSTRUCTION WORKS

Based on the preliminary design of the PHES (FICHTNER, 2019) and the discussions held with its author Fichtner GmbH & Co. KG (Lead consortium partner of STEIGER), the planned underground construction works of vertical shafts (Figure 10 and Figure 11) affecting the sedimentary bedrock aquifers have been defined and taken as a base for the hydrogeological modeling. Construction of horizontal tunnels, water reservoir caverns, and operating rooms will be located in crystalline bedrock and won't influence sedimentary bedrock aquifers groundwater.

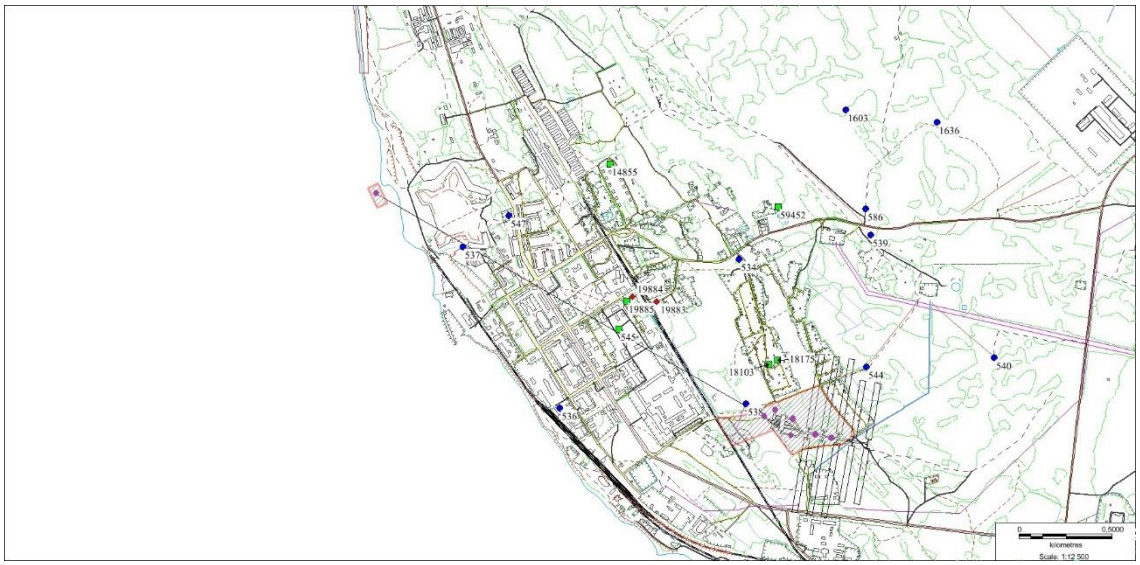

Figure 10. Location of vertical shafts (purple dots) and the underground facilities in the PHES area

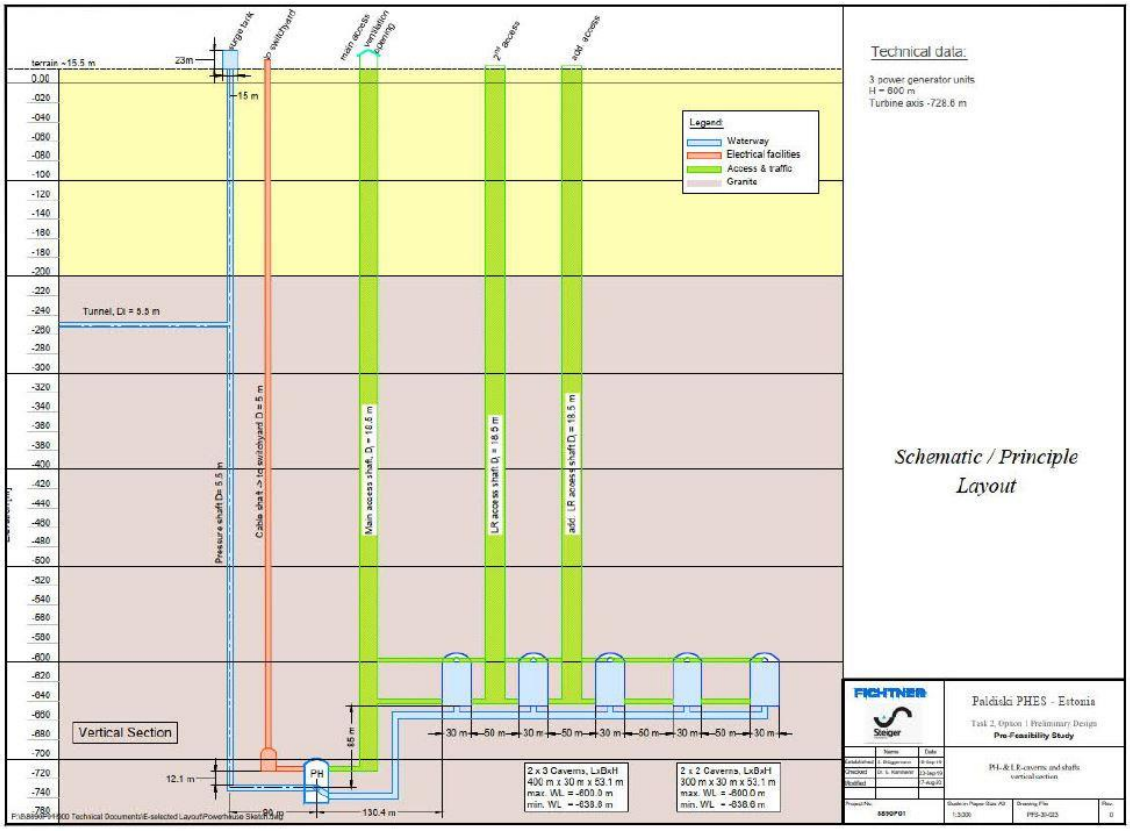

Figure 11. Cross-section schematics of the vertical shafts and underground facilities in the PHES area

The construction of shafts (including the crystalline basement section) is planed into a period from July 2022 till December 2024. Beginning of the construction is not same for all the shafts. Construction beginning time for 4 out of 6 shafts is estimated to be July 2020.

Construction of the shafts is divided into 2 separate stages.

The estimated beginning and ending dates for construction of 6 shafts in the first stage:

- 15 m diameter Surge shaft till -250 m Excavation and support: July - December 2022 Completion of the internal concrete lining (from -206m till -250 m): October - December 2024;
- 13-19.5 m diameter Main Access Shaft Excavation and support: July 2022 - September 2023;
- 13-19.5 m diameter Ventilation Shaft Excavation and support: July 2022 - September 2023;
- 13-19.5 m diameter Additional Access Shaft to the lower reservoir caverns Excavation and support: July 2022 - September 2023;
- 6.5 m diameter The water intake shaft on an artificial island - Excavation and support: April to September 2023; completion of the internal concrete lining (from -206m till -250 m): October - December 2024
- 13-19.5 m diameter Access Shaft to the lower reservoir caverns Excavation and support: July 2022 - September 2023;

The construction of one shaft in the second stage:

– 5 m diameter Cable shaft (power evacuation shaft) Excavation and support

As the estimated schedule above is preliminary and may change in the future, a conservative approach has been selected for the hydrogeological modeling where all the shafts at the appropriate stage will be constructed in parallel so the maximum impact to the groundwater drawdown will be considered. Meaning that in case the shafts will be not constructed in parallel the actual impact to the groundwater drawdown will be smaller.

While excavating the vertical shafts, sedimentary rocks are going to be treated with freezing or grouting to lower the water inflow and it is intended to install a concrete lining in the shafts immediately after each 1 m excavation cycle.

8. HYDROGEOLOGICAL AND GEOPHYSICAL FIELDWORK

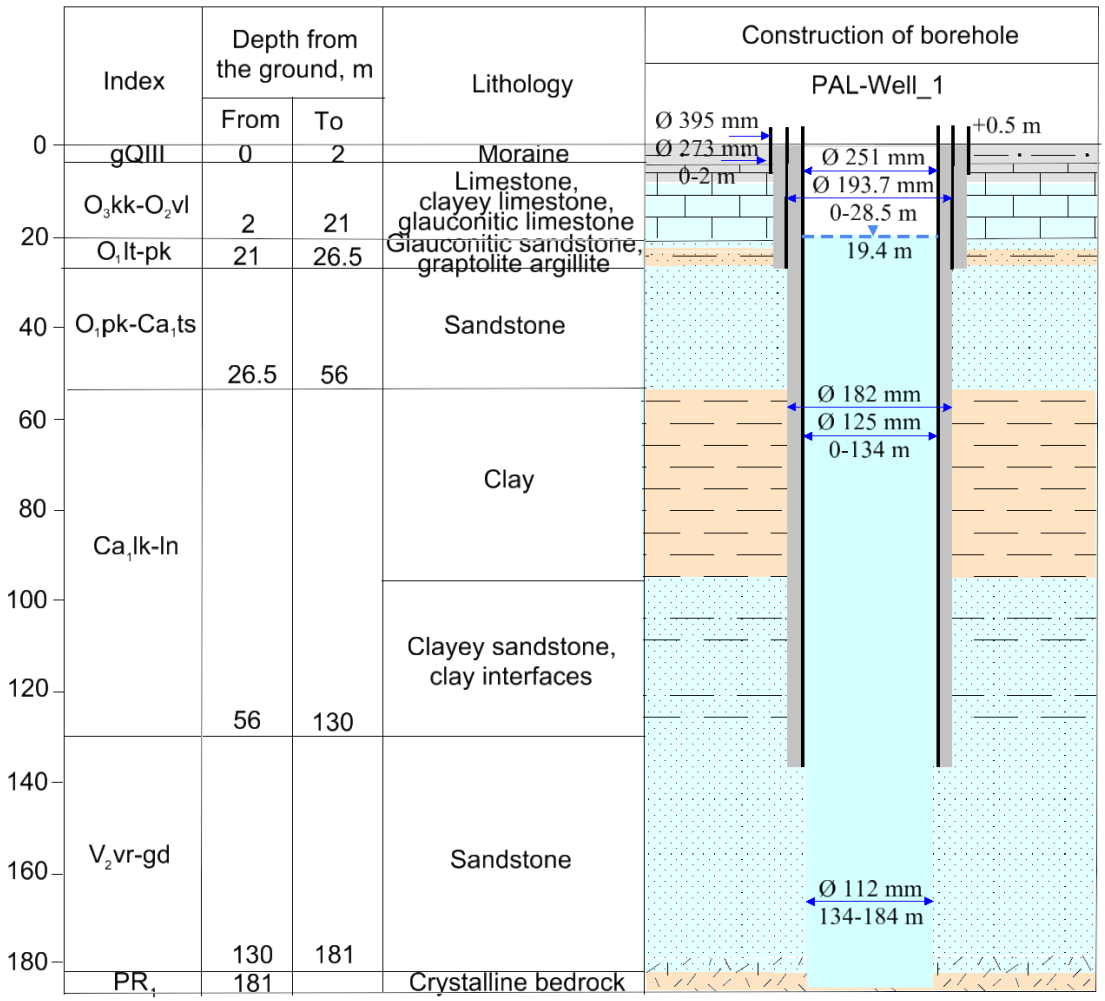

Figure 12. Construction design of the first PAL-Well_1 (ground elevation from sea level 16.15 m; aquifer is marked with light blue and aquitard with beige)

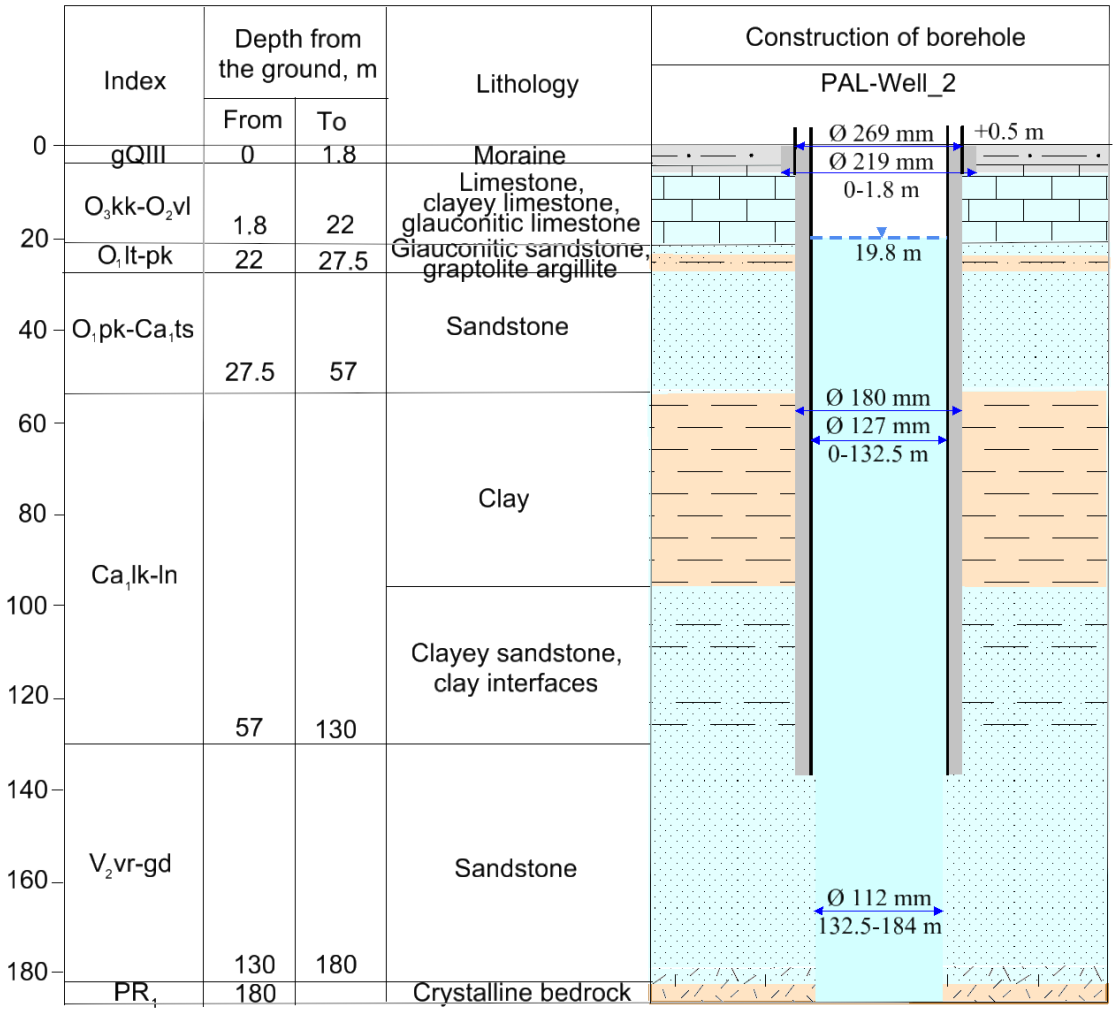

Figure 13. Construction design of the second PAL-Well_2 (ground elevation from sea level 16.64 m; aquifer is marked with light blue and aquitard with beige)

In terms of hydrogeological studies, new base data has been gathered from three boreholes located on the territory of Pallase 16 (Figure 14) that were drilled during the STEIGER conducted investigations.

The first borehole was the survey well PAL-Well_1 (X = 6 578 525.8; Y = 504 498.4) for hydrogeological studies (Figure 12).

Second borehole PAL-Well_2 (X = 6 578 598.5; Y = 504 456.9) is an additional survey well that was completed reaching the upper part of the crystalline basement (180.75 m from ground level and -164.25 m from ocean level) (Figure 13).

Third borehole PAL-1 (X = 6 578 754.36; Y = 504 451,79) was drilled by wire-line core drilling method to get precise geological information of the area (results are presented in Appendix 1).

In PAL-WELL series boreholes pumping tests, borehole geophysical tests and measurements were made, and in PAL-1 core logging and geophysical measurements were made.

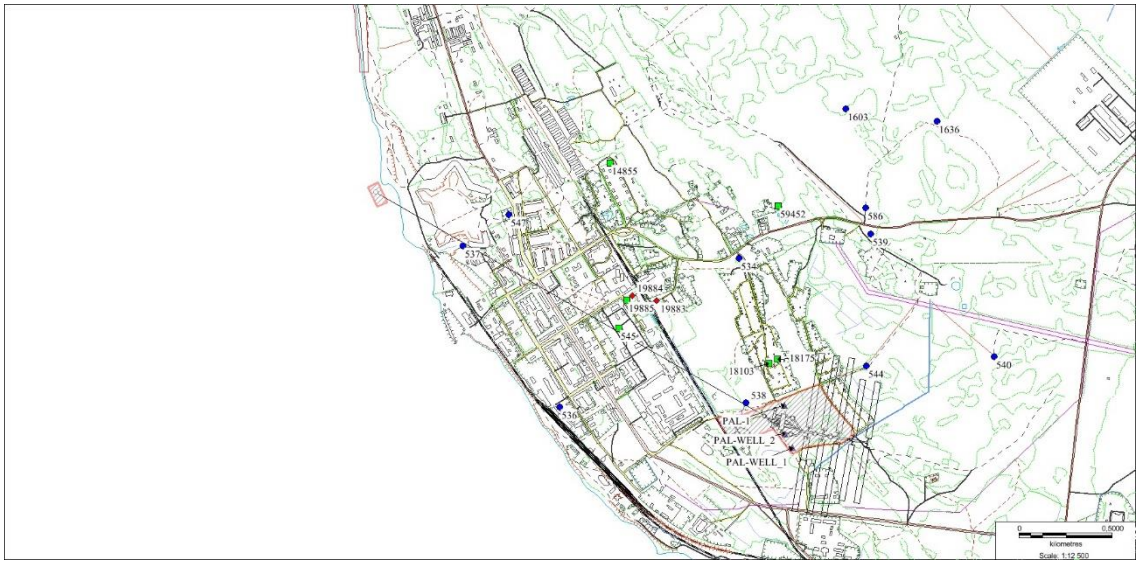

Figure 14. Location of boreholes (purple triangles) in the Pallase 16 area (Estonian Land Board Geoportal)

8.1. Pumping tests and the hydrodynamic parameters

Pumping tests were performed to estimate the hydrodynamic parameters (hydraulic conductivity, transmissivity, storability if possible) of the aquifer forming rocks and to obtain data for calculating hydrodynamic parameters. These tests were performed for each aquifer of geological cross-section: Ordovician (S-O), Ordovician-Cambrian (O-Ca), and Cambrian-Vendian (Ca-V) aquifer. Pumping tests for O and O-Ca aquifers were performed from the drilled PAL-Well_1 in separate stages at the time the corresponding section had been drilled open. The measured static water levels (see Table 4) prior each of the pumping tests were different, indicating that the well construction and the corresponding aquitards were with sufficient sealing properties. This is further proven by the differences seen in the water compositions based on the conducted water quality testing (see the Chapter 8.2). Also, pumping test was carried out in borehole PAL-1, that opens the crystalline basement.

Additional PAL-Well_2 opening Ca-V aquifer was drilled ~75 m away from the PAL-Well_1. Thus, the pumping test for Ca-V aquifer was performed in this new borehole (Figure 15). However, the first PAL-Well_1 was used as an observation borehole during the Ca-V pumping test.

Figure 15. Pumping test in Cambrian-Vendian aquifer in PAL-Well_2

Submersible pumps Grundfos SQ 1-70 (flow rate up to 1 m^3/h), SQ 7-40 (flow rate up to 7 m^3/h) and Pedrollo 4HR 18/22 (flow rate up to 25 m^3/h) were used for pumping tests. Before every pumping test and occasionally during the pumping test, the groundwater level or potentiometric surface was measured with Eijkelcamp water level meter in every borehole. Water level displacement during the pumping and recovery were measured continuously with dataloggers (Van Essen CTD-Diver or TD-Diver) that measure water column pressure. Also, barometric pressure, which is needed for compensating data, were measured during the pumping tests.

Pumping tests in O-Ca and Ca-V wells were conducted at a constant flow rate. After finishing the pumping, the dataloggers remained in wells to measure recovery. Only recovery of water level was measured for S-O aquifer and for crystalline basement, as the boreholes emptied in less than 10 min of pumping at flow rate 1 m^3/h. The Time interval of measuring the water column pressure was 30 sec and 15 min for barometric pressure.

Pumping test in O-Ca aquifer was stopped after the manual measuring of water level showed no significant changes in drawdown for half an hour. The data obtained after the testing from dataloggers showed that water level continued to decline slightly. According to the water level data, the expected drawdown would have been less than 5 cm per hour, decreasing further over time. Previous similar studies in the O-Ca aquifer have shown that stabilizing of water table could not be fully achieved even after 72 h of pumping. Also, the water level may not recover within 72 h. The results of the calculations are more precise for a longer data series. However, based on the past experience it can be seen that

there are no significant differences in the results of O-Ca aquifer hydrodynamic parameters in case of extended pumping times.

Pumping test data acquired from divers were interpreted with the groundwater data management software Diver-Office to obtain groundwater levels. Water level changes during the tests are shown in Figure 16 to Figure 19. The process of the pumping tests was documented in the protocols (see Appendix 3).

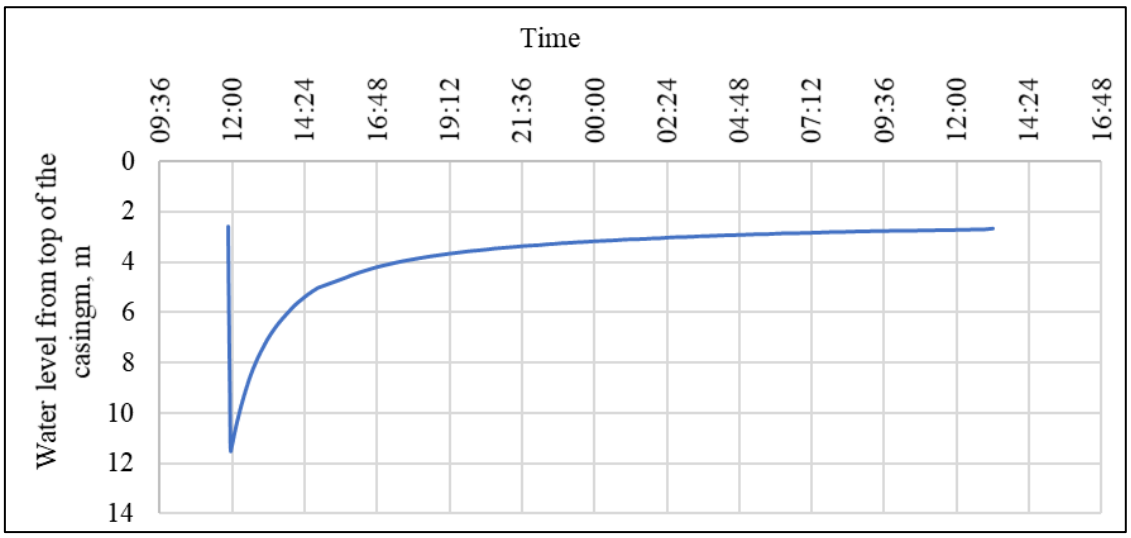

Figure 16. Recovery test in S-O aquifer (23.01 - 24.01.2020) in PAL-Well_1

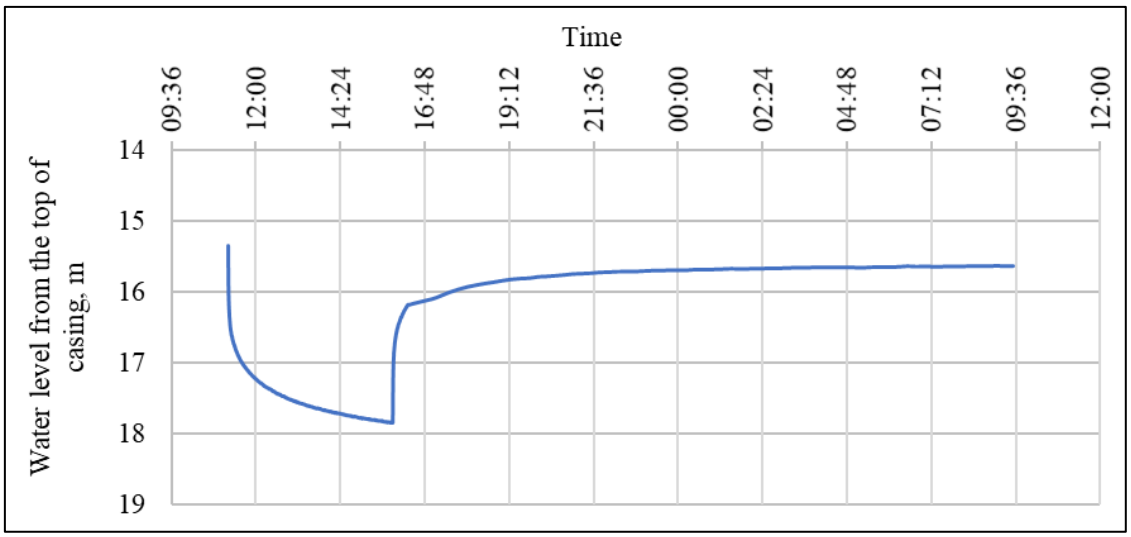

Figure 17. Pumping and recovery test in O-Ca aquifer (11.02 - 12.02.2020) in PAL-Well_1

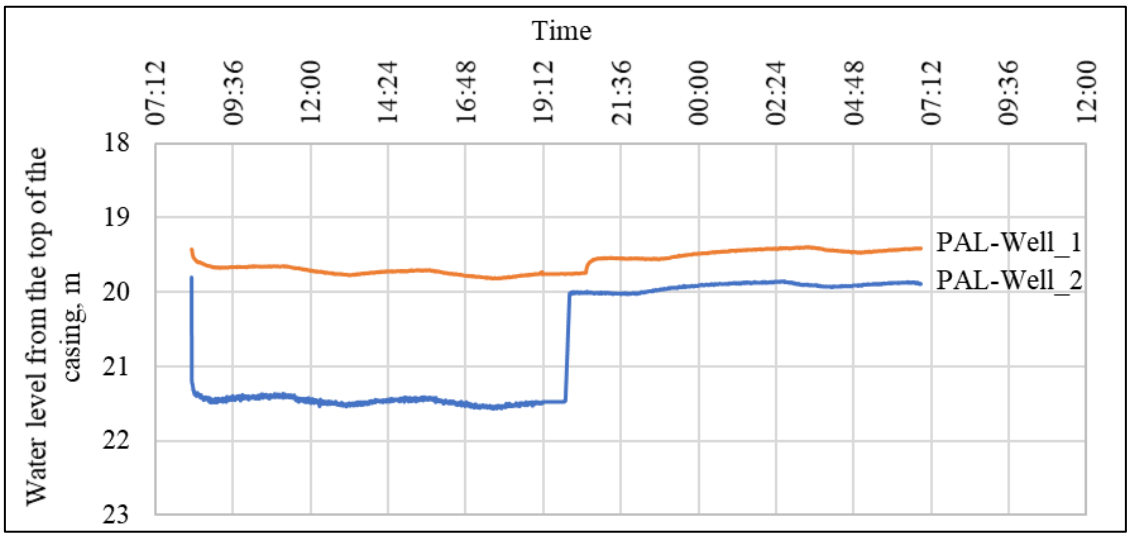

Figure 18. Pumping and recovery test in Ca-V aquifer (29.04 - 30.04.2020) in PAL-Well_2

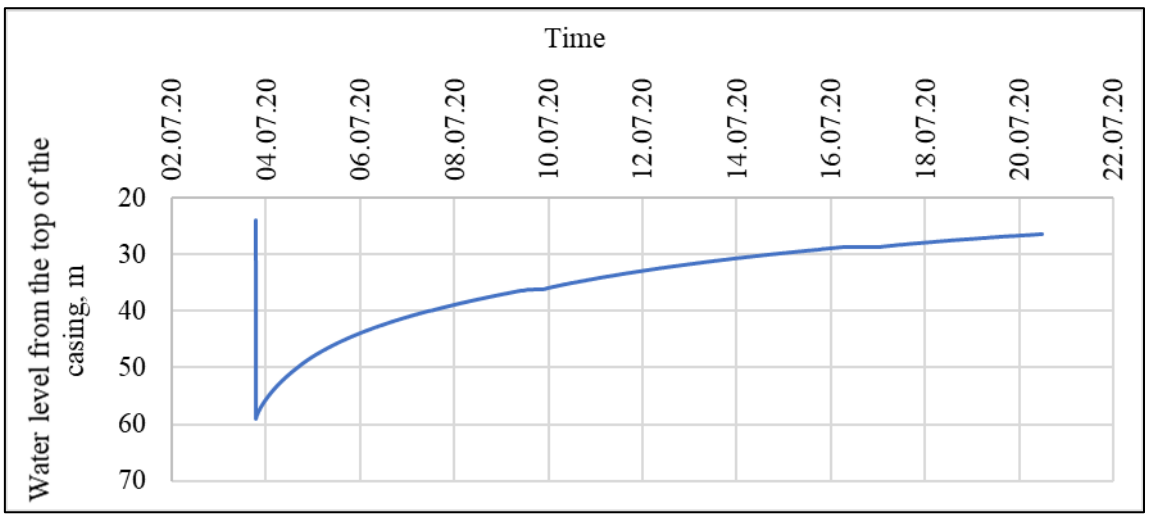

Figure 19. Recovery test in crystalline basement (03.07.2020 - 20.07.2020) in PAL-1 borehole

Data obtained from pumping tests were used to calculate hydrodynamic parameters with the Aqtesolv Software, using the Theis (1935) solution suitable for confined aquifers (O-Ca and Ca-V) and Hvroslev (1951) solution suitable for recovery tests both in the unconfined (S-O) and confined (PR) aquifers. Hydrodynamic parameters for Ca-V aquifer were calculated using results of pumping only. Data from water level recovery were not used as probably water reflux into the well occurred after finishing pumping. Reports of calculations are provided in Appendix 4.

Transmissivity or hydraulic conductivity is calculated from the following equation:

$$K = T/b, \text{ where}$$

K - hydraulic conductivity (m/d)
T - transmissivity (m^2/d)
b - thickness of aquifer (m)

Specific capacity is calculated from the equation below:

$$S_c = Q/(h_0 - h), \text{ where}$$

S_c - specific capacity (l/s×m)
Q - pumping rate (l/s)
h_0 - h − drawdown (m)

The results of the pumping tests and calculations are presented in the summarizing Table 4 below. The thicknesses of aquifers in table 4 result from the open interval of the well and may not represent the actual thicknesses of aquifers used for hydrogeological modelling and inflow calculations. Those values were only used to calculate hydraulic parameters. However, in the hydrogeological model and for inflow calculations clayey sedimentary rocks layers which do not form strong aquitard, are included in aquifers (for example Sämi formation from Lontova stage). Due to the conservative approach, the calculated K values are used for these clayey sedimentary rocks as well. Storativity is given only for Ca-V aquifer, as the calculated values of storativity obtained from single-well pumping test may be overestimated.

Table 4. Summary of the pumping tests

Borehole	PAL-Well_1	PAL-Well_1	PAL-Well_2	PAL-Well_1	PAL-1
Aquifer	S-O	O-Ca	Ca-V		PR
The thickness of the aquifer, m*	20	29	58		
Field test	Recovery test	Pumping test/ recovery test	Pumping test/ recovery test	Observation well	Recovery test
Submersible pump used for pumping test	-	Grundfos SQ 7-40	Pedrollo HR4 18/22		-
Flow rate, l/s	-	1.50	6.44	-	-
Flow rate, m^3/h	-	5.40	23.20	-	-
Time of pumping, h	-	5	12		-
Time of recovery, h	4	17	12		400
Static water table from ground level, m	2.64	15.34	19.81	19.42	23.7
Static water table from mean sea level, m	13.51	0.81	-3.17	-3.27	-7.1
Maximum water level displacement, m	8.90	2.50	1.77	0.39	35.08
Specific capacity, l/s×m	-	0.60	3.62	-	-

Transmissivity, m^2/d	0.7	52.2	529.9	-
Hydraulic conductivity, m/d	0.04	1.8	9.14	4.576×10^{-6}
Storativity	-	-	0.0008	-

*Based on the open interval of the well

Calculated hydraulic parameters of O-Ca and Ca-V aquifers generally match historic data as given in Chapter 4. Hydraulic parameters of crystalline basement have been little studied previously. However, hydraulic conductivity of crystalline basement calculated from pumping test data is similar to the data obtained from the packer tests (Appendix 11).

Only the hydraulic conductivity obtained for the Ordovician aquifer does not match the historic values. Results of the geophysical study and pumping test suggest that PAL-Well_1 was drilled in monolithic limestone with very low permeability, this is further supported by the drilling of PAL-1 borehole where no circulation losses of this drilled section occurred. During the siteworks, additional pumping tests from nearby historical survey wells PRK0019884 and PRK0019883 failed as the wells were deemed to be not suitable for pumping tests because of oil or bitumen contamination. However, the values of hydraulic parameters of the Ordovician carbonate rocks vary on a large scale, depending on the fractures and fissures present in rocks. Previous studies (Kink, et al., 1996a) in Paldiski area showed that transmissivity values of Ordovician limestone varied from 0.3 m^2/d to 50 m^2/d, referring to the heterogeneity of carbonate rocks. In Estonia, the average lateral hydraulic conductivity of the S-O aquifer system forming carbonate rocks, based on historic data, is estimated to be 8.1 m/d. Due to conservative approach, the given historic value is used for hydrogeological modelling and the inflow calculation.

8.2. Groundwater quality

To describe the groundwater quality of the area, one groundwater sample from each studied aquifer was taken during the pumping test site works. Taking of the groundwater samples were carried out per Water Act1 and the regulation No. 49 on methods of sampling established by the minister of the Environment of the Republic of Estonia. Also, the standards mentioned below were followed:

- EVS-EN ISO 5667-1 Water quality – Sampling – Part 1: Guidance on the design of sampling programs and sampling techniques;
- EVS-EN ISO 5667-3 Water quality – Sampling – Part 3: Preservation and handling of water samples;
- EVS-ISO 5667-11 Water quality – Sampling – Part 11: Guidance on sampling of groundwaters.

In the laboratory, the following chemical and physical parameters were analyzed: color, turbidity, odor, chemical oxygen demand (COD_{Mn}), electrical conductivity, pH, total hardness, ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), chloride (Cl), sulfate (SO_4), bicarbonate (HCO_3), iron (Fe), manganese (Mn), fluoride (F), boron (B), barium (Ba), arsenic (As), selenium (Se), mercury (Hg), cadmium (Cd), chrome (Cr), nickel (Ni), lead (Pb), copper (Cu), phenols and effective dose. Groundwater samples were analyzed in the following laboratories:

– Groundwater samples - Laboratory of Geological Survey of Estonia (accreditation certificate No. L093) and Estonian Environmental Research Centre (accreditation certificate No. L008);
– Effective dose - Testing Centre of the University of Tartu, Laboratory of Nuclear Spectroscopy (accreditation certificate No. L151).

In situ, pH, electrical conductivity, temperature, oxygen content, and saturation were measured using multiparameter probe Aquaread Aquaprobe AP-2000 and flow-through cell (Figure 20). The measured electrical conductivity values were automatically converted to 20° C. Taking of the groundwater samples were protocolled (see Appendix 5).

Figure 20. Multiparameter probe Aquaread Aquaprobe AP-2000 and flow-through cell for groundwater in situ testing

Additionally, 10 groundwater samples were collected from a selection of PHES area neighboring water wells (Figure 21) and from different aquifers. Groundwater samples were taken from the following wells: 51456 (O-Ca), 52342 (Ca-V), 539 (Ca-V), 538 (Ca-V), 544 (Ca-V), 540 (Ca-V), 534 (Ca-V), 58316 (Ca-V), 56402 (O-Ca), 16702 (O-Ca). Collected water samples were tested in the laboratory to the same parameters as groundwater samples in the previous chapter, excluding the effective dose.

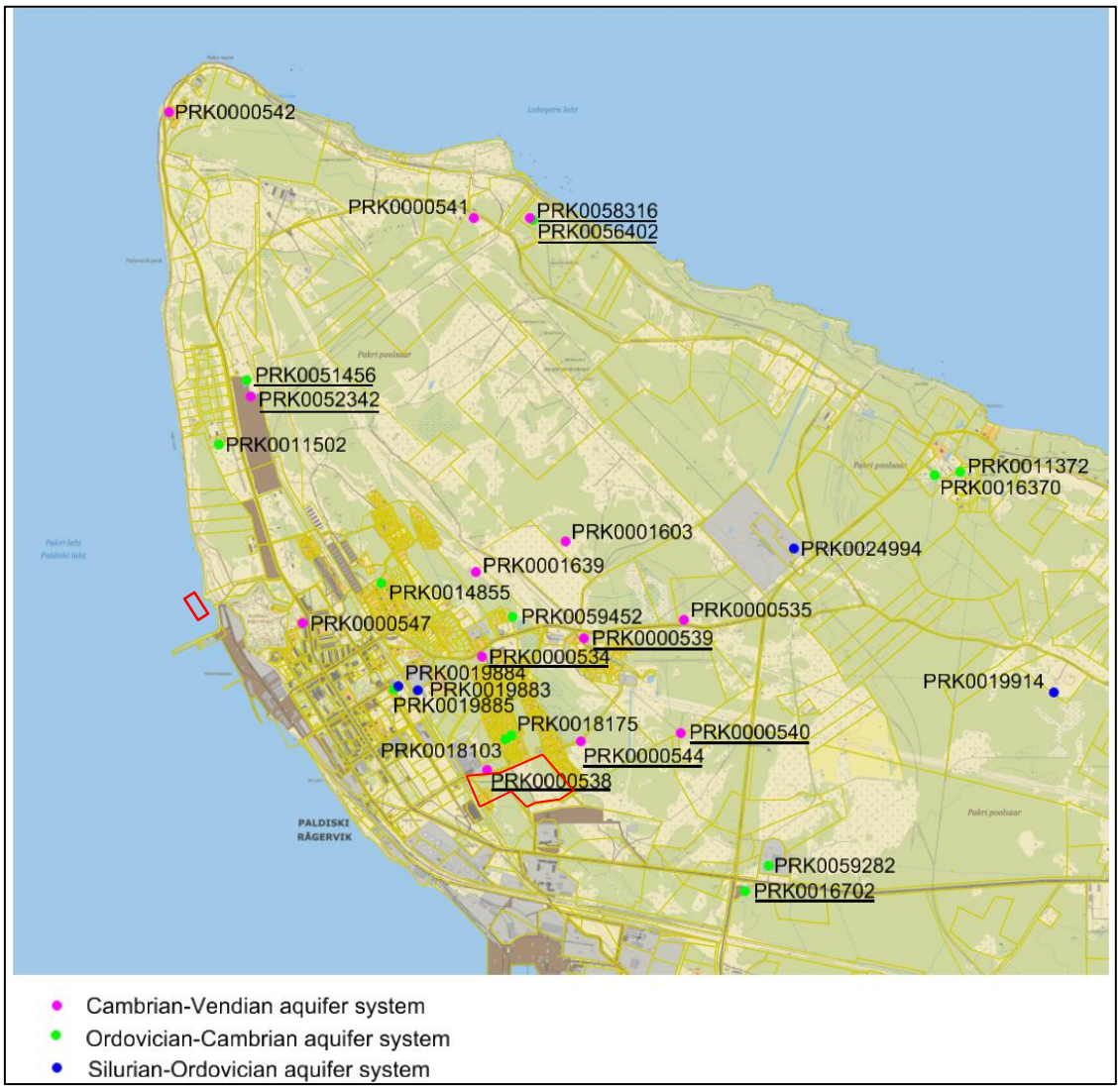

Figure 21. Location of the historic water wells based on Environmental registry (wells where groundwater samples were taken, have been underlined)

The results of the groundwater analyses are provided in Appendix 6. It can be concluded that all the analyzed components from PAL-Well Ca-V aquifer and most of the analyzed components from S-O and O-Ca aquifers meet the requirements for drinking water in regulation No. 61 established by Minister of Social Affairs. Water analyses from O and O-Ca aquifers show high Fe concentrations, respectively 1160 µg/l and 490 µg/l. Also, F concentrations were slightly over the permitted value of 1.5 mg/l (Figure 22 to Figure 24). The indicative dose (sum of effective doses of Ra-226 and Ra-228) was over the permitted value of 0.1 mSv/year in Ca-V groundwater, being 0.233 mSv/year. Heavy metals, phenols, and nitrogen concentrations were below permitted values and in most cases below the detection limit (see Appendix 6). Chemical composition of the water from the crystalline basement was not compared to chemical data from other hydrogeological units and to the requirements for drinking water, as the water from crystalline basement is not used for drinking water supply.

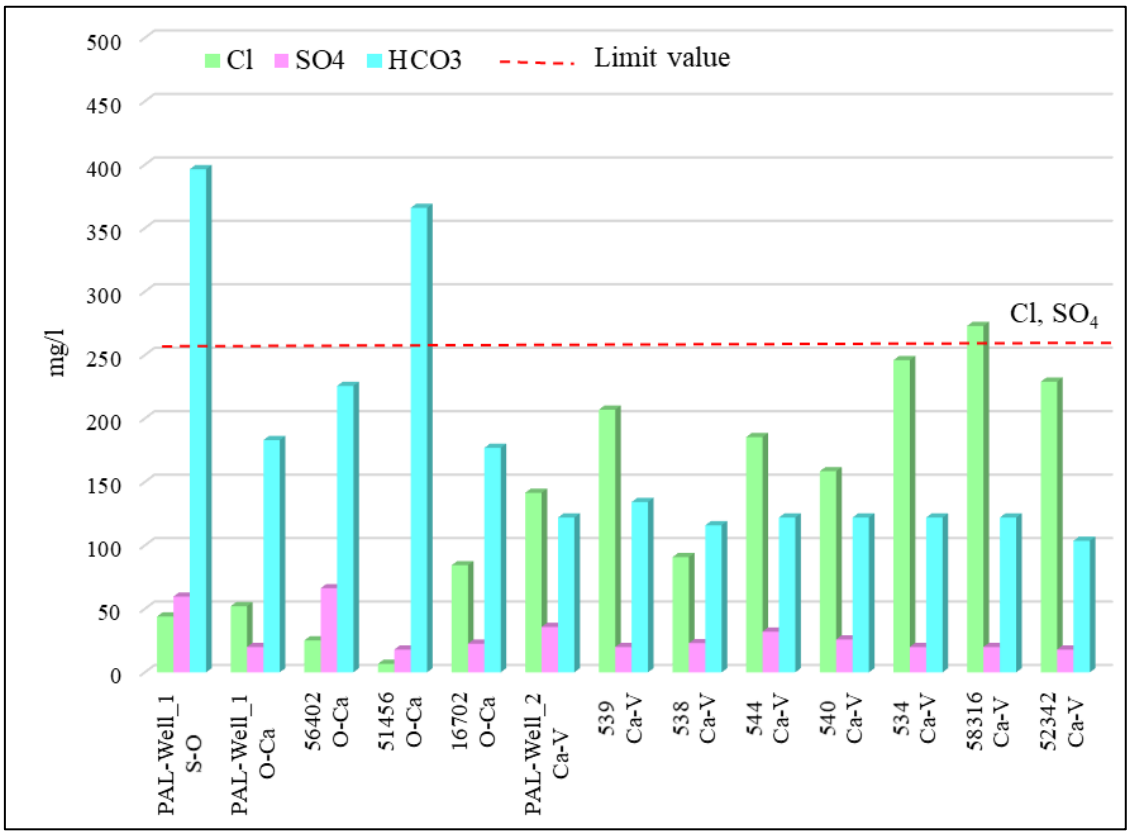

Figure 22. Concentrations of main anions in groundwater samples

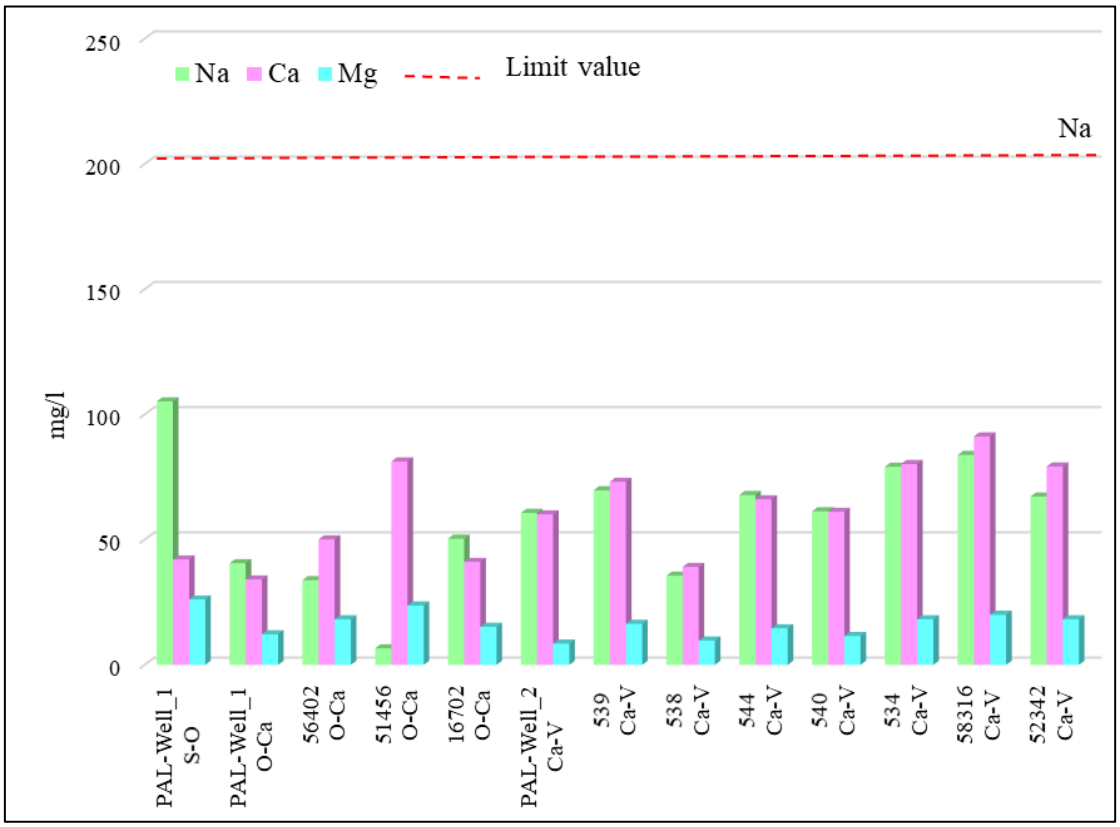

Figure 23. Concentrations of main cations in groundwater samples

Most of the analyzed components from historic wells meet the requirements for drinking water in regulation No. 61 established by the Minister of Social Affairs. Water analyses from historic wells showed Fe concentrations (up to 1020 µg/l) over the permitted value of 200 µg/l in five Ca-V wells and one O-Ca well. Cl concentration was slightly over the permitted value of 250 mg/l in one Ca-V well (Figure 22). Heavy metals, phenols, and nitrogen concentrations were below permitted values in all wells, in most cases below the detection limit (see Appendix 6).

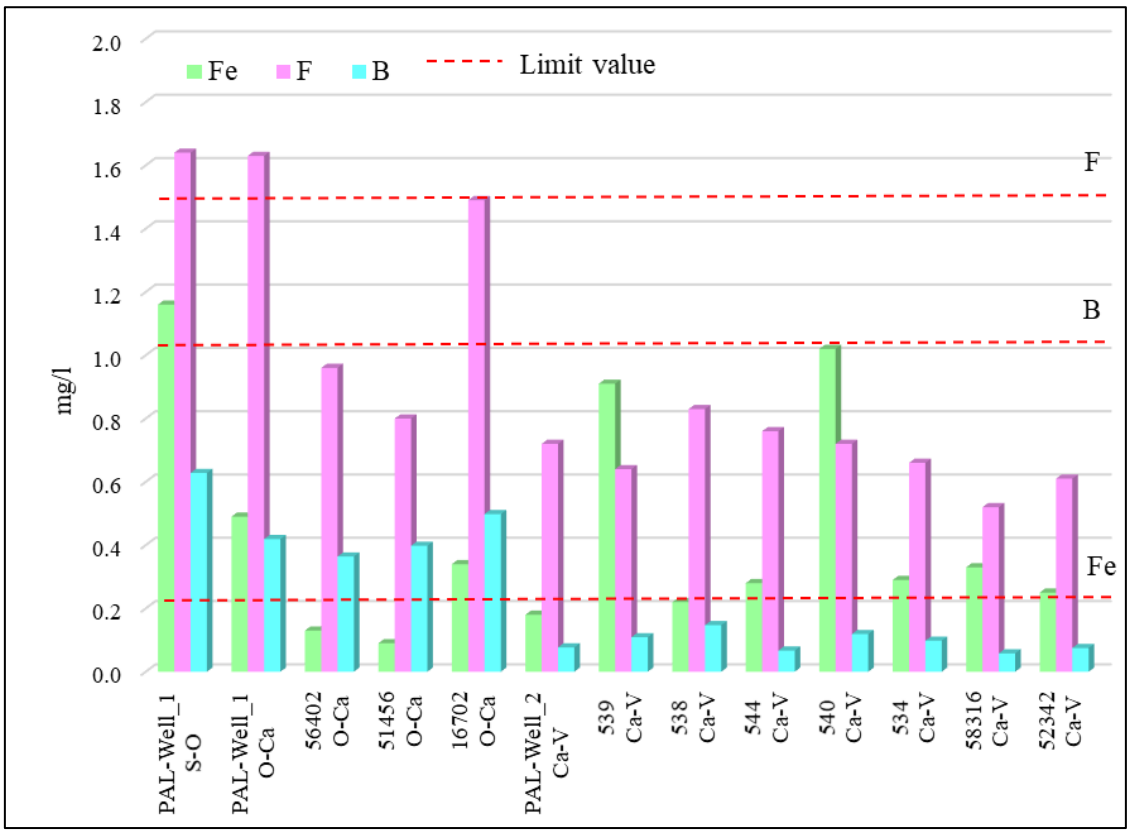

Figure 24. Fe, F and B concentrations in groundwater samples

To describe the chemical type of groundwater hydrochemistry software AquaChem was used. Piper diagrams are constructed considering the main cation (Na, K, Ca, Mg) and anion (Cl, SO_4, HCO_3) contents in groundwater samples. The Piper diagram (Figure 25) shows that chemical types of groundwater in different aquifers are distinguishable, indicating the presence of aquitards between aquifers. Ca-V aquifer is characterized by groundwater rich in Ca, Na, Cl, and SO_4. The groundwater of O-Ca aquifer is predominantly rich in Ca, Mg, and HCO_3. However, most of the O-Ca water analyzes (PAL-Well, PRK0056402, PRK0016702) showed a mixed type of water with some Na and Cl presented. Groundwater in O aquifer is predominantly characterized by Ca-Mg-HCO_3 water type. Although, near the sea Na and Cl may dominate in S-O aquifer. Thus, the groundwater of S-O aquifer in the area of study site can be considered as a mixed type of water. Groundwater of crystalline basement is saline with higher Na ja Cl concentrations. Two seawater samples taken to compare saline groundwater showed remarkably higher K, Mg and SO_4 concentrations in addition to high Na and Cl concentrations.

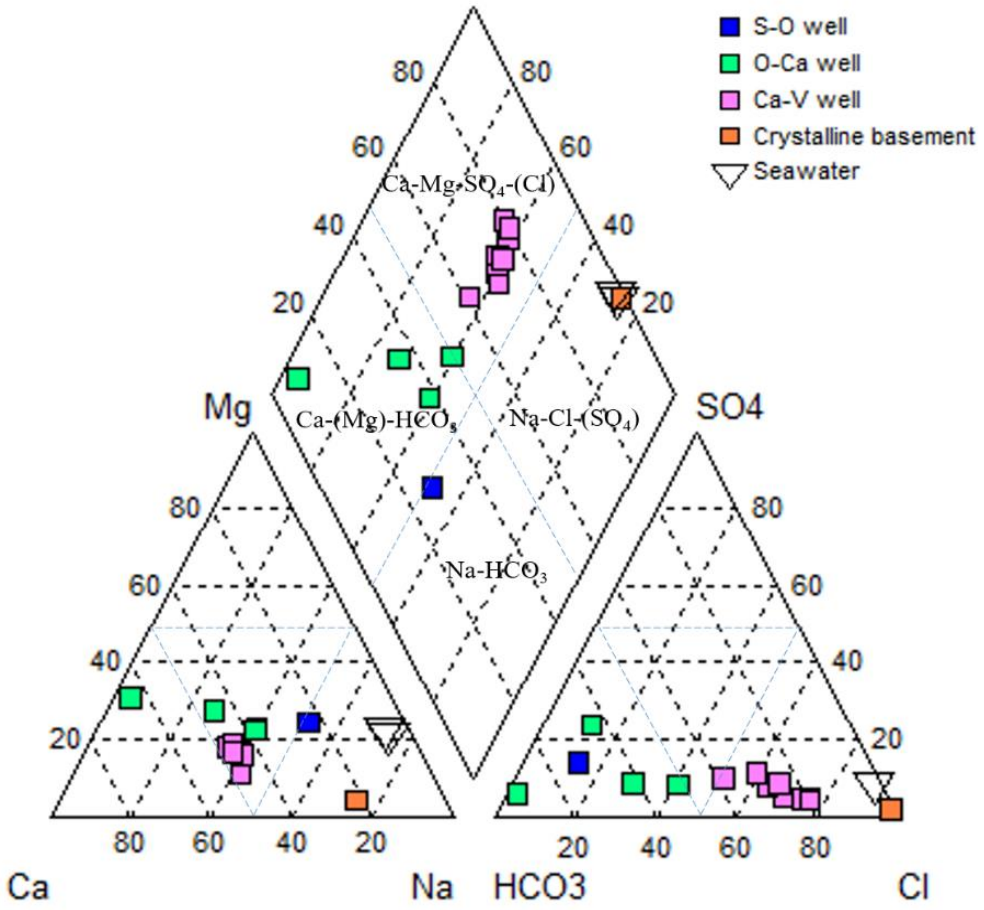

Figure 25. Groundwater chemical composition presented in Piper diagram

8.3. Water level in the Paldiski area

On 29.04.2020 and 03.11.2020 water levels were monitored to obtain reference and input data for the hydrogeological model in the Paldiski area. Most of the water supply wells are inaccessible for measuring groundwater levels. Thus, water levels were measured in accessible hydrogeological survey wells in the area. The wells are shown in Table 5.

Table 5. Monitored groundwater levels

Well	Coordinates (L-EST97)		Absolute height, m	Aquifer	Water level	
	X	Y			From the ground, m	Absolute height, m
29.04.2020						
PRK0019885	6 579 308.4	503 614.7	15.2	O-Ca	14.5	0.7
PRK0019884	6 579 331.7	503 641.6	14.8	S-O	0.7	14.1
PRK0019883	6 579 305.6	503 771.8	16.5	S-O	1.3	15.2
03.11.2020						
PRK0019885	6 579 308.4	503 614.7	15.2	O-Ca	14.6	0.6
PRK0019884	6 579 331.7	503 641.6	14.8	S-O	0.8	14.0
PRK0019883	6 579 305.6	503 771.8	16.5	S-O	1.4	15.1
19914	6 579 289.0	508122.0	15.5	S-O	14.4	1.1
P1	6 579 476.2	508 293.2	15.1	S-O	1.0	14.0
P2	6 579 524.4	508 307.4	14.3	S-O	0.3	13.9
P3	6 579 537.6	508 307.0	14.3	O-Ca	12.4	1.9
PRK0001146	6 570 590.3	492 720.1	3.7	S-O	2.5	1.2
PRK0001144	6 570 586.2	492 726.3	3.7	Ca-V	4.6	-0.9
PRK0001145	6 570 577.1	492 729.0	3.4	O-Ca	1.5	1.9

Additionally, absolute heights of water levels in bonds cutting into the Ordovician limestones were measured (Figure 4 on the south-east end of the Põdra road). The absolute heights of water level were 21.6 m (29.04.2020) and 20.9 m (03.11.2020).

8.4. Borehole geophysical logging

The borehole geophysical logging was performed in all three boreholes. Caliper and natural gamma logging were used to obtain information about geology and impeller flowmeter, fluid temperature and conductivity logging were used for hydrodynamic parameters. The logging equipment is produced by Robertson Geologging Ltd. (http://www.geologging.com/).

Measurements were performed for each aquifer of geological cross-section: Silurian-Ordovician (S-O), Ordovician-Cambrian (O-Ca), and Cambrian-Vendian/Ediacaran (Ca-V) aquifer. Impeller flowmeter measurements for S-O and O-Ca aquifers were performed from the drilled PAL-Well_1 in separate stages at the time the corresponding section had been drilled open and Ca-V was performed in PAL-Well_2 (Appendix 7). Geological information about the extent of aquitards was obtained by natural gamma logging through the casing.

All geophysical measurements except temperature and conductivity were made twice. The first measurements were the main measurements to collect data and repeated measurements were for controlling the data. Conductivity and temperature measurements were made first with direction from top to bottom, caliper and natural gamma were logged next with direction from bottom to up and the impeller flowmeter was the last tool to be logged with. Impeller flowmeter measurements were made statically in different depths while pumping water from the borehole.

In PAL-Well_1 Ordovician aquifer was logged by Marko Häelm and by Priit Kallaste from STEIGER on 24.01.2020 conducting all previously mentioned measurements. Due to a lack of water inflow into the well, impeller flowmeter measurements were unsuccessful. Secondly, Ordovician aquitard and Ordovician-Cambrian aquifer was logged also by Marko Häelm and by Priit Kallaste on 13.02.2020 conducting all measurements in the aquifer.

In PAL-Well_2 Lükati-Lontova aquitard and aquifer were logged by Siim Tarros from Geological Survey of Estonia on 13.04.2020 conducting all measurements that were intended in the aquifer. Because of the natural gamma logging starting from ground level, additional information was obtained about O and O-Ca aquifers and aquitard between them.

Due to PAL-1 core logging and natural gamma data correlation, precise geological boundaries can be also assigned to the PAL-Well_1 and PAL-WEell_2 drilling data.

Aquitards tend to have higher natural gamma radiation emittance so spikes in natural gamma graphs indicate the possibility of claystone or shale layers. All geophysical descriptions are given from ground level for easier graph reading and well height from sea level is given in header of the graph. On the geophysical graphs (Appendix 7) spike out in the natural gamma graph can be seen (PAL Well_1 at the depth of 21 m and in PAL-Well_2 at the depth of 22 m) indicating beginning of shale and ending 5-5.5 m deeper, marking the range of the Ordovician aquitard. Lükati-Lontova aquitard is not so much distinguishable on the natural gamma graph (PAL-Well_2) as Ordovician was but with beginning at depth of 57.2 m from ground level is quite well distinguishable from O-Ca aquifer. The end of the aquitard is on a natural gamma graph in the depth of 102.5 m counting in the first sand and clay layer of Sämi member.

Based on the core logging of PAL-1 and borehole geophysical measurements of PAL-Well_1, PAL-Well_2, and PAL-1, the thickness of Ordovician complex is estimated to be approximately 21 m -22 m. (from 17.5 m AMSL to -4.5 m UMSL), the thickness of Türisalu argillites is 5 - 5.5 m (-4.5 m to -10 m UMSL), and the thickness of Ordovician-Cambrian aquifer is approximately 29 m - 30 m (-10 m to -39 m UMSL) (Figure 7).

Based on the geophysical measurements of the PAL-Well_2 and core logging of PAL-1, the average thickness of the Lükati-Lontova aquitard is 45 m (-39 m to -84 m UMSL) and C-V aquifer is approximately 81 m (-84 m to -165 m UMSL).

As mentioned above due to a lack of water inflow into the well, impeller flowmeter measurements were unsuccessful in Ordovician aquifer. Ordovician-Cambrian measurements showed constant inflow through well walls and also through bottom of the well. Cambrian-Vendian impeller flowmeter measurements showed constant inflow through well walls from -132 m to -150 m. From -150 m to -160 m inflow is small or non-existent and from -160 m till -175 m inflow continues to be constant again.

9. HYDROGEOLOGICAL MODEL

The Hydrogeological model is based on data obtained from the previous historic hydrogeological studies, field works carried out by STEIGER within the framework of this project, and on the materials of the national geological mapping of Paldiski map sheet.

The model is developed using GMS (Groundwater Modeling System) version 6.5 software package which uses the MODFLOW 2000 (Modular groundwater flow) model for hydrological calculations. The model can be used to calculate the groundwater hydraulic pressure for any point in the modeling area at any point in time, and thereby estimate the extent of the dewatering effect associated with underground excavation works (spread of the cone of depression).

To fulfill the purpose of the study a static model was built to model the possible effects on the aquifers during the construction of the vertical shafts. The choice of the static model is based on the concept of conservatively considering the maximum possible impact of construction works.

GMS consists of different modules. A modular software program has the advantage that it is characterized by the fact that a program can be separated into independent, interchangeable modules, which subsequently can be incorporated as a module or package into GMS and Modflow. In practice, these modules or packages are specific features of the hydrologic system like geology, precipitation, wells, or rivers. The division of the program into modules facilitates the examination of each hydrologic feature in the model independently.

9.1. Grid design

Within Modflow, the study area is subdivided into finite difference blocks, with parameters attributed to each block.

The information that modules carry is incorporated into the model grid, based on which it is possible to make hydrogeological calculations. The model area is divided into a grid. The size of the squares in the horizontal plane is determined by the number of squares and the length and width of the territory, and the vertical distribution based on the sum of water-bearing and holdings layers (Figure 26).

The model area has a rectangular shape with borders of 20.6 times 16.3 kilometers with a size area of ~ 335.8 km². This chosen size is based on the estimated total areal impact on the modeled groundwater horizons and the distribution of wells and information points. Coordinates (LEST-97) in the x-direction range from 492872 to 513447 and coordinates in the y-direction range from 6570019 to 6586278.

The whole model area (Figure 27) is divided into 23.3 x 29.4 m three-dimensional blocks, which form a computational grid on which the MODFLOW model is built. The grid size has been chosen so that it would accommodate all the PHES vertical shafts and the nearest water supply well into different cells.

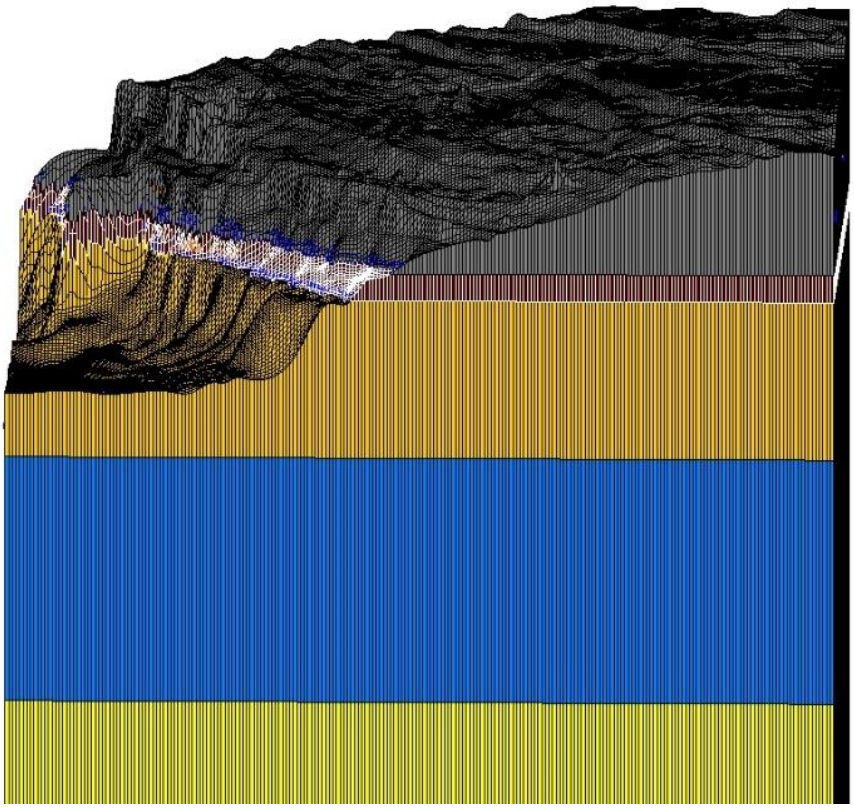

Figure 26. Groundwater model west-east cross-section in Paldiski area

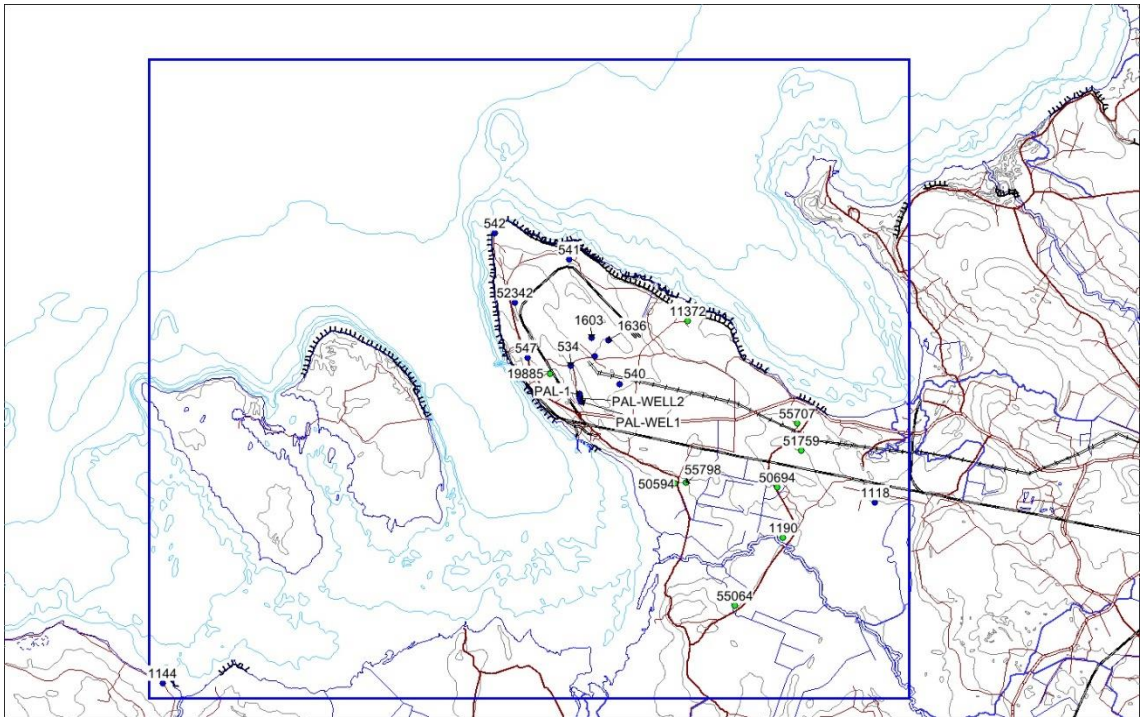

Figure 27. Groundwater model area in the blue square with Ordovician-Cambrian (green circles) and Cambrian-Vendian (blue circles) wells used for model input

Based on the geological and hydrogeological setting (Chapter 4 and 8), 5 different hydrogeological layers (Table 6) were used in the model, where the greatest detail is focused on the PHES project area and its immediate surroundings (this is possible due to the studies carried out by STEIGER within the framework of this project). The bottom of the model is the hanging wall of the crystalline basement that lies 165 m beneath the sea level (constant value for the whole model). The maximum height of the model is 25.5 m above sea level.

Table 6 summarizes the consolidated information obtained from the historic reports and the ongoing studies carried out by STEIGER within the framework of this project, this info forms the geological and hydrogeological setting input of the model. In regarding of Ordovician aquifer horizontal hydraulic conductivity differences in table 4 and table 6, both values are correct. Note, table 4 values represent the situation of drilling and conducting pumping test in solid limestone, to be more conservative a value representing fractured limestone situation (a historic value of 8.1 m/d) was used in the model. As Ordovician and Lükati-Lontova aquitards are composed from different materials (Appendix 1) their horizontal hydraulic conductivity values also differ from each other based on historic data so a uniform value for horizontal conductivity cannot be used for both aquitards.

Table 6. Model stratification with historical and recent hydrogeological parameters (new data marked blue)

Layer		Medium thickness (m)	Head, m	K (m/d)		Layer color in the model
				horizontal	vertical	
O	1. Layer: Aquifer	22	13.5	8.1	1.6	
	2. Layer: Aquitard	5	6.3	10^{-3}	10^{-6}	
O-Ca	3. Layer: Aquifer	29	0.81	1.8	0.4	
Ca-V	4. Layer: Aquitard	45	-1.18	10^{-6}	10^{-6}	
	5. Layer: Aquifer	81	-3.17	9.14	1.83	

Note, in the hydrogeological model the clayey Sämi formation which does not form strong aquitard is included to the Ca-V aquifer total thickness.

The ground elevation data from the official Estonian Land Board Digital elevation model was used to form the surface relief. Altitude data obtained were entered into the model as 2D points. The 2D point information was interpolated to the model grid for surface relief using the natural neighbor method (Figure 28).

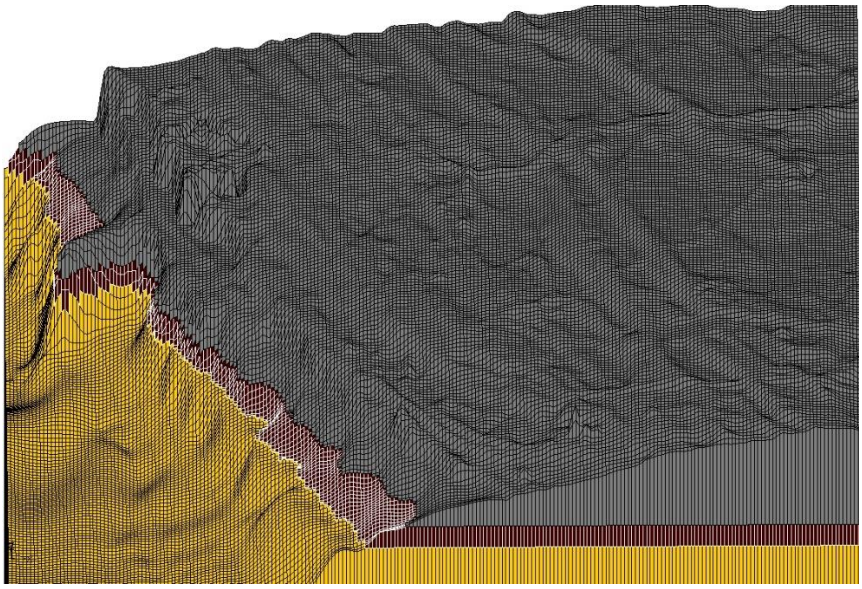

Figure 28. Surface relief of the modeled area of Paldiski city

9.2. Boundary conditions

Specifying the boundary conditions of the ground-water flow system means assigning a boundary to every point on the boundary surface. Usually, the selection of boundary conditions for a conceptual or numerical model involves considerable simplification of actual hydrogeologic conditions.

The wells opening the groundwater layer of the Ordovician, Ordovician-Cambrian, and Cambrian-Vendian aquifers are concentrated in the territory of the city of Paldiski (Figure 9), village of Laoküla, village of Kersalu, village of Vihterpalu and in the small borough of Klooga, therefore this outer boundary of the concentrated wells and maximum size of modeling area that modeling software can accommodate, was used as the main boundary size condition of the model. The chosen modeling area size is considered to be sufficient to reliably estimate the PHES construction activities effect to the local groundwater bodies.

The boundary conditions of the groundwater model are defined as follows:

- The northern boundary conditions of the model were determined based on the:
  - Ordovician aquifer boundary condition has been set as drain until the top boundary of the graptolite argillite. The set drain boundary condition extends from the northern point of the peninsula until to the point where the top boundary of the graptolite argillite unit is below the sea level, from this point onwards the boundary condition has been set as constant head.
  - Ordovician-Cambrian aquifer boundary condition has been set as constant head in full extent of the peninsula.
  - Cambrian-Vendian aquifer boundary condition has been set as constant head to the outcrop line extending in the sea bottom.
- The western and eastern boundary conditions (specified head) of the model were determined for the Ordovician and Ordovician-Cambrian layers by the groundwater layer outcropping in the sea and for the Cambrian-Vendian layer by interpolating groundwater head data and implementing it as a specified head value.

– The southern boundary conditions of the model were determined based on the water levels of the existing wells by interpolating groundwater head data and implementing it as a specified head value.

On the first layer of the model a drain and river modules were used to discharge accumulated water as it is done in real situation on the base of peninsula. Due to modeling grid being wider than real drain dich then natural drain situation is represented by fewer drain diches in model but with enough to reach current water level. Neto infiltration has been set for whole first layer as a single value. For the bottom of the model no flow condition has been set.

Due to the small number of the Ordovician and Ordovician-Cambrian water complex wells, that are accessible, it is difficult to assess the natural water level of the region in the respective groundwater layer.

For the first model layer, the **Quaternary and Ordovician deposits**, hydraulic heads decrease from a value of 22 m in the middle of the Paldiski peninsula to a value of 0 m on the sea border.

For the third layer, the **Ordovician-Cambrian aquifer**, the hydraulic head decreases from a value of 2 m in the middle of the Paldiski peninsula to a value of 0 m on the sea border.

For the fifth layer, the **Cambrian-Vendian aquifer**, hydraulic heads decrease from 0 m in the north to -8.5 m in the southeast and -7.3 m in the southwest corner.

For the layers that are classified as the aquitards (layers 2 and 4), initial hydraulic heads also have to be defined before the model can be operated. Since no observation well data are present for these layers, the average value between the layer on top and below is taken as initial hydraulic head for each of these impermeable layers.

9.3. Recharge

At the top of the model, groundwater recharge has been taken into account. Values for groundwater recharge can be entered through the Recharge flow package. The recharge is assigned to the highest active layer. Groundwater recharge is defined as the precipitated water minus the evapotranspiration water. Value for groundwater recharge (37% from precipitation) is based on the input that evapotranspiration accounts for 63% (see Chapter 6.2) and that a median precipitation average is 577 mm/y (see Chapter 6.1), so daily groundwater supply of 0.00058 m/d is assigned to the top layer of the model. This value represents the average situation at any given time at any location in the model area.

9.4. Model input for scenario modeling

As described in Chapter 7, the construction of vertical shafts are done and also modeled in two stages with the conservative approach that the shafts will be constructed in parallel within the appropriate stage. The water extraction from the shafts has been conservatively considered to be simultaneous and simulated one aquifer at a time by using well function

in modeling software to pump out certain amount of groundwater from proposed shaft area (water extractions is based on groundwater amounts and not by head).

To assess the impacts of the PHES shafts construction works to the local groundwater, a set of modeling scenarios have been prepared. Based on these set of scenarios it's possible to suggest groundwater inflow limit values for the shafts construction works that would not cause unacceptable effects to the local groundwater. These values would be set for the construction works as not to be exceeded and the construction contractor would be responsible to foresee suitable mitigation methods (freeze wall or grouting) to bring the groundwater inflows to the limits.

Based on the SEA report prepared by Skepast&Puhkim OÜ (S&P), it is necessary to consider two possible scenarios (scenario 1 and scenario 3) that have been given as limiting design criteria for the construction works. Additionally, two additional maximum inflow scenarios have been incorporated to model also the lower and higher water extraction values (scenario 2 and scenario 4) and assess the most suitable limit value to be set for the construction of PHES shafts:

- 1. Scenario predicts groundwater level in aquifers due to potential seepage/leakage of groundwater to the completed shafts after the construction. The groundwater inflow into a single vertical shaft is 43.2 m^3/d/100 m (amount defined in SEA report, expert estimate):
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time.
  - 2. Stage: Total of 1 vertical shaft is constructed at a time.
- 2. Scenario predicts groundwater level in aquifers due to low volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 250 m^3/d:
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 1500 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 250 m^3/d water extraction).
- 3. Scenario predicts groundwater level in aquifers due to middle volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 500 m^3/d (amount defined in SEA report):
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 3000 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 500 m^3/d water extraction).
- 4. Scenario predicts groundwater level in aquifers due to high volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 1000 m^3/d:
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 6000 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 1000 m^3/d water extraction).

9.4.1. First scenario

In the first scenario, the vertical shaft area is divided vertically into three parts: Ordovician, Ordovician-Cambrian, and Cambrian-Vendian. For the first two aquifers (O and O-Ca) rate of 43.2 m^3/d/100 m is recalculated to match the thickness of the aquifer and for the Cambrian-Vendian aquifer the whole 43.2 m^3/d is implemented. In the model, groundwater abstraction points represent vertical shafts that reach into the corresponding aquifer, and drawdown is modeled. After interpreting the results, abstraction points are removed and entered into a next aquifer layer for the next model run to get drawdown results for that specific target aquifer.

For one vertical shaft, the total amount of water abstracted is 9.5 m^3/d in the Ordovician aquifer, 12.5 m^3/d in the Ordovician - Cambrian aquifer and the Cambrian-Vendian aquifer 43.2 m^3/d (see Appendix 8.1).

The abstraction rate for one vertical shaft in one layer is calculated from the following equation.

$$\frac{Q_1}{h_1} = \frac{Q_2}{h_2} => Q_2 = \frac{Q_1 * h_2}{h_1}, \text{ where}$$

Q_1 – the amount of water per day per 100 m (m^3/d/100 m)
Q_2 - the amount of water per day per aquifer thickness (m^3/d/m)
h_1 - thickness of aquifer as 100 m
h_2 - thickness of real aquifer (m)

In the first stage, a total of 6 shafts are modeled simultaneously in an aquifer except in Ordovician aquifer where only 5 shafts are modeled simultaneously because the water intake shaft does not have the Ordovician aquifer present (has been eroded).

The total amount of water pumped out in the first scenario from the Ordovician aquifer is around 47.5 m^3/d, in the Ordovician-Cambrian aquifer 75 m^3/d and the Cambrian-Vendian 259.2 m^3/d (see Appendix 8.1).

In the second stage, when only one vertical shaft is constructed total amount of water abstracted is 9.5 m^3/d in the Ordovician aquifer, 12.5 m^3/d in the Ordovician - Cambrian aquifer and in the Cambrian-Vendian aquifer 43.2 m^3/d as previously stated and calculated in Appendix 8.1.

9.4.2. Second scenario

In the second scenario, groundwater abstraction rate of 250 m^3/d has been considered from every vertical shaft in the corresponding construction stage one aquifer at a time. As in the first scenario, the shaft is divided vertically into three parts: Ordovician, Ordovician-Cambrian, and Cambrian-Vendian. In the model, groundwater abstraction points represent vertical shafts that reach into the corresponding aquifer, and drawdown is modeled. After interpreting the results, abstraction points are removed and entered into a next aquifer layer for the next model run to get drawdown results for that specific target aquifer.

In a first stage total of 6 shafts are modeled simultaneously in an aquifer except in Ordovician aquifer where only 5 shafts are modeled simultaneously because the water intake shaft does not have the Ordovician aquifer present (has been eroded).

The total amount of water pumped out in the second scenario from O aquifer is 1250 m^3/d and from O-Ca and Ca-V aquifer 1500 m^3/d (for calculations see Appendix 8.2).

In second stage, when only one vertical shaft is constructed the water abstracted per aquifer is 250 m^3/d.

9.4.3. Third scenario

In the third scenario, groundwater abstraction rate of 500 m^3/d has been considered from every vertical shaft in the corresponding construction stage one aquifer at a time. As in the first scenario, the shaft is divided vertically into three parts: Ordovician, Ordovician-Cambrian, and Cambrian-Vendian. In the model, groundwater abstraction points represent vertical shafts that reach into the corresponding aquifer, and drawdown is modeled. After interpreting the results, abstraction points are removed and entered into a next aquifer layer for the next model run to get drawdown results for that specific target aquifer.

In the first stage, a total of 6 shafts are modeled simultaneously in an aquifer except in Ordovician aquifer where only 5 shafts are modeled simultaneously because the water intake shaft does not have the Ordovician aquifer present (has been eroded).

The total amount of water pumped out in the third scenario from O aquifer is 2500 m^3/d and from O-Ca and Ca-V aquifer 3000 m^3/d (for calculations see Appendix 8.3).

In second stage, when only one vertical shaft is constructed the water abstracted per aquifer is 500 m^3/d.

9.4.4. Fourth scenario

In the fourth scenario, groundwater abstraction rate of 1000 m^3/d has been considered from every vertical shaft in the corresponding construction stage one aquifer at a time. As in the first scenario, the shaft is divided vertically into three parts: Ordovician, Ordovician-Cambrian, and Cambrian-Vendian. In the model, groundwater abstraction points represent vertical shafts that reach into the corresponding aquifer, and drawdown is modeled. After interpreting the results, abstraction points are removed and entered into a next aquifer layer for the next model run to get drawdown results for that specific target aquifer.

In a first stage total of 6 shafts are modeled simultaneously in an aquifer except in Ordovician aquifer where only 5 shafts are modeled simultaneously because the water intake shaft does not have the Ordovician aquifer present (has been eroded).

The total amount of water pumped out in the fourth scenario from O aquifer should be 5000 m^3/d but modelling has demonstrated that it would be possible to extract only 675

m^3/d due to cells of extraction running try. From O-Ca and Ca-V aquifer total of 6000 m^3/d (for calculations see Appendix 8.4) of water will be pumped out.

In second stage, when only one vertical shaft is constructed the water abstracted per aquifer is 1000 m^3/d.

9.5. Calibration and model verification

Model calibration by standard techniques requires a primary (historical) database for key variables plus statistical expertise. As mentioned before lack of data in Ordovician and Ordovician-Cambrian water levels makes calibration quite difficult. The current model has been calibrated so that modeled water levels in the PHES area would be as similar as possible to measurements gathered in real life. For calibration groundwater level must be changed in model boundary conditions to achieve near natural water levels in measurement points. By achieving this calibration we can consider the model to be verified. The summary of the calibration results has been given in the Table 7.

Calibration in the Ordovician aquifer is problematic because the only accessible source of groundwater level to be used as boundary condition was an artificial lake in the eastern part of the model and only observation points were well No. 19883 and 19884 (Figure 14). The difference between modeled and measured groundwater levels is approximately 12.5 cm which is in the limits of the expected natural groundwater level fluctuation.

Calibration in Ordovician-Cambrian aquifer is problematic because there was no accessible groundwater level information near the boundary area and only measurable information was acquired from PAL-Well_1 and well No. 19885. The difference between modeled and measured groundwater levels (based on PAL-Well_1) is approximately 1 cm which is in the limits of the expected natural groundwater level fluctuation.

Calibration in Cambrian-Vendian aquifer was more straightforward than with the other aquifers. Due to a lack of qualitative information from the local water supply company (see Chapter 5.2), historic water levels were also used to estimate new measurement quality of water supply wells. The difference between modeled and measured groundwater levels (based on PAL-Well_1) is approximately 0.05 m which is in the limits of the expected natural groundwater level fluctuation.

Table 7. Results of comparing the measured and calculated groundwater levels

Name of the aquifer	Well cadaster number	Measured groundwater levels (m)	Calculated groundwater levels (m)	Measured and calculated groundwater difference (m)
O	19884	14.10	14.25	0.15
O	19883	15.20	15.1	0.1
O-Ca	19885	0.70	0.71	0.01
Ca-V	PAL-Well_2	-3.17	-3.22	0.05

Note, the hydrogeological modeling results presented in the next chapter show the average drawdown to which the natural fluctuation of the corresponding groundwater level must be added or deducted.

10. RESULTS OF SITUATION MODELING

10.1.Groundwater inflow into the vertical shaft during the construction

By using the built hydrogeological model and PHES construction information presented in Chapter 7 it is possible to estimate the amount of groundwater that would be flowing into the vertical shaft during construction works in case no mitigation (freezing or pre-grouting) would be done for decreasing the groundwater inflow.

For the estimation a drain module was used in modeling software to drain whatever amount of water needed to keep the open shaft area (Figure 29) dry. In addition, separate calculations were made to cross-check the model estimation data, all the results are presented in table 12.

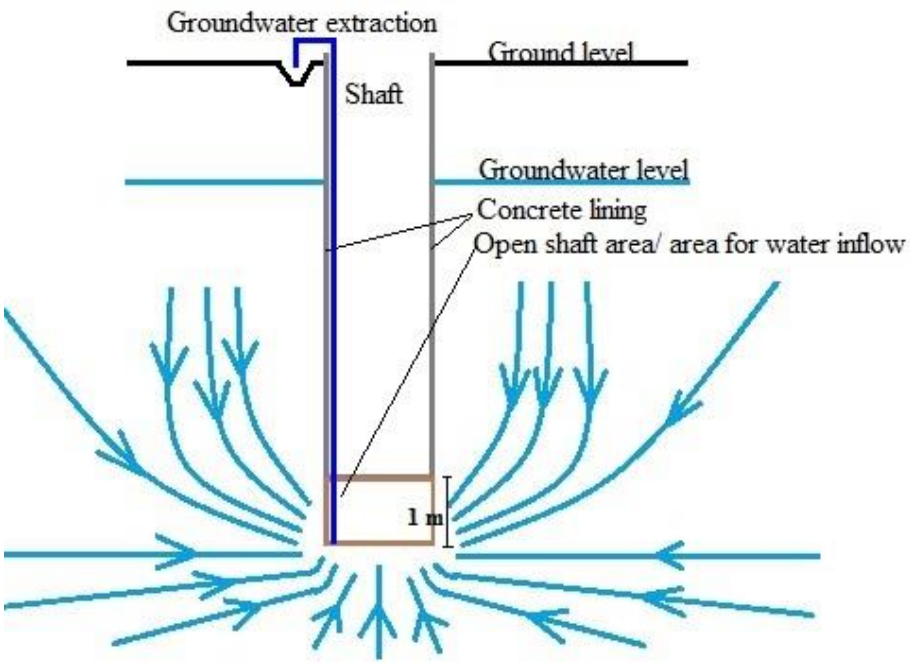

Figure 29. Water inflow into the shaft.

For water inflow calculations following formulas were used:

Confined aquifer (Wang et al., 2020)

$$Q = 2.73\frac{KMS}{\lg\frac{R}{r}}$$

Unconfined aquifer (Wang et al., 2020)

$$Q = 1.366\frac{K(2H - S)S}{\lg\frac{R}{r}}$$

Radius of influence of well (Sichardt formula)

$$R = 3000S\sqrt{K}$$

Only possible groundwater inflow into the shaft could occur through the shaft bottom and the 1 m vertical open wall as it is intended to install a concrete lining in the shaft immediately after each 1 m excavation cycle (Figure 29). Lining represents 0.4 - 0.5 thick reinforced concrete to secure vertical shaft wall and to isolate shaft from groundwater.

When describing the size of the excavated shaft by using diameter, in addition to shafts inner diameter two times of shaft lining thicknesses should be taken into account. The sum of inner shaft diameter plus two times of lining thickness gives a total diameter of excavated shaft which allows the calculation of total shaft area from where water can flow in.

For groundwater inflow (quantity) into other size diameter shafts parallel models were created (not as accurate as original model). Different necessary diameters in all aquifers were modeled for groundwater inflow amounts. These amounts were later recalculated into change in percent value compared to 19.5 m diameter model. Percentages were then used as a multiplier to evaluate real inflows into different diameter shafts on basis of the real 19.5 m (diameter) shaft inflow model.

If the shaft is made through solid limestone (as encountered in PAL-Well and PAL-1 drillings at the PHES area), the groundwater inflow from the Ordovician aquifer will not occur. In the case of fractured limestone, inflow values may somewhat differ from modeled because the fracture amount and size determine the inflow rate.

Table 11. Data input

Parameters		Unit	S-O (unconfined aquifer)	O-Ca (confined aquifer)	Ca-V (confined aquifer)
K	Hydraulic conductivity	m/d	8.1	1.8	9.14
		m/s	0.000094	0.000021	0.000106
M	Thickness of the aquifer	m	22	29	81
S	Drawdown	m	22	41	162
R	Radius of influence of the well (shaft)	m	639	561	4999
r	Well (shaft) radius	m	9.75		
			6.50		
			3.25		
			3.00		
			2.90		
H	Initial piezometric head (from the bottom of aquifer)	m	22	41	162

Table 12. Results of the modeling and calculations

Silurian-Ordovician aquifer							
r_w	Well (shaft) radius	m	9.75	6.5	3.25	3.0	2.90
Q	Inflow from sedimentary rocks (calculated)	m^3/d	2 948	2 688	2 335	2 300	2 286
Q	Inflow from sedimentary rocks (modelled)	m^3/d	1 697	1 550	1 340	1 320	1 316
Ordovician-Cambrian aquifer							
r_w	Well (shaft) radius	m	9.75	6.5	3.25	3.0	2.90
Q	Inflow from sedimentary rocks (calculated)	m^3/d	3 319	3 017	2 611	2 571	2 555
Q	Inflow from sedimentary rocks (modelled)	m^3/d	3 225	3 180	2 540	2 500	2 480
Cambrian-Vendian aquifer							
r_w	Well (shaft) radius	m	9.75	6.5	3.25	3.0	2.90
Q	Inflow from sedimentary rocks (calculated)	m^3/d	120 827	113 454	102 738	101 629	101 167
Q	Inflow from sedimentary rocks (modelled)	m^3/d	130 675	125 760	111 100	109 900	109 400

Based on the raw groundwater inflow estimates (Table 11) it can be concluded that the water volumes are many folds larger than the modeled 4 scenarios. As such, suitable inflow prevention mitigation (freezing or pre-grouting) is needed to be implemented for the shafts construction works to reduce groundwater inflow into the shafts to acceptable limits. In case of pre-grouting there should be collaboration with local water company to prevent grout inflow to the nearest water supply well while pre-grouting is in progress.

Also, during the shaft sinking and construction works it is imperative to make sure that the three main aquifers will not be allowed to interconnect and will be sealed from each other properly.

10.2. Modeled groundwater levels and drawdown maps

10.1.1. Ordovician aquifer

Groundwater level changes in the Ordovician aquifer may differ drastically if the shaft is excavated through solid limestone or fractured limestone. If the shaft is made through solid limestone the effects to the groundwater will not occur. The drilling works conducted by STEIGER on the PHES project area have not encountered heavily fractured limestones in the Ordovician aquifer and the conducted pumping test (see Chapter 8.1)

has yielded low hydraulic conductivity. Because of this, only historic data (see chapter 4.2) has been used to model the possible situation when the shaft is made through fractured limestone. The outcome of groundwater modeling in the Ordovician aquifer has been presented in Figure 29 to Figure 37 (pre- and postprocessing data of the computational analysis in Appendix 9.1 – Appendix 9.9).

As expected, the first scenario parameters do not influence groundwater levels in the extent to form a considerable drawdown (Figure 30, Figure 31, Appendix 9.2 and Appendix 9.3).

In the second scenario, where 250 m^3/d is extracted per shaft, a maximum of 4 m drawdown is expected in the shaft area in the first stage and 1.5 m in the second stage (Figure 32, Figure 33, Appendix 9.4 and Appendix 9.5). In case of shaft construction penetrating a fractured part of bedrock and local drainage ditches water does not infiltrate through fractures into O aquifer near the construction site or wells, the drawdown in the nearest Ordovician wells No. 19883 and 19884 is expected to be 0.6-0.5 m (Table 8)

Based on the third scenario, where 500 m^3/d is extracted per shaft, a maximum of 10 m drawdown is expected in the shaft area in the first stage and 3.2 m in the second stage (Figure 34, Figure 35, Appendix 9.6 and Appendix 9.7). In case of shaft construction penetrating a fractured part of bedrock and local drainage ditches water does not infiltrate through fractures into O aquifer near the construction site or wells, the drawdown in Ordovician wells No. 19883 and 19884 is expected to be 1.55-1.3 m (Table 8), but if drainage water, near the wells or northwest of the PHES area, infiltrates through fractures into groundwater then there may not be any influence on the previously mentioned wells.

In the fourth scenario, where 1000 m^3/d is extracted per shaft, a maximum model cells run dry showing that such amount of water cannot be taken out in long period of time so maximum amount of water 575 m^3/d was simulated. A 15.3 m drawdown is expected in the shaft area in the first stage and 7.21 m in the second stage (Figure 36, Figure 37, Appendix 9.8 and Appendix 9.9). In case of shaft construction penetrating a fractured part of bedrock and local drainage ditches water does not infiltrate through fractures into O aquifer near the construction site or wells, the drawdown in the nearest Ordovician wells No. 19883 and 19884 is expected to be 1.85-1.55 m (Table 8)

Table 8. Modeled Ordovician groundwater level drawdowns in local wells inside the area of effect

Scenario	1 (43.2 m^3/d per shaft)		2 (250 m^3/d per shaft)		3 (500 m^3/d per shaft)		4 (575* m^3/d per shaft)	
Stage	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)
Drawdown in m, 19883	0	0	0.6	0.15	1.55	0. 2	1.85	0.75
Drawdown in m, 19884	0	0	0.5	0.15	1.3	0.15	1.55	0.6
Drawdown in m, 24994	0	0	0.1	0	0.4	0	0.55	0.2

*Model cells running dry with higher inflow

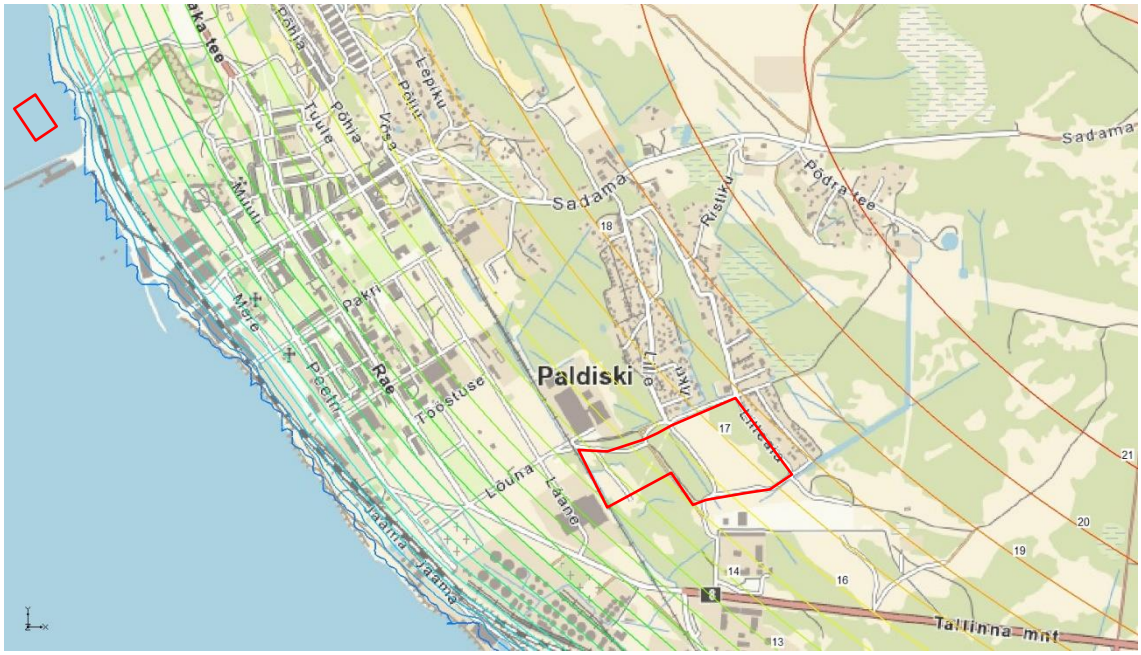

Figure 30. Static groundwater level (referenced to sea level) of the Ordovician aquifer without PHES activities

1. Scenario (43.2 m^3/d per shaft) of Ordovician aquifer

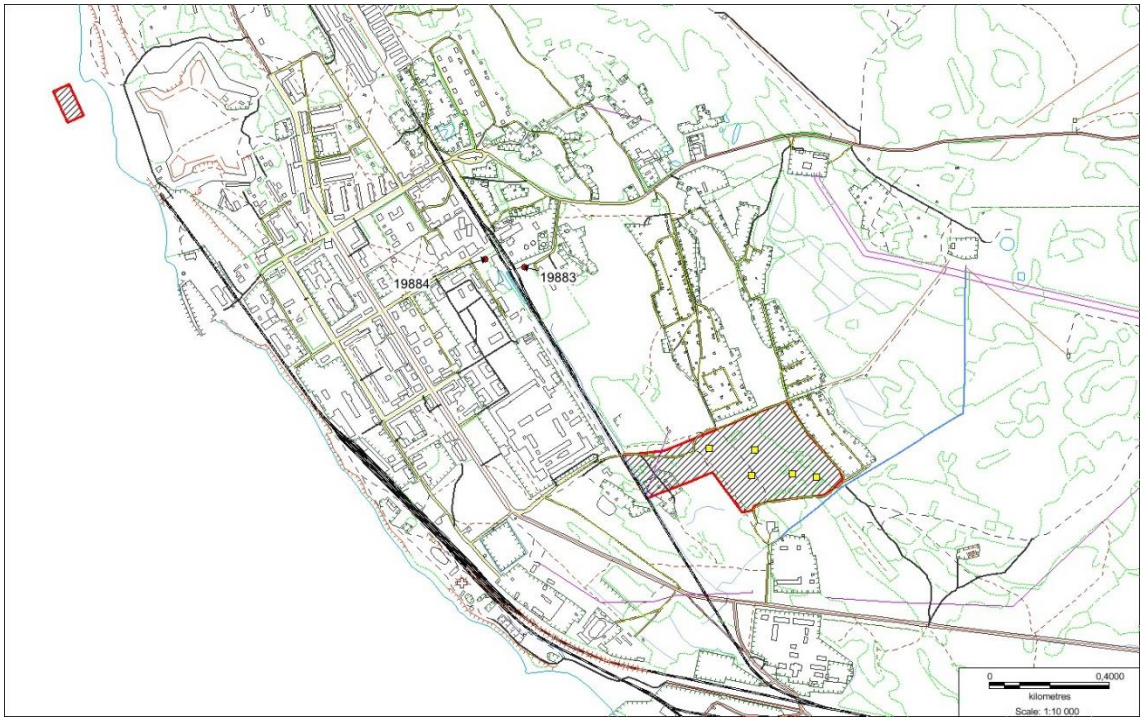

Figure 31. The results of modeling drawdown in the O aquifer, representing the first stage (6 shafts) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

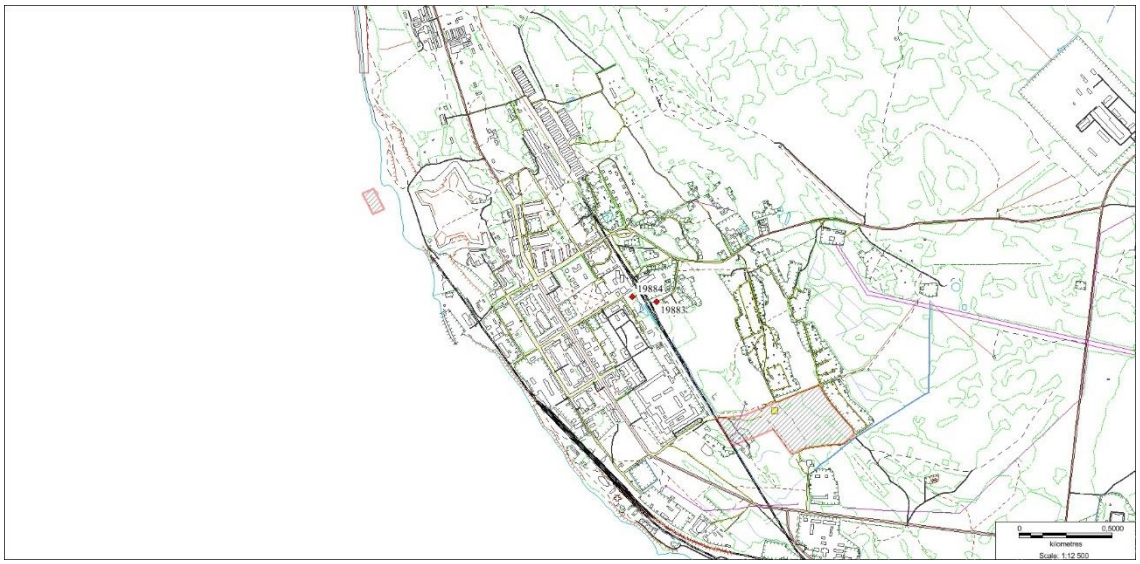

Figure 32. The results of modeling drawdown in the O aquifer, representing the second stage (1 shaft) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

2. Scenario (250 m^3/d per shaft) of Ordovician aquifer

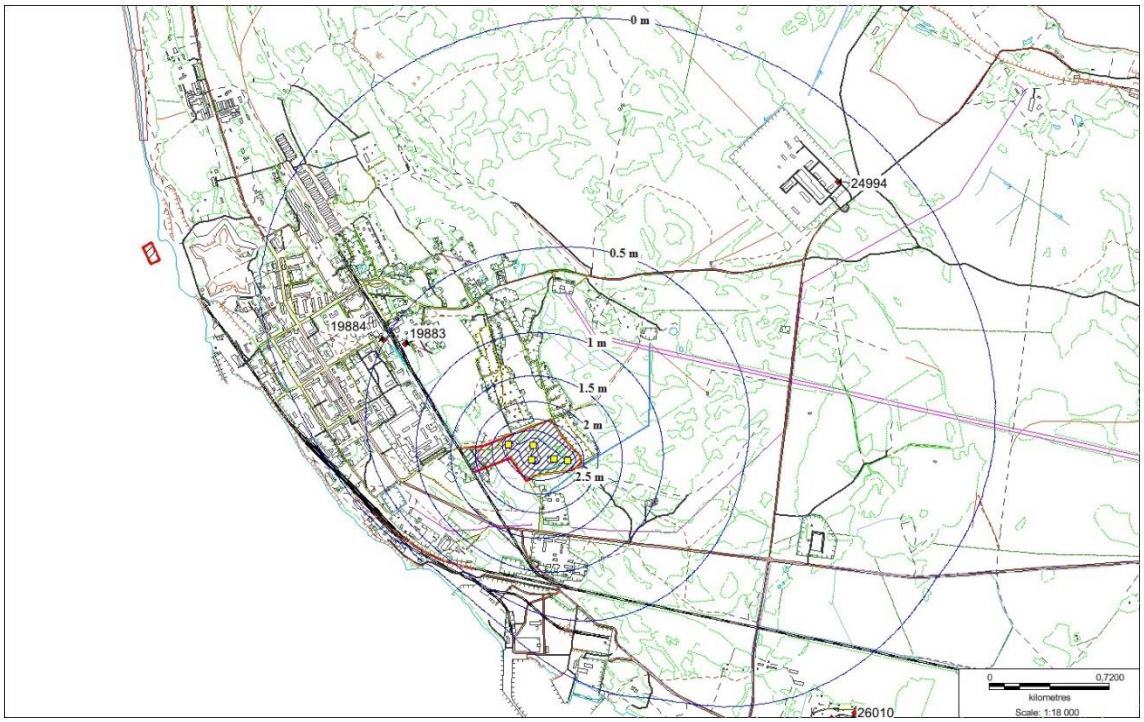

Figure 33. The results of modeling drawdown in the O aquifer, representing the first stage (6 shafts) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

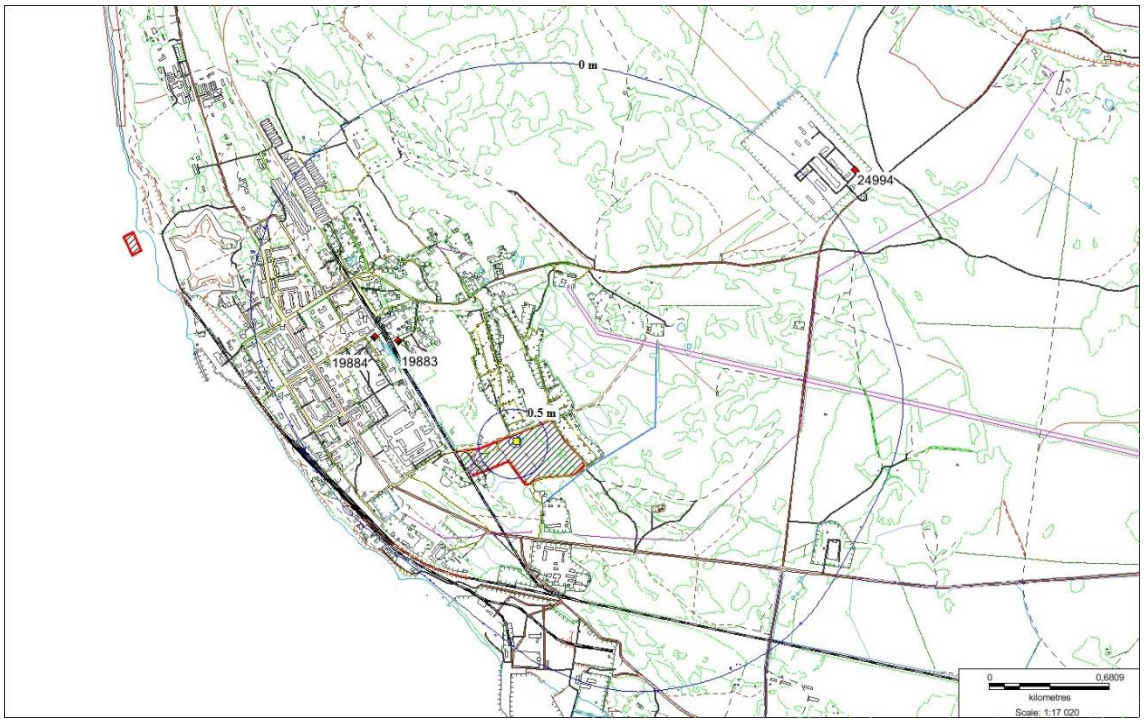

Figure 34. The results of modeling drawdown in the O aquifer, representing the second stage (1 shaft) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

3. Scenario (500 m^3/d per shaft) of Ordovician aquifer

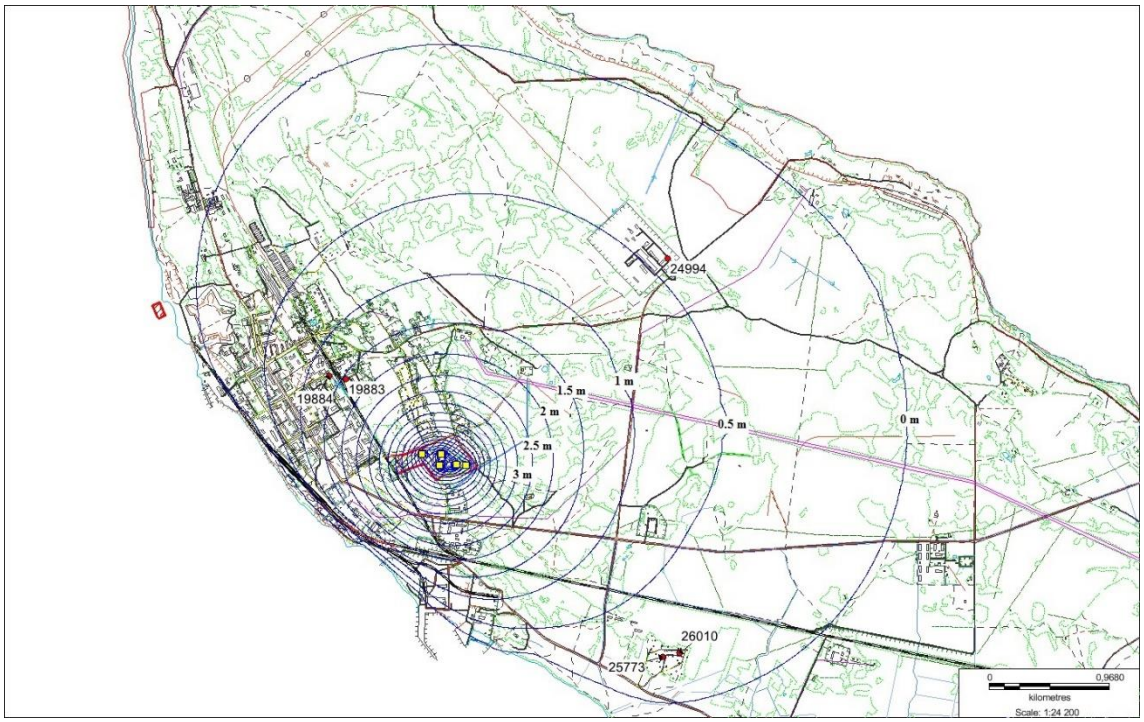

Figure 35. The results of modeling drawdown in the O aquifer, representing the first stage (6 shafts) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

Figure 36. The results of modeling drawdown in the O aquifer, representing the second stage (1 shaft) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

4. Scenario (575 m^3/d per shaft) of Ordovician aquifer

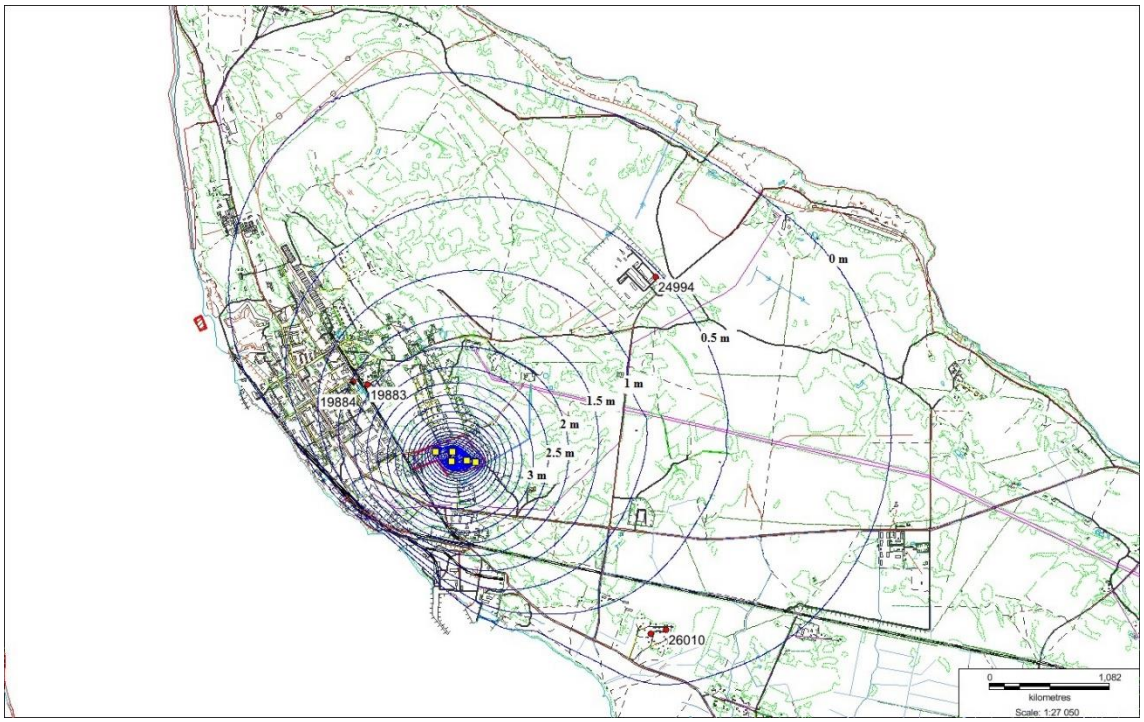

Figure 37. The results of modeling drawdown in the O aquifer, representing the first stage (6 shafts) of the first scenario (575 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

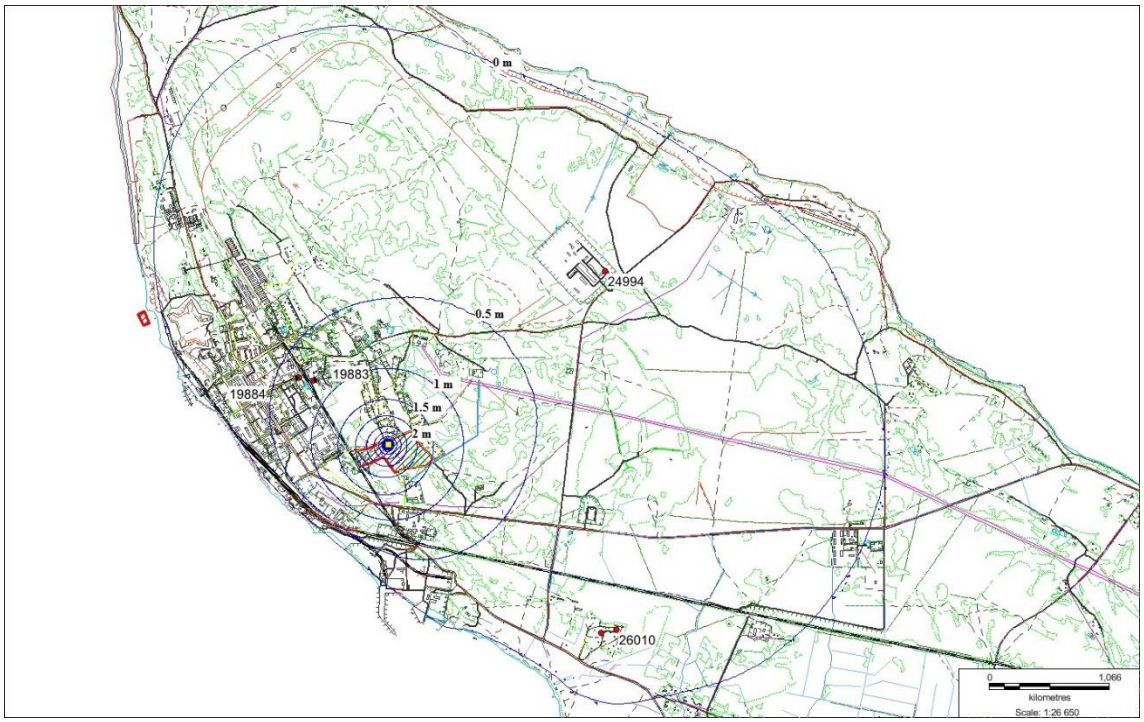

Figure 38. The results of modeling drawdown in the O aquifer, representing the second stage (1 shaft) of the second scenario (575 m^3/d per shaft). Yellow dots represent shafts intersecting the O aquifer

10.1.2. Ordovician-Cambrian aquifer

The outcome of groundwater modeling in Ordovician-Cambrian aquifer has been presented in Figure 38 to Figure 46 (pre- and postprocessing data of the computational analysis in Appendix 9.1 and Appendix 9.10 - Appendix 9.17). As expected, the first scenario parameters do not influence groundwater in extents to form a considerable drawdown (Figure 39, Figure 40, Appendix 9.10 and Appendix 9.11).

Based on the second scenario, where 250 m^3/d is extracted per shaft, a maximum of 10.9 m drawdown is expected in the shaft area in the first stage and 4.2 m in the second stage (Figure 41, Figure 42, Appendix 9.12 and Appendix 9.13). The largest impact is expected for nearby O-Ca wells No. 18103 and 18175 with a drawdown of up to 5.85 m. Drawdown effect on all the local wells in the area of influence is shown in table 9.

In the third scenario, where 500 m^3/d is extracted per shaft, a maximum of 21.8 m drawdown is expected in the shaft area in the first stage and 8.3 m in the second stage (Figure 43, Figure 44, Appendix 9.14 and Appendix 9.15). The largest impact is expected for O-Ca wells No. 18103 and 18175 with a drawdown of up to 12 m. Drawdown effect on all the local wells in the area of influence is shown in table 9.

Based on the fourth scenario, where 1000 m^3/d is extracted per shaft, a maximum of 40.5 m drawdown is expected in the shaft area in the first stage and 16.6 m in the second stage (Figure 45, Figure 46, Appendix 9.16 and Appendix 9.17). The largest impact is expected for O-Ca wells No. 18103 and 18175 with a drawdown of up to 24 m. Drawdown effect on all the local wells in the area of influence is shown in table 9.

Table 9. Modeled Ordovician-Cambrian groundwater level drawdowns in local wells inside the area of effect

Scenario	1 (43.2 m^3/d per shaft)		2 (250 m^3/d per shaft)		3 (500 m^3/d per shaft)		4 (1000 m^3/d per shaft)	
Stage	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)
Drawdown in m, 18103	0	0	5.85	1.4	12	2.85	24	5.85
Drawdown in m, 18175	0	0	5.85	1.4	12	2.75	24	5.75
Drawdown in m, 545	0	0	1.75	0.35	3.75	0.75	7.75	1.65
Drawdown in m, 19885	0	0	1.80	0.35	3.9	0.75	8	1.7
Drawdown in m, 59452	0	0	2.5	0.5	5.25	1	10.75	2.15
Drawdown in m, 14855	0	0	1.15	0.2	2.6	0.4	5.35	1

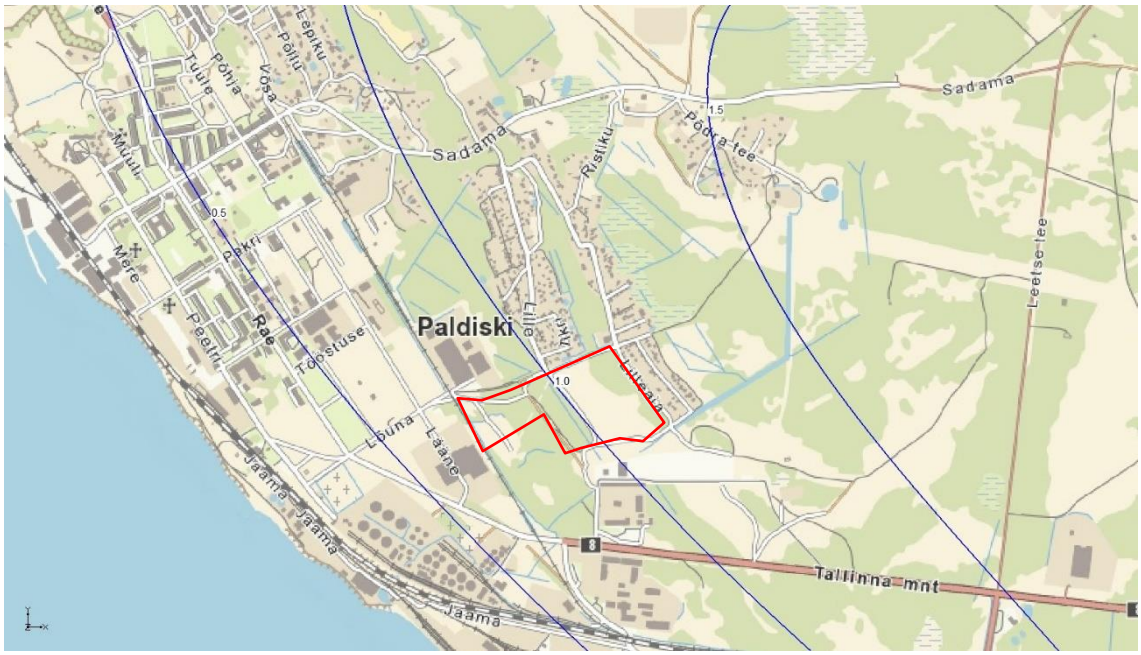

Figure 39. Static groundwater level (referenced to sea level) of the Ordovician-Cambrian aquifer without PHES activities

1. Scenario (43.2 m^3/d per shaft) of Ordovician-Cambrian aquifer

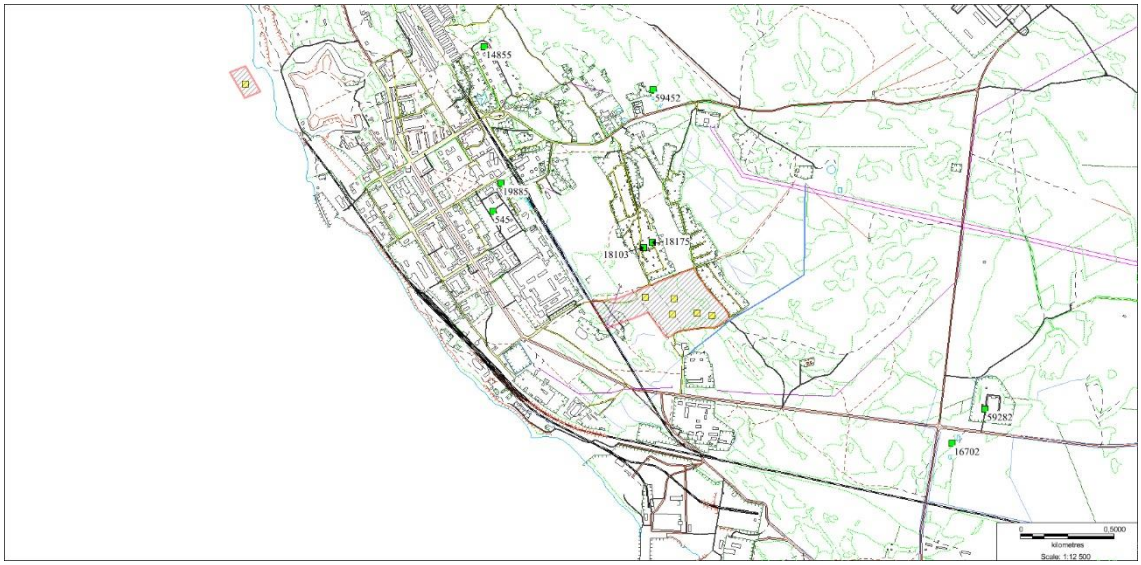

Figure 40. The results of modeling drawdown in the O-Ca aquifer, representing the first stage (6 shafts) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

Figure 41. The results of modeling drawdown in the O-Ca aquifer, representing the second stage (1 shaft) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

2. Scenario (250 m^3/d per shaft) of Ordovician-Cambrian aquifer

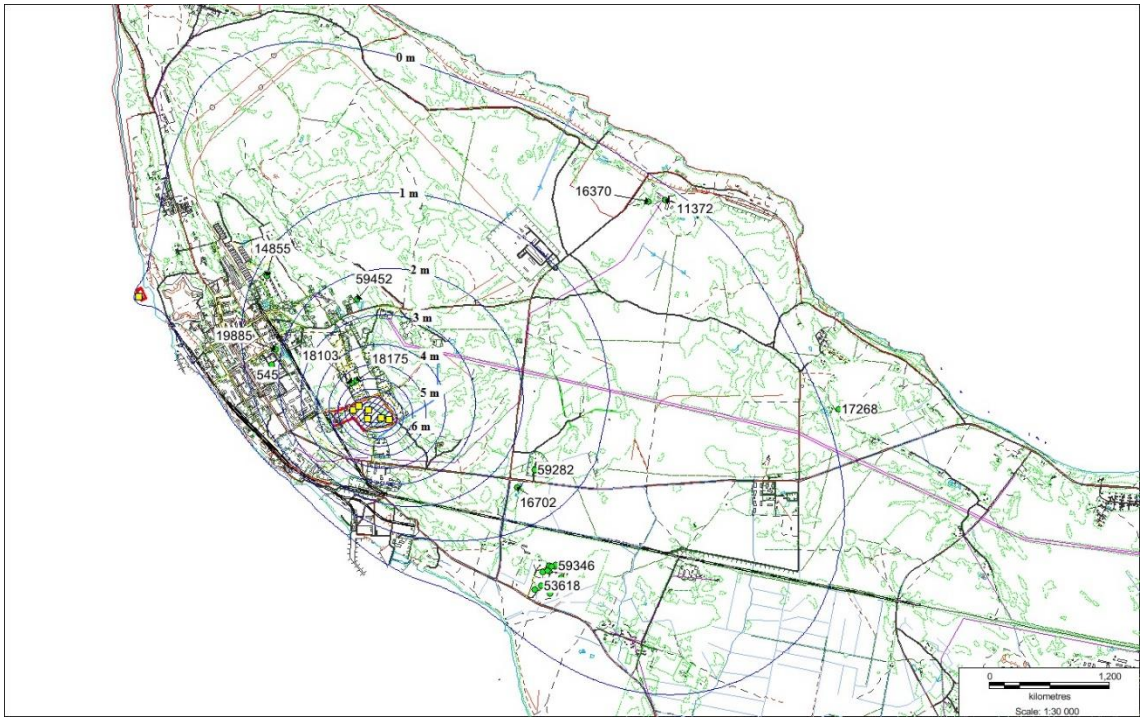

Figure 42.The results of modeling drawdown in the O-Ca aquifer, representing the first stage (6 shafts) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

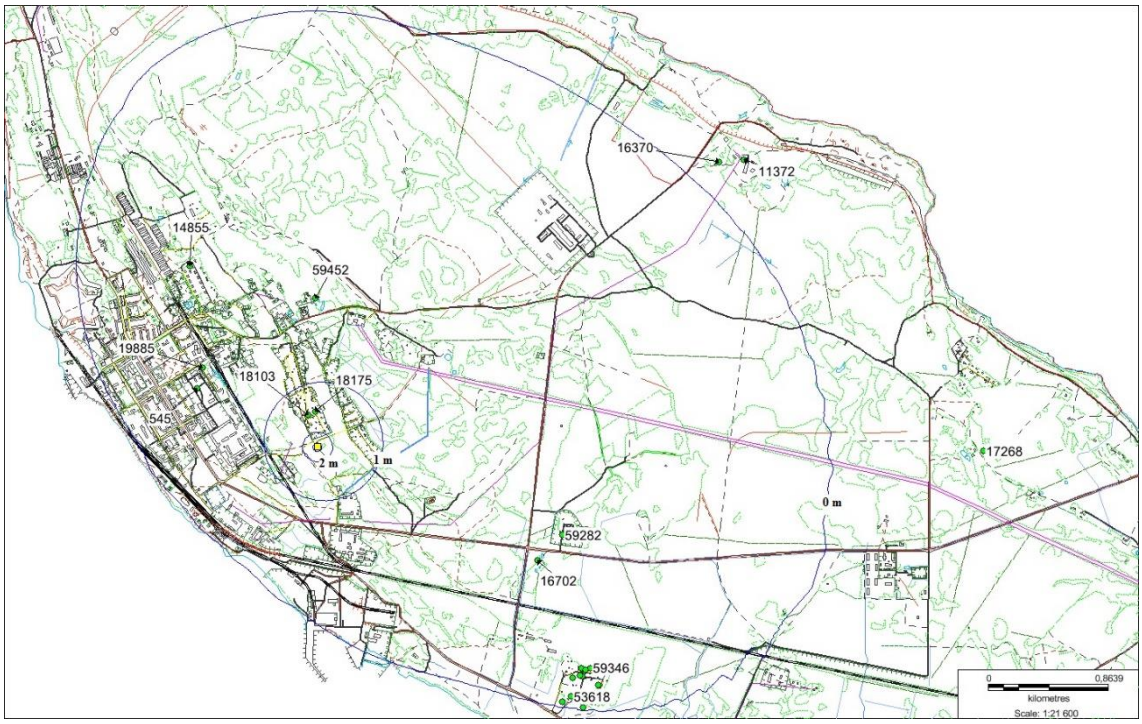

Figure 43. The results of modeling drawdown in the O-Ca aquifer, representing the second stage (1 shaft) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

3. Scenario (500 m^3/d per shaft) of Ordovician-Cambrian aquifer

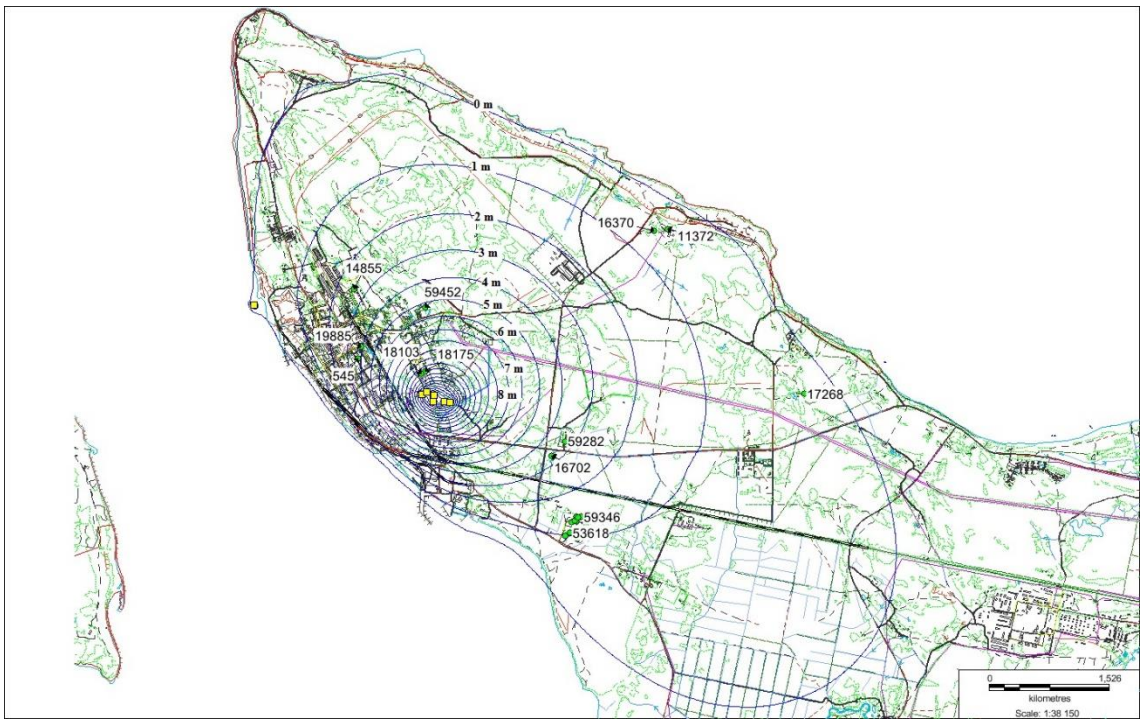

Figure 44. The results of modeling drawdown in the O-Ca aquifer, representing the first stage (6 shafts) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

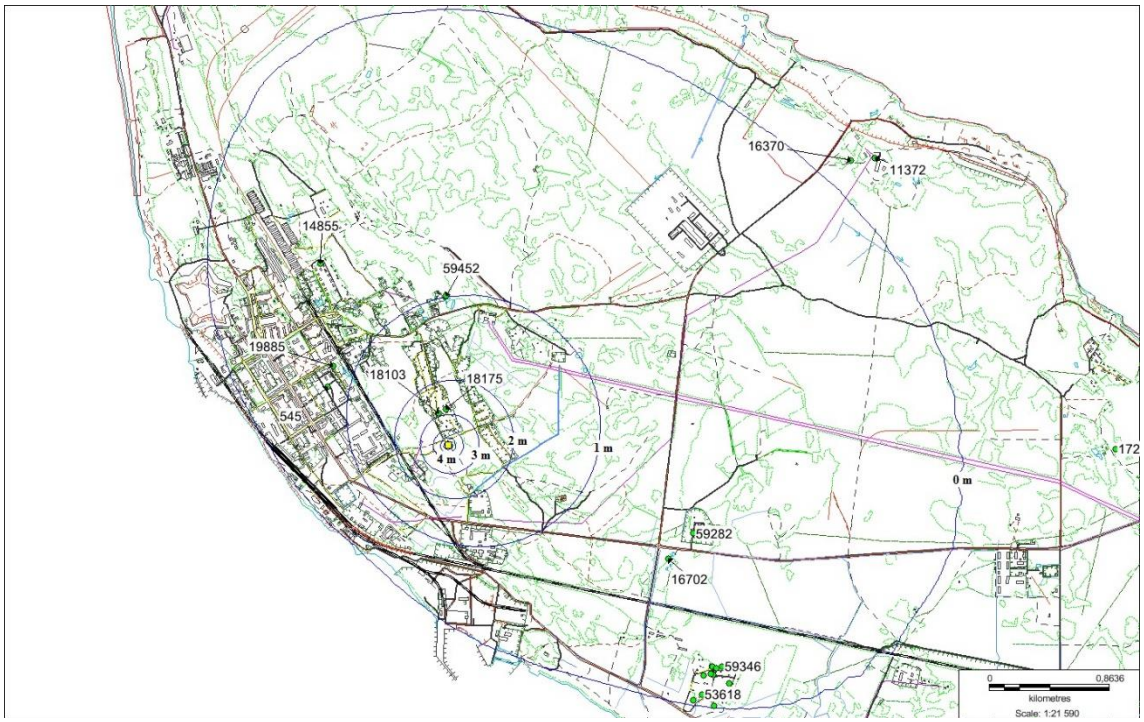

Figure 45. The results of modeling drawdown in the O-Ca aquifer, representing the second stage (1 shaft) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

4. Scenario (1000 m^3/d per shaft) of Ordovician-Cambrian aquifer

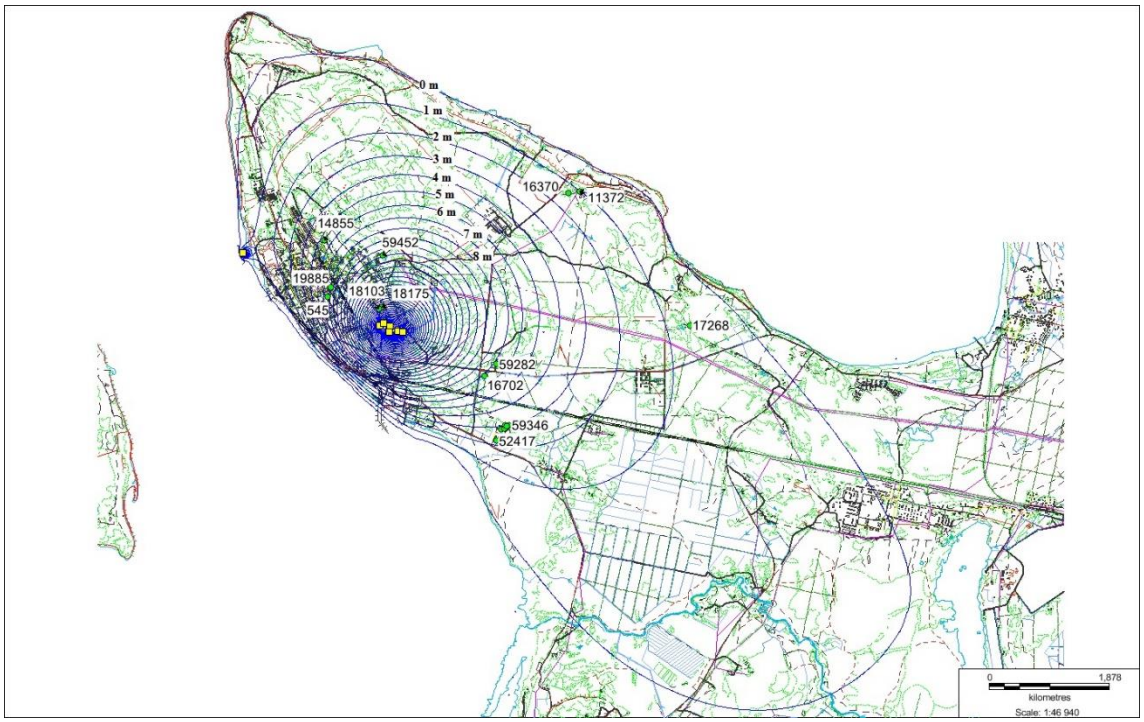

Figure 46.The results of modeling drawdown in the O-Ca aquifer, representing the first stage (6 shafts) of the fourth scenario (1000 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

Figure 47. The results of modeling drawdown in the O-Ca aquifer, representing the second stage (1 shaft) of the fourth scenario (1000 m^3/d per shaft). Yellow dots represent shafts intersecting the O-Ca aquifer

10.1.3. Cambrian-Vendian aquifer

The outcome of groundwater modeling in Cambrian-Vendian aquifer has been presented in Figure 47 to Figure 55 (pre- and postprocessing data of the computational analysis in Appendix 9.1 and Appendix 9.18 - Appendix 9.25).

As expected, the first scenario parameters do not influence groundwater levels in the extent to form a considerable drawdown (Figure 48, Figure 49, Appendix 9.18 and Appendix 9.19). Drawdown effect on all the local wells in the area of influence is shown in table 10.

Based on the second scenario, where 250 m^3/d is extracted per shaft, a maximum 1.23 m of drawdown is expected in the shaft area (Figure 50, Figure 51, Appendix 9.20 and Appendix 9.21). The largest impact is expected for the nearest Ca-V wells No. 538 and 544 with possible drawdown of up to 0.75-0.65 m.

In the third scenario, where 500 m^3/d is extracted per shaft, a maximum 2.4 m of drawdown is expected in the shaft area (Figure 52, Figure 53, Appendix 9.22 and Appendix 9.23). The largest impact is expected for the nearest Ca-V wells No. 538 and 544 with possible drawdown of up to 1.55-1.35 m.

Based on the fourth scenario, where 1000 m^3/d is extracted per shaft, a maximum 4.9 m of drawdown is expected in the shaft area (Figure 54, Figure 55, Appendix 9.24 and Appendix 9.25). The largest impact is expected for the nearest Ca-V wells No. 538 and 544 with possible drawdown of up to 2.85-3.25 m.

Table 10. Modeled Cambrian-Vendian groundwater level drawdowns in local wells inside the area of effect

Scenario	1 (43.2 m^3/d per shaft)		2 (250 m^3/d per shaft)		3 (500 m^3/d per shaft)		4 (1000 m^3/d per shaft)	
Stage	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)	1 (6 shafts)	2 (1 shaft)
Drawdown in m, 538	0	0	0.75	0	1.55	0.23	3.25	0.6
Drawdown in m, 544	0	0	0.65	0	1.35	0.15	2.85	0.45
Drawdown in m, 534	0	0	0.4	0	0.95	0.09	2.25	0.3
Drawdown in m, 539	0	0	0.38	0	0.85	0.04	1.75	0.26
Drawdown in m, 536	0	0	0.37	0	0.8	0.01	1.3	0.23
Drawdown in m, 586	0	0	0.37	0	0.8	0.02	1.75	0.23
Drawdown in m, 547	0	0	0.25	0	0.6	0	1.5	0.12

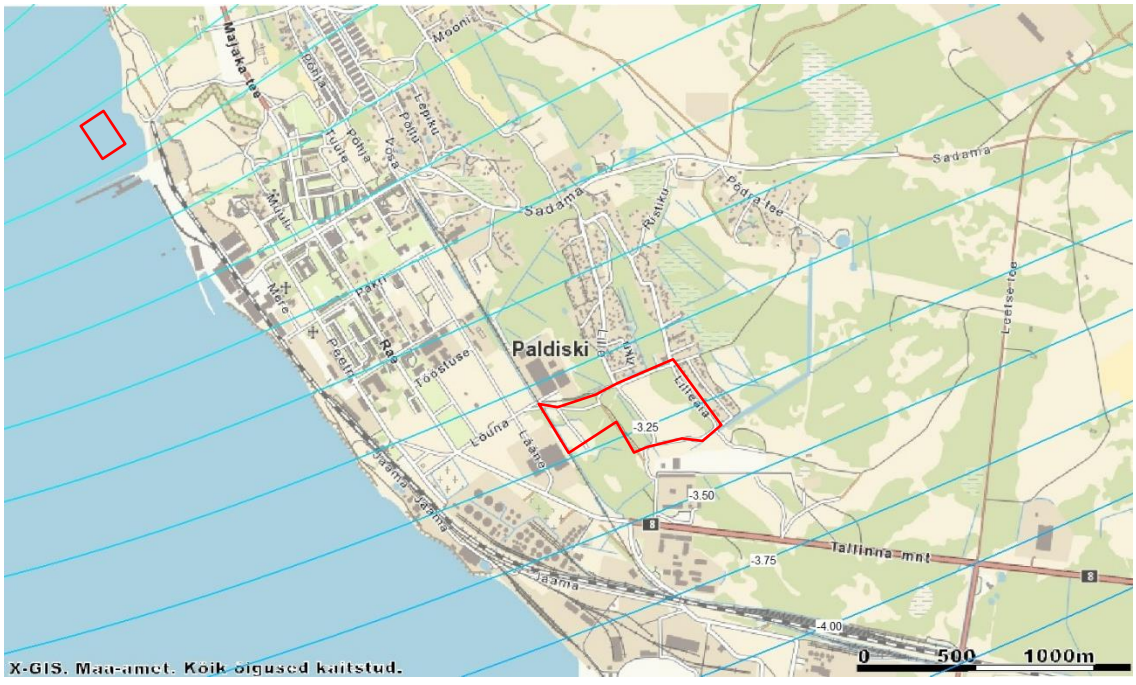

Figure 48. Static groundwater level (referenced to sea level) of the Cambrian-Vendian aquifer without PHES activities

1. Scenario (43.2 m^3/d per shaft) of Cambrian-Vendian aquifer

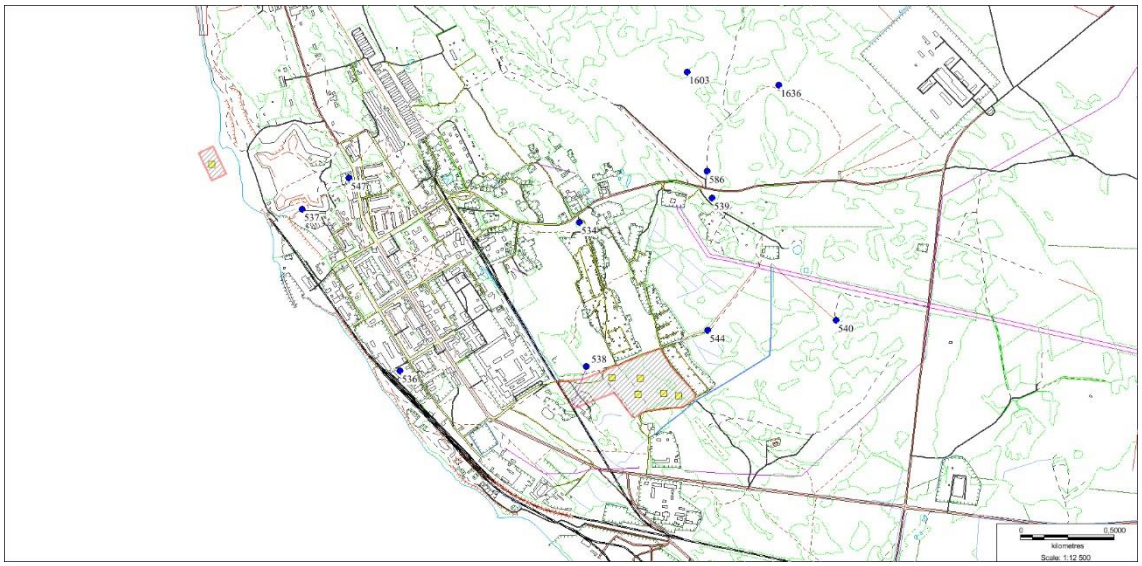

Figure 49. The results of modeling drawdown in the Ca-V aquifer, representing the first stage (6 shafts) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

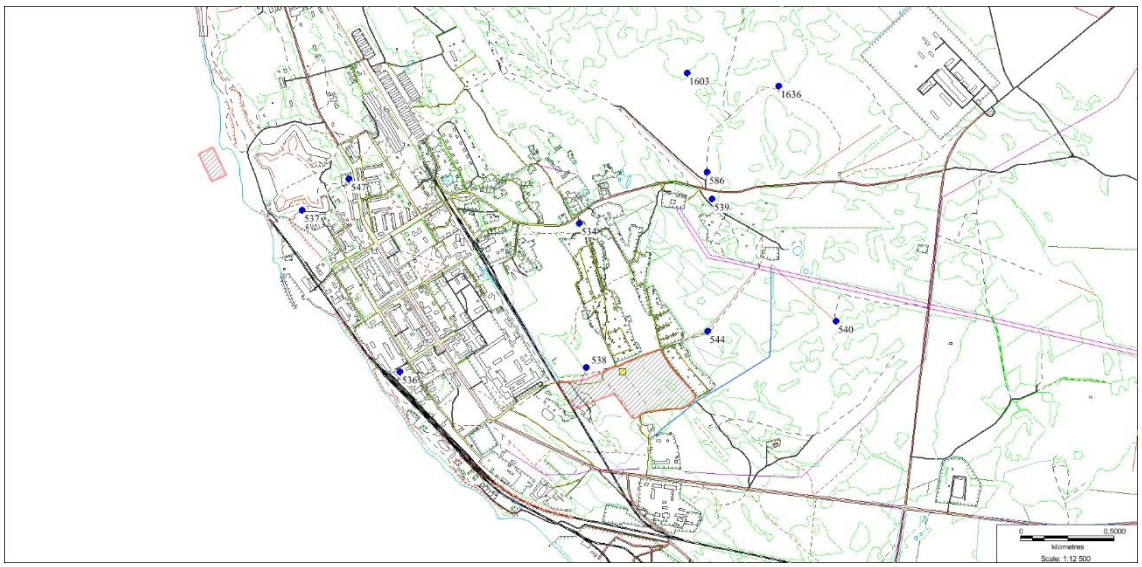

Figure 50. The results of modeling drawdown in the Ca-V aquifer, representing the second stage (1 shaft) of the first scenario (43.2 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

2. Scenario (250 m^3/d per shaft) of Cambrian-Vendian aquifer

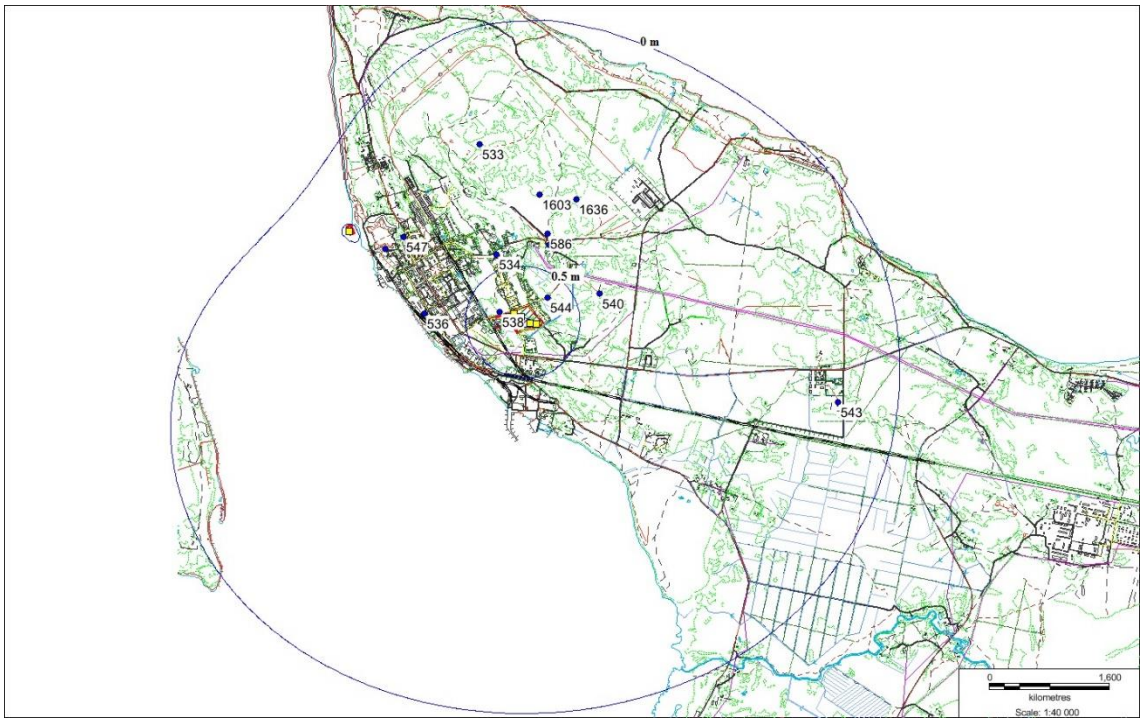

Figure 51. The results of modeling drawdown in the Ca-V aquifer, representing the first stage (6 shafts) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

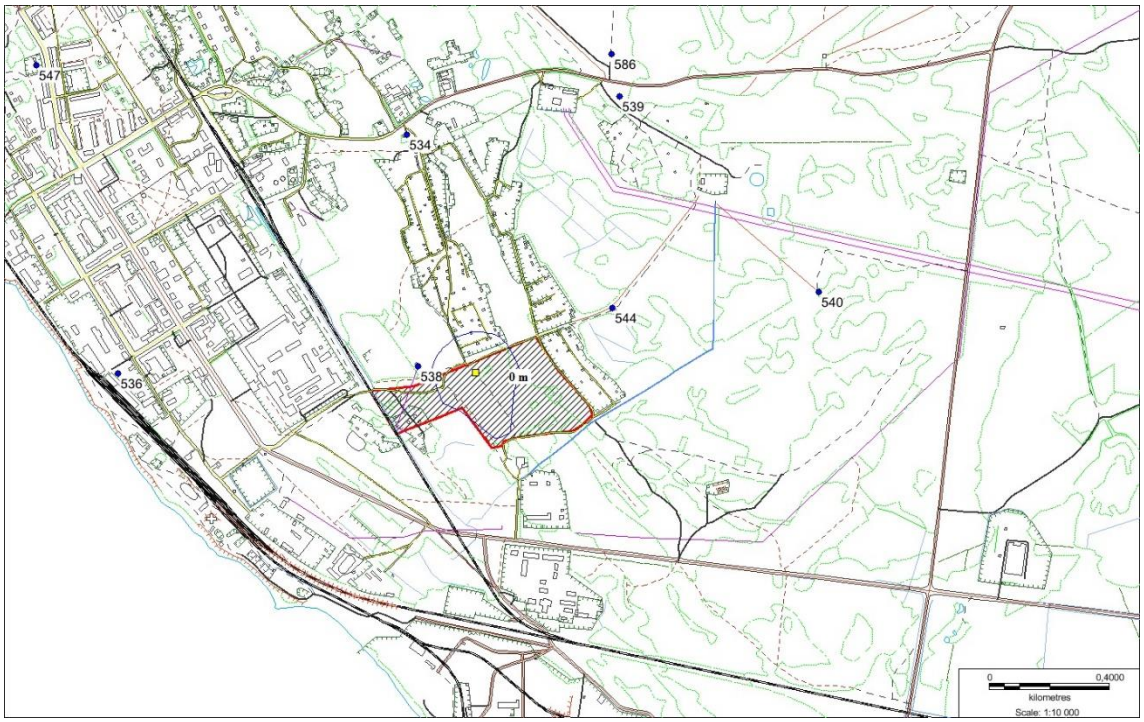

Figure 52. The results of modeling drawdown in the Ca-V aquifer, representing the second stage (1 shaft) of the second scenario (250 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

3. Scenario (500 m^3/d per shaft) of Cambrian-Vendian aquifer

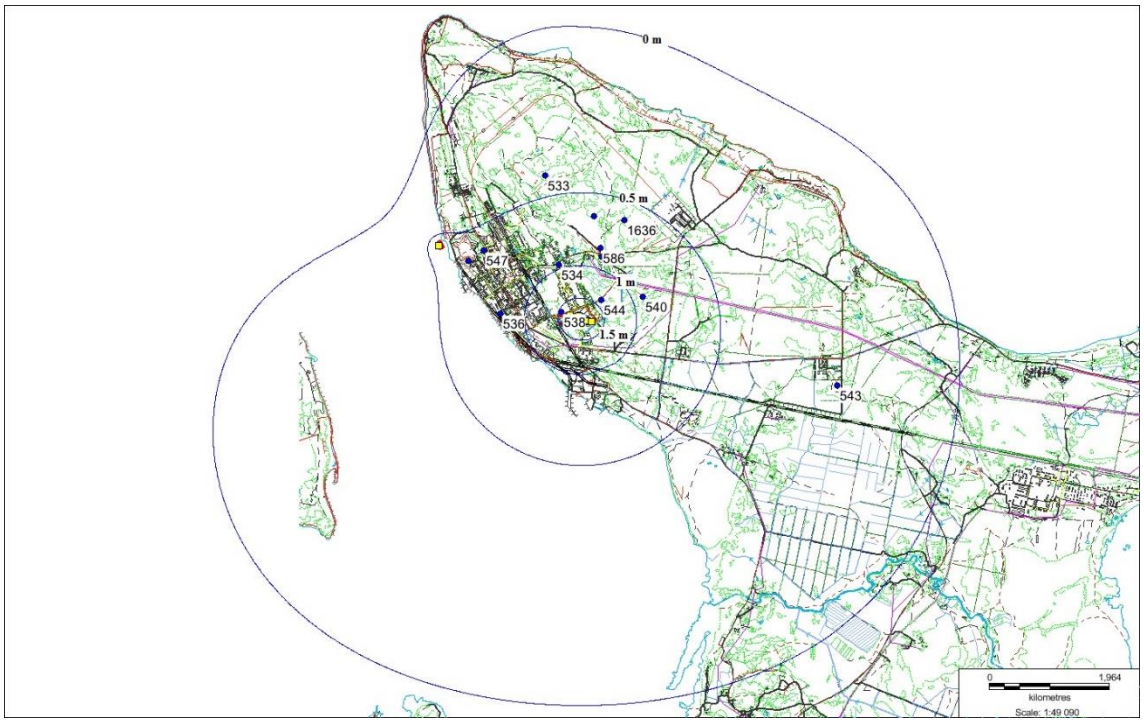

Figure 53. The results of modeling drawdown in the Ca-V aquifer, representing the first stage (6 shafts) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

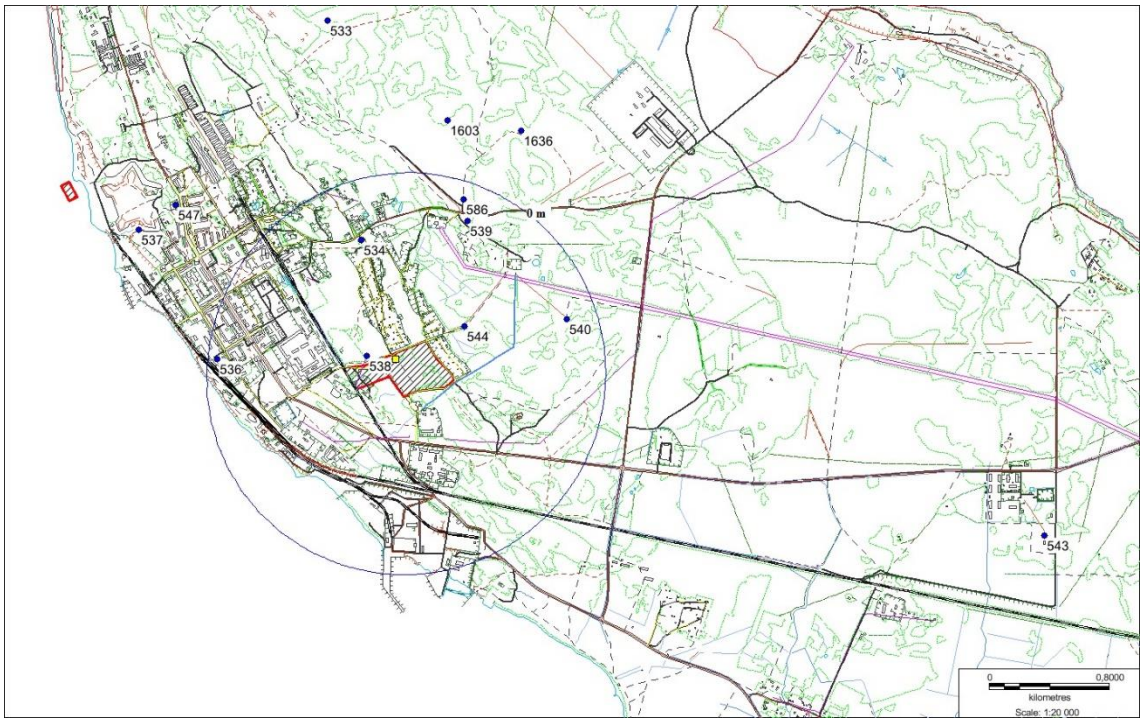

Figure 54. The results of modeling drawdown in the Ca-V aquifer, representing the second stage (1 shaft) of the third scenario (500 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

4. Scenario (1000 m^3/d per shaft) of Cambrian-Vendian aquifer

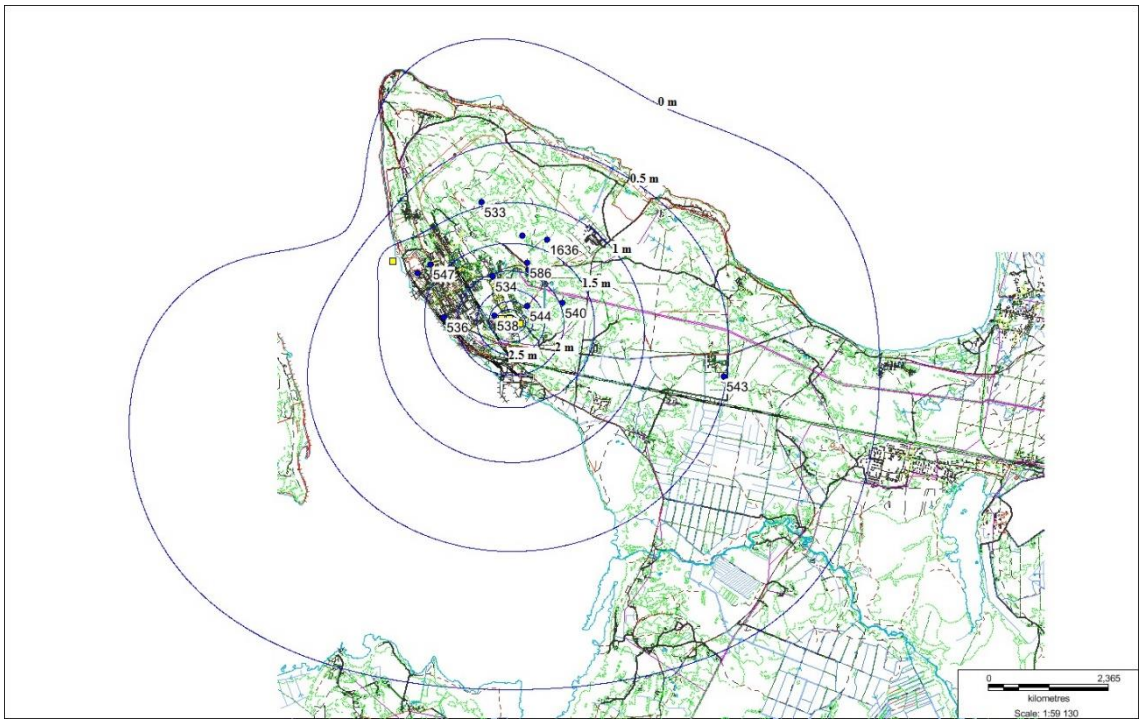

Figure 55. The results of modeling drawdown in the Ca-V aquifer, representing the first stage (6 shafts) of the fourth scenario (1000 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

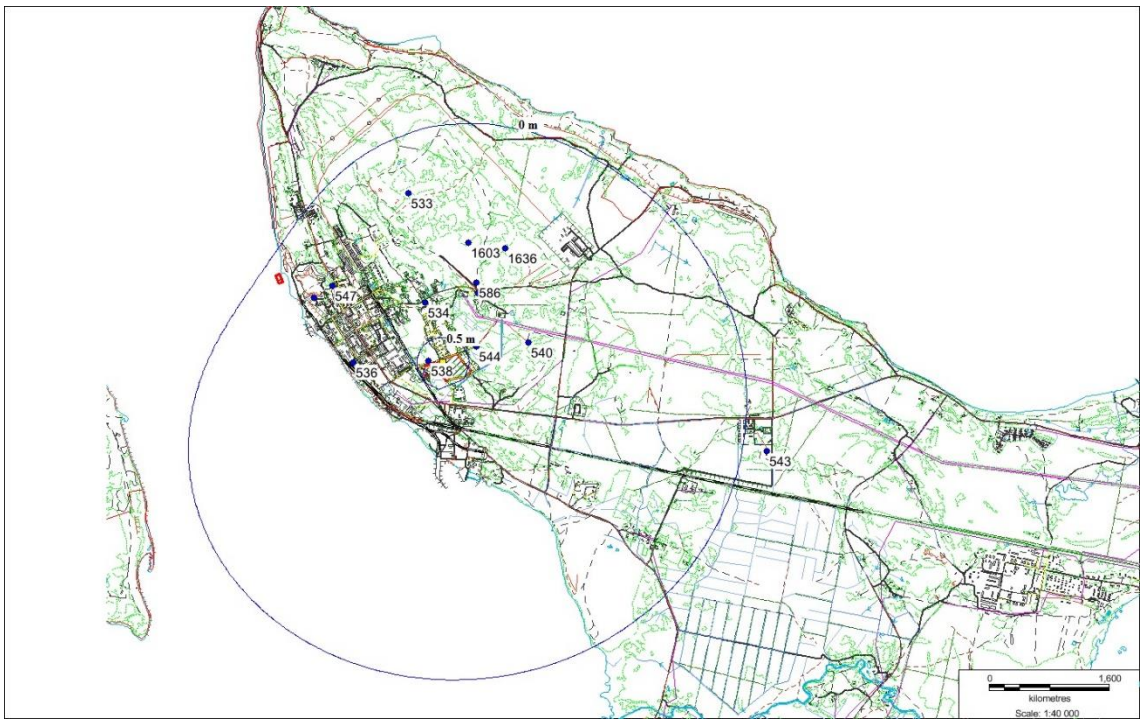

Figure 56. The results of modeling drawdown in the Ca-V aquifer, representing the second stage (1 shaft) of the fourth scenario (1000 m^3/d per shaft). Yellow dots represent shafts intersecting the Ca-V aquifer

10.3.Water quality changes during construction

10.3.1. Seawater intrusion

The exploitation of coastal aquifers always produces lowering of the water table levels which are protected by the effects in the coastal strip of the sea level. When the extracted volumes are greater than the recharge, the salinization process begins in the aquifer as the seawater flows upon the land.

Based on Chapter 10.2 modeling results it is safe to assume that the rate of groundwater extracted in scenario 1 is not enough in any of the three aquifers to influence groundwater levels to an extent that it would induce seawater intrusion.

In scenario 2 and 3 extraction influence on groundwater levels is much stronger than in scenario 1. In the Ordovician aquifer, considerable drawdown is expected but when comparing modeled static groundwater level to the possible drawdown then it can be concluded that the groundwater level will remain higher than the sea level.

In the Ordovician-Cambrian aquifer, seawater intrusion will happen in artificial island area but not on the rest of the coastal area although drawdown seems to reach seawater front. As O-Ca aquifer is only 29 m thick it does not take long time to excavate and install lining for the vertical shaft and let the maximum modeled drawdown to form.

In the Cambrian-Vendian aquifer, seawater intrusion at the artificial island area is not probable because it is protected by 45 m thick Lontova blue clay aquitard with a vertical hydraulic conductivity of 10^{-6} m/d isolates the aquifer from the potential seawater inflow.

The maximum amount of water that would be concurrently pumped out of Cambrian-Vendian aquifer in case of the suggested scenario 3 during PHES shafts construction works in Pallase territory is 2500 m^3/d, it makes up 1/4 amount of the groundwater that was pumped from Cambrian-Vendian aquifer in Soviet Union era. With Paldiski city groundwater total usage of 1000 m^3/d and groundwater extraction while building artificial islands vertical shaft (additional 500 m^3/d) it makes up total of 4000 m^3/d that is 40 % of maximum extraction amount compared to the Soviet era when saltwater intrusion was not detected in Cambrian-Vendian wells.

Based on Chapter 10.1 and 10.2 and historic information it can be concluded that seawater intrusion into groundwater is not realistic when staying within the suggested inflow limit values.

10.3.2. Surface water and groundwater quality

Groundwater flowing into the vertical shafts during the construction works need to be pumped out and directed to the drainage ditches. The pumped water is not treated, and no chemicals are added. Thus, only natural groundwater is directed to the drainage. As there is no significant aquitard between Quaternary deposits and Ordovician limestone, the sediments and carbonate rocks are hydrodynamically connected. Therefore, small amount of water from ditches may infiltrate through bottom sediments to groundwater of S-O aquifer. S-O aquifer is not used for water supply in the area. O-Ca and Ca-V aquifers, that

are used for water supply, are covered by aquitard that prevents water infiltration to those aquifers.

Most of the analyzed components from S-O, O-Ca and Ca-V aquifers meet the requirements for drinking water in regulation No. 61 established by Minister of Social Affairs (see chapter 8.2). Thus, no deterioration in surface water and groundwater quality is expected. Groundwater of crystalline basement is saline with higher Na ja Cl concentrations. However, the results of packer and pumping tests of crystalline basement showed very low permeability (see chapter 8.1), that is characteristic of aquitard. Therefore, the expected amount of crystalline basement water pumped out during construction is extremely low. Saline groundwater dilutes with precipitation and fresh surface water in ditches. Most of the water from ditches flow to the sea, only small amount may infiltrate to groundwater. As a conclusion, the proposed activity will not lead to a deterioration of surface water and groundwater quality.

10.4. Uncertainties

There are several uncertainties related to this report and modeling results that must be considered:

- This report has not assessed the impact of possible emergencies, as these scenarios can be identified during the FEED design made by Fichtner GmbH & Co. KG. The risks of flooding of underground space because of the shaft lining breakage and the corresponding safety concept shall be considered in the FEED design.
- Due to the lack of long-term groundwater survey info it is not possible to conduct the standard hydrogeological model calibration and accuracy assessment. As such a margin of error for drawdown modeling results should be considered (natural groundwater fluctuation from mean value).
- The drilling works of PAL-Wells and PAL-1 conducted by STEIGER on the PHES project area have not encountered heavily fractured limestones in the Ordovician aquifer although the fractured locales may be present in the area. The amount and sizes of the fractures in the vertical shaft area determine real inflow and drawdown in the Ordovician aquifer.

Recommendations to improve model quality further in the next stages of the project:

- Drilling additional monitoring wells in the model boundary area, perform pumping tests in those wells and establishing long-term groundwater monitoring points for different aquifers.
- Use the already existing wells (PAL-Well_2, unused water supply wells or other unused wells) to perform pumping tests in those wells and establishing long-term groundwater monitoring points for different aquifers.
- Acquire access to the so-far inaccessible existing wells to measure the groundwater level and perform downhole geophysical measurements.

11. SUMMARY

Energiasalv Pakri OÜ plans to build a 500 MW PHES on the Pallase 16 and 18 properties and a 2.6 ha artificial island with water intake in Paldiski Bay to supply the station with water per the solution proposed by detail planning. During the construction of vertical shafts, the excavation works intersect through sedimentary bedrock where three: Silurian-Ordovician (S-O), Ordovician-Cambrian (O-Ca) and Cambrian-Vendian (Ca-V) aquifer systems can be distinguished. O-Ca and Ca-V aquifer systems provide water supply for the PHES neighboring households and industries. The public water supply of the Paldiski city is mainly based on the Ca-V aquifer system. Therefore, the possible impact of construction work on local water supply, including groundwater level and quality needs to be assessed.

The hydrogeological study aimed to gather the hydrogeological information, compile a 3D hydrogeological model, and use it to assess the possible impact of the construction of vertical shafts on the groundwater in the PHES area.

To carry out the hydrogeological study, 2 hydrogeological survey wells (PAL-Well_1 and PAL-Well_2) were drilled to assess the filtration properties of Ordovician, Ordovician-Cambrian, and Cambrian-Vendian aquifers. Also, borehole PAL-1 was drilled by a wire-line core drilling method to get precise geological information of the area.

Pumping tests were performed in all three aquifers and based on the results of the tests, the hydrodynamic parameters (specific capacity and hydraulic conductivity) were calculated. In PAL-Well_1, PAL_Well_2 and PAL-1 geophysical measurements were made to confirm geological and hydrogeological data. Besides, the water level of local historic wells was measured and historic data of the area was gathered from the literature.

Core lithological and borehole geophysical logging showed that the thickness of the Ordovician aquifer is approximately 22 m, Ordovician-Cambrian aquifer is 29 m and Cambrian-Vendian aquifer is 81 m. The thickness of the Ordovician aquitard is approximately 5 m and Lükati-Lontova aquitard 45 m.

Based on the results of the pumping test, hydraulic conductivity of the Ordovician aquifer is calculated to be 0.04 m/d and specific capacity was not possible to calculate due to well running dry during pumping. As the pumping test in Ordovician aquifer shows that borehole is in solid limestone an historic value of 8.1 m/d has been used in the groundwater model. For Ordovician-Cambrian aquifer, the conductivity of 1.8 m/d with specific capacity of 0.6 l/s×m was calculated. For Cambrian-Vendian aquifer, the conductivity of 9.17 m/d with specific capacity of 3.62 l/s×m was calculated.

Available historical and new hydrogeological information was used as an input for the 3D hydrogeological model. Boundary conditions and calibration is based on water levels of model area wells.

It is foreseen that 6 vertical shafts will be constructed in 1 - 2 years (including the crystalline bedrock sections) in the first stage and 1 vertical shaft is constructed in 2 years (including the crystalline bedrock sections) in the second stage. As such, the highest

influence on aquifers will occur in the first construction stage. Biggest drawdown will form on the Pallase territory because 5 out of 6 vertical shafts of the first stage are situated there.

Considering the made raw groundwater inflow estimates it can be concluded that the water volumes are many folds larger than the modeled 4 scenarios. As such, suitable inflow prevention mitigation (freezing or pre-grouting) is needed to be implemented for the shafts construction works to reduce groundwater inflow into the shafts to acceptable limits. In case of pre-grouting there should be collaboration with local water company to prevent grout inflow to the nearest water supply well while pre-grouting is in progress. During the shaft sinking and construction works it is imperative to make sure that the three main aquifers will not be allowed to interconnect and will be sealed from each other properly.

To assess the impacts of the PHES shafts construction works to the local groundwater, a set of modeling scenarios have been prepared. Based on these set of scenarios it's possible to suggest groundwater inflow limit values for the shafts construction works that would not cause unacceptable effects to the local groundwater. These values would be set for the construction works as not to be exceeded and the construction contractor would be responsible to foresee suitable mitigation methods (freeze wall or grouting) to bring the groundwater inflows to the limits. In total, four scenarios in two stages were modeled:

- 1. Scenario predicts groundwater level in aquifers due to potential seepage/leakage of groundwater to the completed shafts after the construction. The groundwater inflow into a single vertical shaft is 43.2 m^3/d/100 m (amount defined in SEA report, expert estimate):
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time.
  - 2. Stage: Total of 1 vertical shaft is constructed at a time.
- 2. Scenario predicts groundwater level in aquifers due to low volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 250 m^3/d:
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 1500 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 250 m^3/d water extraction).
- 3. Scenario predicts groundwater level in aquifers due to middle volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 500 m^3/d (amount defined in SEA report):
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 3000 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 500 m^3/d water extraction).
- 4. Scenario predicts groundwater level in aquifers due to high volume of inflowing groundwater during the construction of the shafts. The groundwater inflow into a single vertical shaft per aquifer is 1000 m^3/d:
  - 1. Stage: Total of 6 vertical shafts are constructed at the same time (with aggregate 6000 m^3/d water extraction).
  - 2. Stage: Total of 1 vertical shaft is constructed (with aggregate 1000 m^3/d water extraction).

Modeling of the first scenario showed that groundwater influence is minimal in all aquifers even when 6 vertical shafts are excavated simultaneously. Modeling showed that there is no notable influence on the nearby groundwater wells nor in neighboring model cells adjacented to extraction cell.

Modeling of the second scenario, when 250 m^3/d amount of water is extracted per vertical shaft from an aquifer, showed that there is no notable influence on the nearby Ordovician groundwater wells as up to 0.6 m of drawdown is expected in the nearest wells. Influence on the nearest local Ordovician-Cambrian wells is up to 5.85 m of drawdown. The expected influence on local Cambrian-Vendian wells during construction is not notable, but still, up to 0.75 m drawdown is expected in the nearest wells.

Modeling of the third scenario, when 500 m^3/d amount of water is extracted per vertical shaft from an aquifer, showed that there is no notable influence on the nearby Ordovician groundwater wells as up to 1.55 m of drawdown is expected in the nearest wells. Influence on some local Ordovician-Cambrian wells is substantial and up to 12 m of drawdown is expected in the nearest wells. The expected influence on local Cambrian-Vendian wells during construction is not notable, but still, up to 1.55 m drawdown is expected in the nearest wells.

Modeling of the fourth scenario, when 1000 m^3/d amount of water is extracted per vertical shaft from an aquifer, showed that there is no notable influence on the nearby Ordovician groundwater wells as up to 1.85 m of drawdown is expected in the nearest wells. Influence on some local Ordovician-Cambrian wells is substantial and up to 24 m of drawdown is expected in the nearest wells. The expected influence on local Cambrian-Vendian wells during construction is not notable, but still, up to 3.25 m drawdown is expected in the nearest wells.

It must be noted that all of those drawdown values are conservative because the model considers all the first stage 6 shafts to be constructed in parallel and can accommodate any construction schedule changes (in case the shafts will not be constructed fully in parallel).

Also, it must be noted that the modeling results are calculated with steady-state model for presented on an infinite timescale (model has been run until equilibrium has been achieved) while the actual shaft construction time single stage is limited to a maximum of 2 years (including the crystalline bedrock sections). This means that the presented results of the hydrogeological model are conservative and can accommodate any construction schedule changes (delays in construction).

This report has not assessed the impact of possible emergencies, as these scenarios can be identified during the FEED design made by Fichtner GmbH & Co. KG. The risks of flooding of underground space because of the shaft lining breakage and the corresponding safety concept shall be considered in the FEED design.

Based on this report, the authors propose that the maximum allowed groundwater inflow limits to be set in the EIA for the PHES construction works per shaft and aquifer should be 500 m^3/d (aggregate of 2500 m^3/d per construction stage) for Ordovician aquifer, 250 m^3/d (aggregate of 1500 m^3/d per construction stage) for the

Ordovician-Cambrian aquifer due to high impact on local wells and 500 m^3/d (aggregate of 3000 m^3/d per construction stage) for the Cambrian-Vendian aquifer.

The total amount of water that would be pumped out of Cambrian-Vendian aquifer because of the PHES shafts construction works in Pallase territory is 2500 m^3/d. With Paldiski city groundwater total usage of 1000 m^3/d and groundwater extraction while building artificial islands vertical shaft (additional 500 m^3/d) it makes up a total of 4000 m^3/d. As the groundwater consumption reserve for Cambrian-Vendian wells in Paldiski has been approved at a total of 4000 m^3/day, the total aggregate extraction amount together with the PHES project activities would not exceed this value.

Based on the modeling and historic data, the seawater intrusion into Ordovician, Ordovician-Cambrian or Cambrian-Vendian wells is not realistic when staying within the suggested inflow limit values.

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