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PILOT DESCRIPTION AND ASSESSMENT

Liepaja SWI, Latvia

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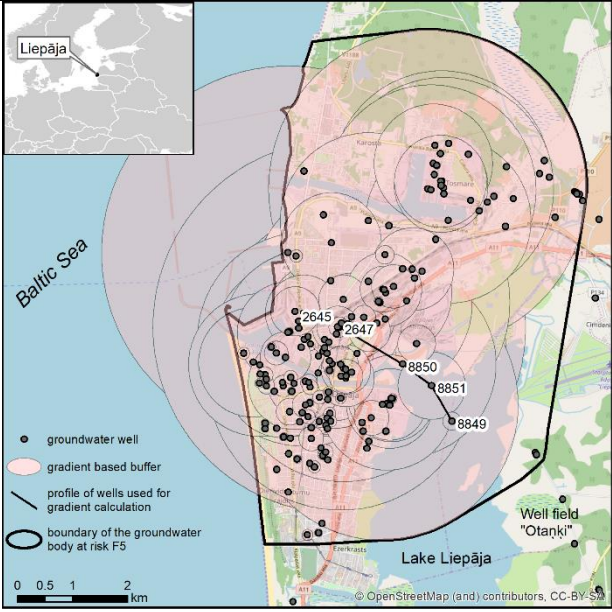
LIST OF ABBREVIATIONS & ACRONYMS

RGWB	Groundwater body at risk according to WFD
LEGMC	Latvian Environment, Geology and meteorology Centre
BL	Background levels
TV	Threshold values
GW	Groundwater
GWB	Groundwater body
SWI	Seawater Intrusion

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1 EXECUTIVE SUMMARY

Pilot name	Liepāja seawater intrusion	
Country	Latvia	
EU-region	Northern Europe	
Area (km ²)	46 km ²	
Aquifer geology and type classification	Sandstones and silicatic alternating sequences, other aquifers (dolomites). Porous and fissured	
Primary water usage	Drinking/ industry	The boundary of delineated groundwater body at risk - F5 (Liepāja seawater intrusion) In last year's depression cone significantly reduced, thus the area affected by seawater intrusion also decreased. However, these changes are due to high decrease of water consumption from affected aquifers and are related to economic aspects (closing of the largest factory and decrease of working places for inhabitants in that area). Still the area is attractive for business and industry (near the port) as well as for tourism, therefore with the increase of economical growth, the consumption may rise, and the hydrogeological conditions are in favour of seawater intrusion. Climate change together with economic growth may lead to higher water consumption from the aquifers at risk and there are no other, better water sources in the territory or they are too expensive to exploit. Delineation of area affected by seawater intrusion was based on chloride concentration gradient along the well profile and gradient based buffers (Bikše and Retike, 2018). Background (BL) and threshold values (TV) delineated according to BRIDGE methodology with stricter criteria for BL delineation (Retike and Bikše, 2018). Calculation of the size of impact on GW resources was based on calculations of seawater fraction (Appelo and Postma, 2005). Ministry of Environmental Protection and Regional Development of the Republic of Latvia, LEGMC, water suppliers, companies Dāvis Borozdins from LEGMC (Latvia) davis.borozdins@lvgmc.lv
Main climate change issues		
Models and methods used		
Key stakeholders		
Contact person		

The pilot territory is located in western part of Latvia, in Liepāja city (affected area by seawater intrusion 46 km²). In the beginning of the 20th century and intensive groundwater abstraction from Upper Devonian Mūru-Žagares (D₃mr-žg) aquifer took place in Liepāja surroundings. First evidence of water level decrease and quality change (high chloride concentrations) in water supply wells were reported in early 1930's. However, regular groundwater monitoring started only in 1961 and already formed depression cone was identified. A decision was made to switch to centralized water supply and install new well field (further from the city, but in the same aquifer). The depression cone continued to expand and it was decided to exploit Middle Devonian Burtnieku and Upper Devonian Gaujas (D₂br+D₃gj) aquifer to reduce the pressure on Upper Devonian Mūru-Žagares (D₃mr-žg) aquifer. New wells in "Otaņķi" in D₂br+D₃gj aquifer were installed in 1967. Other aquifers in the area contain high sulphate content and mineralization, and therefore are unsuitable for water supply. Depression cone started to decline in the beginning of 1990's when consumption rate dramatically decreased because of the collapse of USSR. In about 15 years groundwater level in D₃mr-žg aquifer restored and exceeded the Baltic Sea level. Chloride concentrations decreased in marginal zone of the area affected by seawater intrusion, still in central part of the zone chloride values remain high. Seawater intrusion takes place in freshwater aquifer at city Liepāja - Upper Devonian Mūru-Žagares (D₃mr-žg) partly confined aquifer which is formed of weakly cemented sandstones, siltstones and dolomites in total thickness of 44 - 47 m and at depth of 38 - 43 m. D₃mr-žg is covered by Upper Devonian clayey formations and Quaternary till and sand around Liepāja city. Dominating land use in the pilot area is artificial surfaces, then fallows water bodies and forests and semi-natural areas.

The seawater intrusion impact and situation assessment was performed using several tools, performing hydrogeological modeling, as well as modeling three climate change scenarios. Statistical analysis was performed quantitatively describe the sea-water intrusion in coastal freshwater aquifers. For the assessment of SWI affected area the Chloride ion concentration interpolated maps were developed. For the geostatistical interpolation of the chloride concentration kriging technique was chosen. With the use of available measurements the experimental variograms characterizing the spatial variability of chloride concentrations were constructed. Three model scenarios were defined: Past (historical), Present and Future. Preliminary model runs showed that at modern conditions no seawater intrusion was likely as modelled groundwater heads were above the sea level. That would be true for Future scenario as well if the groundwater abstraction rate would remain the same, but groundwater recharge would increase significantly as is demonstrated below. Such a model would provide little new useful insight into seawater intrusion problem, therefore it was decided to explore how the SWI would develop if groundwater abstraction would increase threefold in the Future compared to Present. The climate change scenarios were selected from ISIMP climate data ensembles of 15 models (5 GCM's x 3 RCP's). From scenarios with global warming level of +3°C degrees and +1°C relative to a reference period (1980-2010) the 2nd highest and 2nd lowest scenario regarding precipitation change for each region of interest, based on annual mean change were selected. Correction factors for monthly mean temperature, total precipitation and evapotranspiration was provided.



Results of modelling demonstrated that present groundwater abstraction rates in Liepāja city were sustainable, and gradual recovery of freshwater *D₃mr-žg* aquifer affected by seawater intrusion was expected to continue confirming previously observed trends in water levels and quality. It was found that in future climatic conditions increased groundwater recharge was to be expected. As a result even three-fold increase of present groundwater abstraction and preserving present configuration of abstraction wells was not likely to trigger renewed seawater intrusion. In a case of climate change scenario with expected 3°C average temperature rise, increased groundwater recharge (by up to 50%) was expected. As a result even threefold increased groundwater abstraction compared to modern situation with current configuration of abstraction wells was not likely to result in renewed seawater intrusion into Upper Devonian Mūri-Žagare aquifer within groundwater body F5 and its surrounding.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

Liepāja is a coastal city with water supply originating from two Devonian aquifers. One of them – upper Devonian Mūri-Žagare (*D₃mr-žg*) aquifer – was affected by seawater intrusion that reached its culmination in 80th of the 20th century. After the implementation of certain measures (new well field installation, use of other alternative aquifers), the rate of intrusion development started to subside. Due to decreased water abstraction since late 20th century retreat of the seawater intrusion was observed.

The report was compiled under the agreement between the Latvian Environment, Geology and Meteorology Centre (LEGMC) and the University of Latvia.

The aim of this study is to assess the potential impact of climate change on the future development of SWI by modelling different future scenarios and assessing the potential situation. In this coastal urban area, intensive water abstraction resulted in the formation of a depression cone, which led to the development of SWI into the main aquifer that was used for drinking water abstraction. Various measures were performed to reduce the development of intrusion. In the 1990s, water abstraction declined significantly, contributing to the recovery of water levels and the reduction of the intrusion process. Overall, potential future development scenarios and modeling results point to a reduction of SWI impact. In a case of climate change scenario with average temperature rise, increased groundwater recharge was expected.



According to modeling results, even threefold increased groundwater abstraction compared to modern situation with current configuration of abstraction wells was not likely to result in renewed seawater intrusion into Upper Devonian Mūri-Žagare aquifer within groundwater body F5 and its surrounding.

The information obtained in the report would be useful for planning long-term measures to be taken in connection with the development of SWI processes in the area and to identify potential threats to groundwater.

3 PILOT AREA

In the beginning of the 20th century and intensive groundwater abstraction from Upper Devonian Mūru-Žagares (*D3mr-žg*) aquifer took place in Liepāja surroundings. First evidence of water level decrease and quality change (high chloride concentrations) in water supply wells were reported in early 1930's. Depression cone started to decline in the beginning of 1990's when consumption rate dramatically decreased because of the collapse of USSR. In about 15 years groundwater level in *D3mr-žg* aquifer restored and exceeded the Baltic Sea level. Chloride concentrations decreased in marginal zone of the area affected by seawater intrusion, still in central part of the zone chloride values remain high.

Previously the area affected by seawater intrusion in Liepāja was relatively small part of large groundwater body F1 (total area of F1 is 2974 km²) which is in good chemical status. On the one hand it was inappropriate to set whole groundwater body in bad status considering the size of the area really affected by seawater intrusion (less than 20% criterion). On the other hand, GWB must be set in poor status if it is affected by sea or salt water intrusion. Thus, a political decision was made to delineate the area affected by seawater intrusion in Liepāja as a separate groundwater body at risk (RGWB)- F5 in 2018 which is our pilot area.

3.1 Site description and data

3.1.1 Location of pilot area and historical evolution of seawater intrusion

The case study is located in western part of Latvia, in Liepāja city (affected area by seawater intrusion 46 km²). See figure 1.

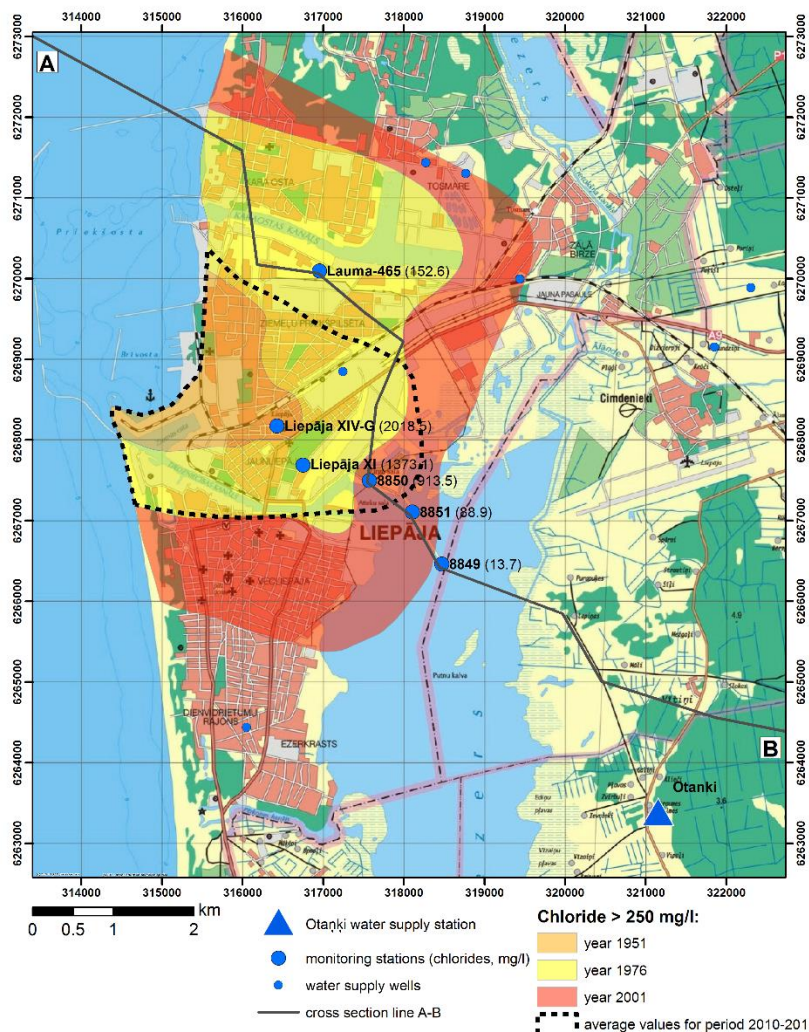


Figure 1. Sea water intrusion evolution in Mūru-Žagares aquifers at city Liepāja from 1951 to 2015

In the beginning of the 20th century and intensive groundwater abstraction from Upper Devonian Mūru-Žagares (D3mr-žg) aquifer took place in Liepāja surroundings. First evidence of water level decrease and quality change (high chloride concentrations) in water supply wells were reported in early 1930's. However, regular groundwater monitoring started only in 1961 and already formed depression cone was identified. A decision was made to switch to centralized water supply and the new well field "Otaņķi" was created in 1961. Still, it abstracted groundwater from the same aquifer - D3mr-žg. As a result, depression cone expanded southeast and in 1976 reached "Otaņķi". In 1986 the center of depression cone was located in "Otaņķi"

area and groundwater levels were reported as 14 m below sea level in D₃mr-žg aquifer. In ten years the seawater intrusion has moved 1 km southeast and reached the northern part of the lake “Liepāja”. A specific measure was established to prevent further movement of saltwater - an abstraction of the affected water for technical needs (Janikins et al. 1993).

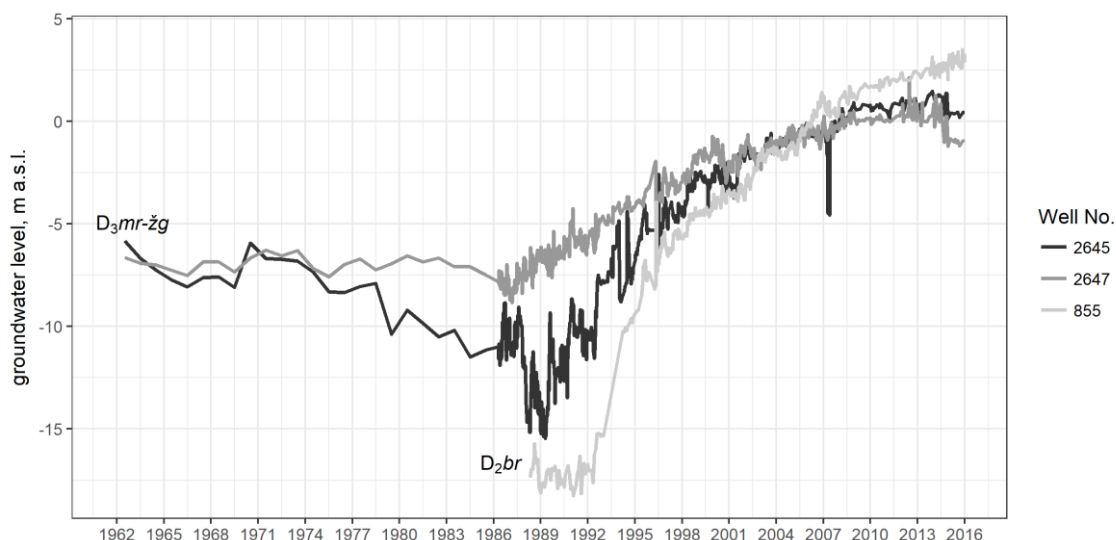


Figure 2. Historical groundwater levels in D₃mr-žg and D₂br aquifers (Bikše and Retike, 2018)

It was decided to exploit Middle Devonian Burtneku and Upper Devonian Gaujas (D₂br+D₃gj) aquifer to reduce the pressure on Upper Devonian Mūru-Žagares (D₃mr-žg) aquifer. New wells in “Otaņķi” in D₂br+D₃gj aquifer were installed in 1967. Other aquifers in the area contain high sulphate content and mineralization, and therefore are unsuitable for water supply.

Depression cone started to decline in the beginning of 1990’s when consumption rate dramatically decreased because of the collapse of USSR. In about 15 years groundwater level in D₃mr-žg aquifer restored and exceeded the Baltic Sea level (Figure 1). Chloride concentrations decreased in marginal zone of the area affected by seawater intrusion, still in central part of the zone chloride values remain high.

3.1.2 Hydrogeological setting

Seawater intrusion takes place in freshwater aquifer at city Liepāja - Upper Devonian Mūru-Žagares (D₃mr-žg) partly confined aquifer which is formed of weakly cemented sandstones, siltstones and dolomites in total thickness of 44 - 47 m and at depth of 38 - 43 m. D₃mr-žg is covered by Upper Devonian clayey formations and Quaternary till and sand around Liepāja city. Deposits of D₃mr-žg aquifer are exposed at the bottom of the Baltic Sea - approximately 5 km from the coast. Cause is the dipping of Devonian deposits towards S-SE (and outcropping at N-NW) and the lack of Quaternary sediments at some areas at the sea.

Underlying formations consist of dolomitic marls, clays, dolomite and sandstones forming several aquitards and minor aquifers. At the depth of 230 - 241 m lies Upper Devonian Gaujas and Middle Devonian Burtneku formation (D₂br+D₃gj) - significant hydraulically connected



aquifer with total thickness of more than 100 m consisting of sandstones and clays. The D_2br+D_3gj aquifer has no direct connection to uppermost aquifers and the Baltic Sea, however, D_2br+D_3gj aquifer is mainly used for industrial water supply due to elevated mineralization and high sulphate content from gypsum dissolution.

Thus, the most important aquifer for water supply needs in Liepāja surroundings is shallow $D_3mr-žg$ freshwater aquifer. It contains good quality drinking water and has been extensively used for decades.

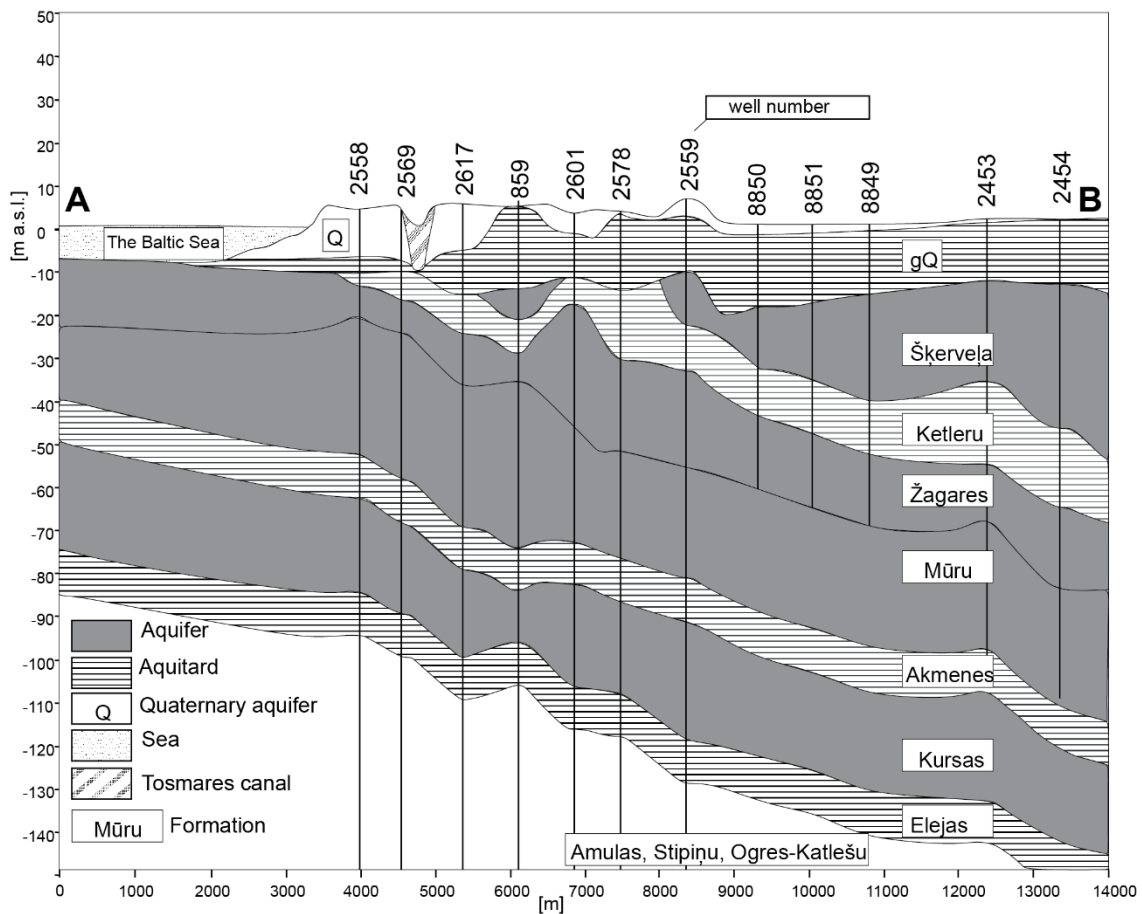


Figure 3. Hydrogeological cross section line A- B (see Fig.1) based on Spalviņš et al. 2004

3.1.3 Surface water bodies

Location of case study, surface water bodies (according to WFD) and location of rivers and lakes is presented in Figure 4.

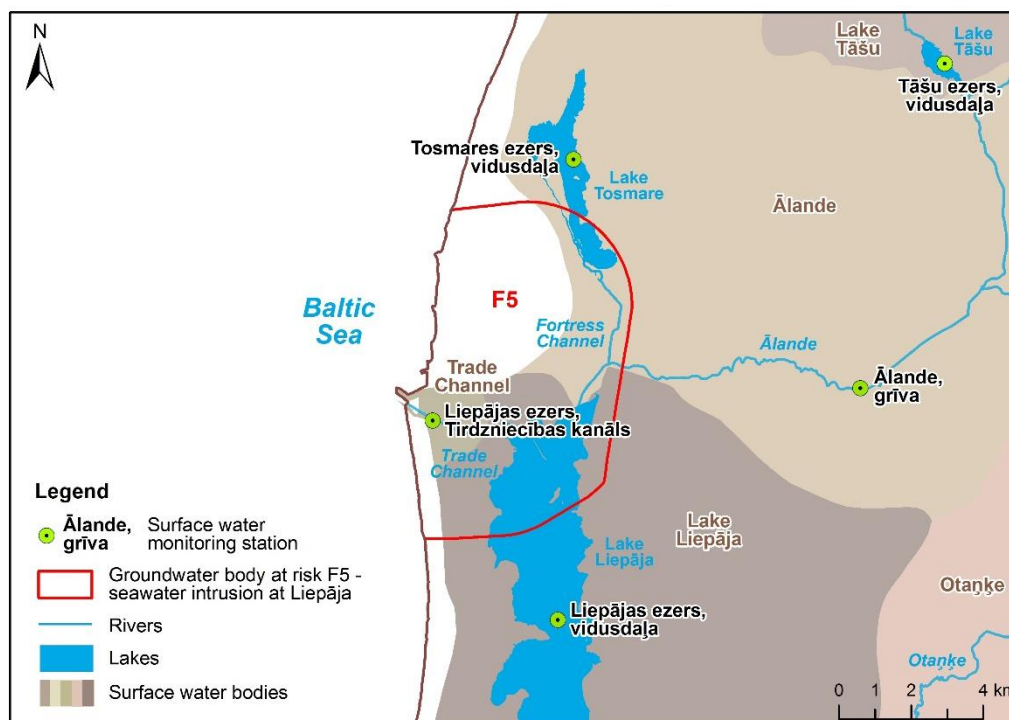


Figure 4. Case study area and surface waters.

3.1.4 Climate

The average precipitation in time period from 1966 till 2017 is 700 mm/y, average evaporation is unknown, but it is less than precipitation. Annual mean temperature is 7.3 °C.

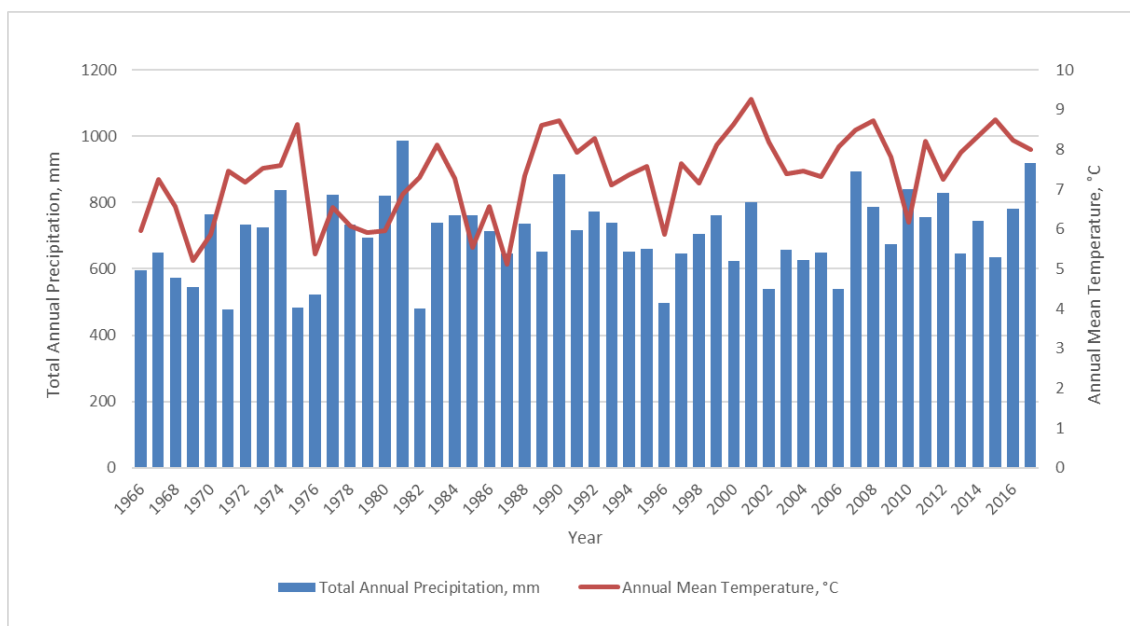


Figure 5. Evolution of annual precipitation and annual mean temperature in nearest meteorological station “Liepāja”



3.1.5 *Land use and soil types, artesian water vulnerability*

Dominating land use in the pilot area is artificial surfaces, then follows water bodies and forests and semi-natural areas. See figure 6.

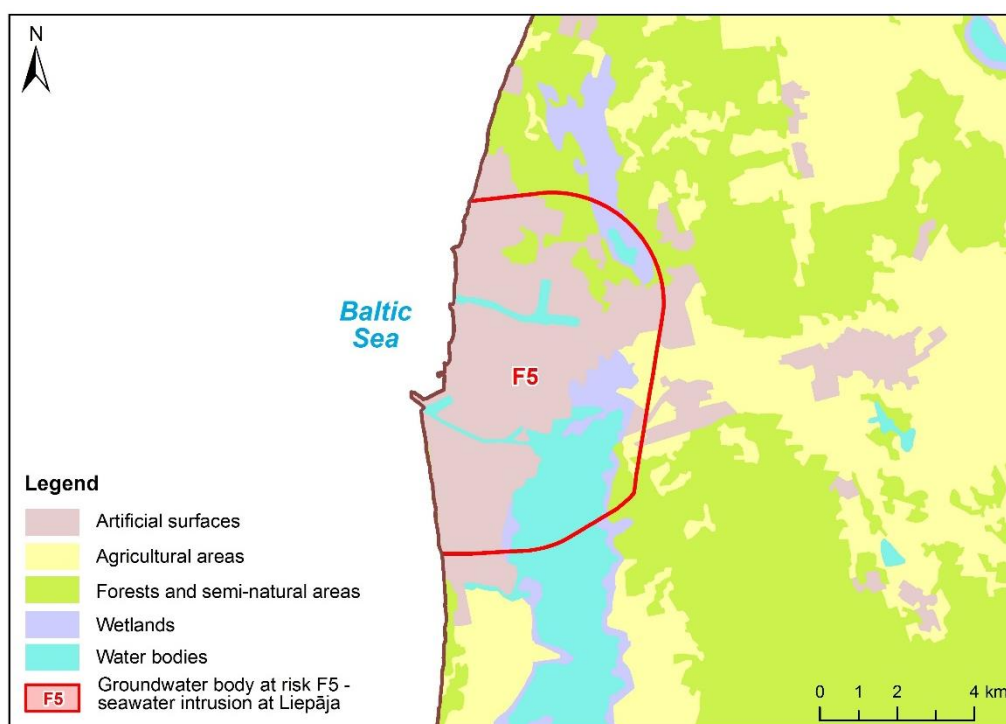


Figure 6. Land use in pilot area from Corine Land Cover

Available data about soil type is only in agricultural lands in small part of pilot's area in Eastern part. Most of the area is dominated by artificial surfaces (city) and water bodies. See figure 7.

Simple vulnerability map shows that pilot area is of low risk of contamination due to upstream areas of artesian waters. See figure 8.

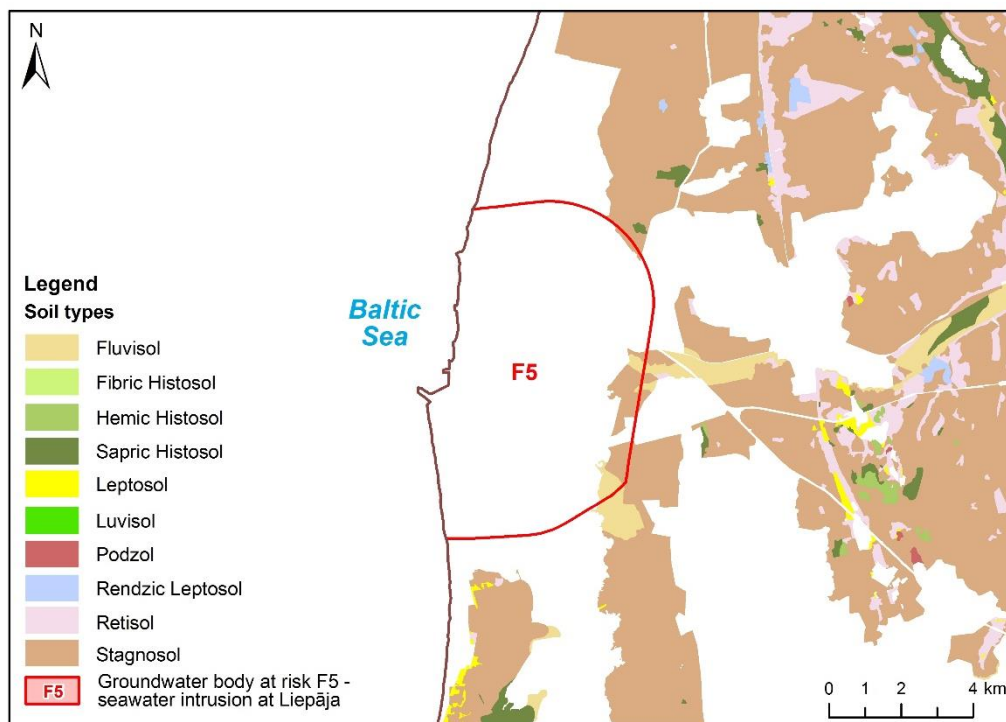


Figure 7. Soil types in agricultural lands in pilot area.

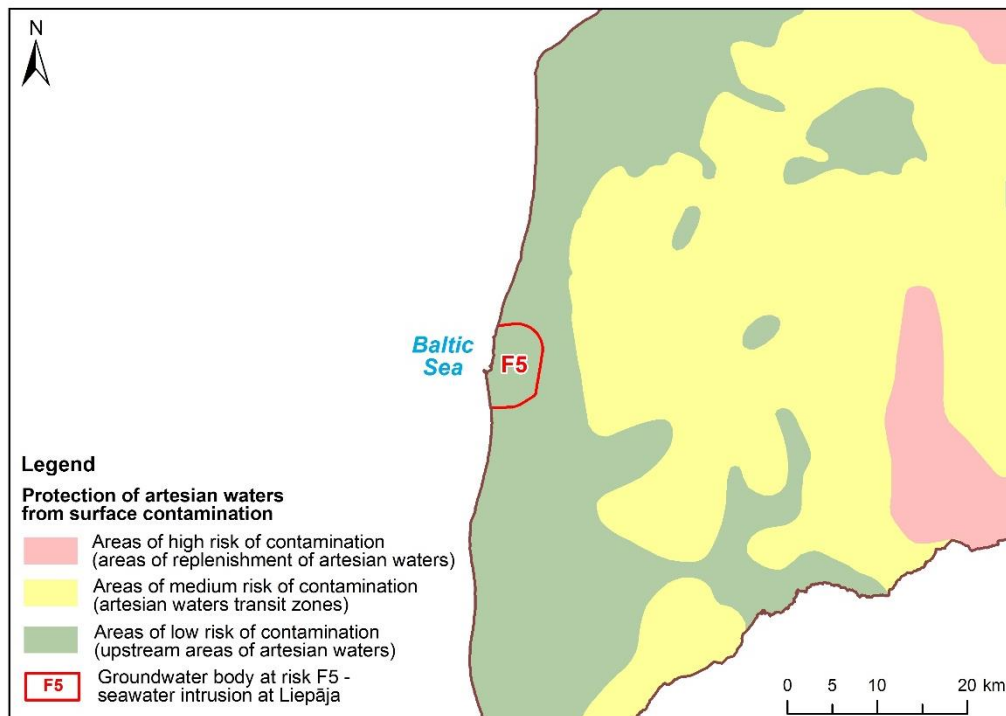


Figure 8. Vulnerability maps for artesian waters

3.1.6 **Abstraction**

There are many water abstraction wells in the pilot area abstracting groundwater directly from the affected aquifer by seawater intrusion and other aquifers. However, we do not have data about small water consumptions (<100 m³/d). See Figure 9.

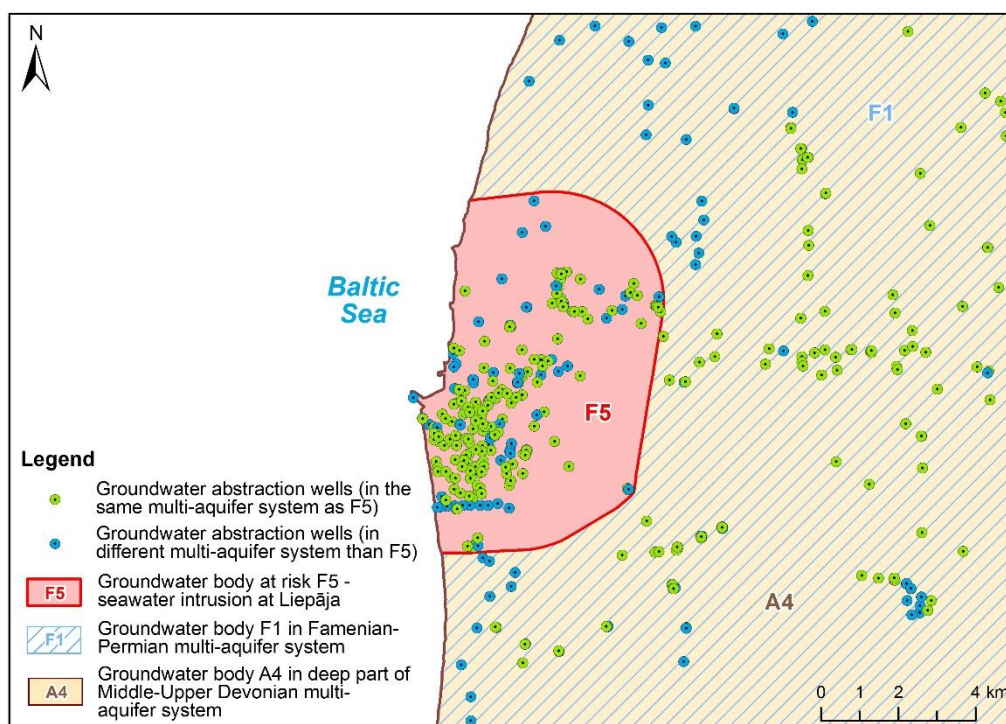


Figure 9. Locations of water abstraction wells in affected aquifer and others

Currently there is a small amount of water abstraction in well fields (areas abstracting groundwater more than 100m³/d) due to bad water quality and low water demand. Liepāja city is mostly supplied with groundwater from Otaņķi water supply station you can see in Figure 10. In Table 1 you can see supply rates in m³ per day in 2017.

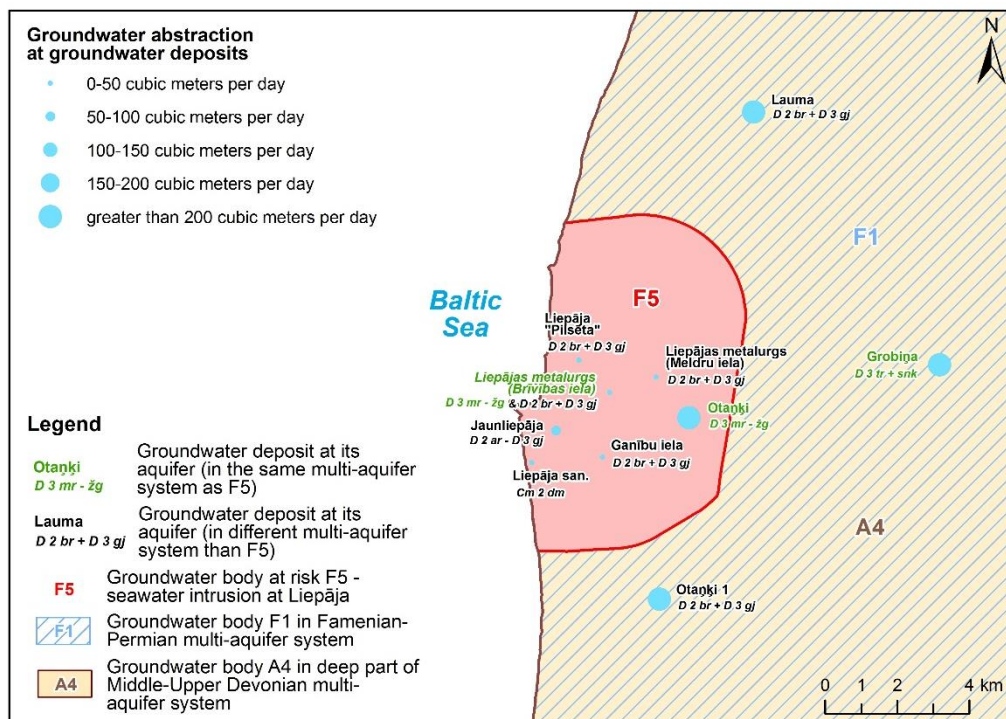


Figure 10. Locations of well fields in affected area

Table 1. Water supply in well fields in 2017 (see locations in figure 10).

Well field	Aquifer	Groundwater type	Purpose of groundwater abstraction	Groundwater abstraction (2017), m ³ per day
Ganību iela	D ₂ br + D ₃ gj	sulphate freshwater	production, technical and household purposes	23.22
Grobiņa	D ₃ tr + snk	freshwater	drinking water production, centralized water supply	415.88
Jaunliepāja	D ₂ ar- D ₃ gj	sulphate freshwater	drinking water production, decentralized water supply	59.49
Lauma	D ₂ br + D ₃ gj	freshwater	drinking water production, centralized water supply	811.71
Liepāja "Pilsēta"	D ₂ br + D ₃ gj	sulphate freshwater	drinking water production, decentralized water supply	3.39



Liepāja san.	$Cm_2 dm$	saltwater	medical needs - procedures	0.13
Liepājas metalurģs (Brīvības iela)	$D_3 mr - žg$	freshwater	technical purposes	0.00
	$D_2 br + D_3 gj$	sulphate freshwater		0.00
Liepājas metalurģs (Meldru iela)	$D_2 br + D_3 gj$	sulphate freshwater	technical purposes	13.99
Otaņķi	$D_3 mr - žg$	freshwater	drinking water production, centralized water supply	3243.68
Otaņķi 1	$D_2 br + D_3 gj$	sulphate freshwater	drinking water production, centralized water supply	3556.49

3.2 Climate change challenge

Based on the EEA map, Latvia is expected to be affected by climate change by the issues outlined in Figure 11, which are relevant to Northern Europe. The climate changes planned in the territory of Latvia are related to the increase of the average air temperature. This could affect the reduction of snow and ice cover periods. Atmospheric precipitation is also expected to increase, especially in the winter season, and with the increase in average air temperature, the maximum and minimum air temperatures will also increase. Changes in air temperature and precipitation in the future could affect various natural processes - the area will become suitable for heat-loving plants and crops. Warmer winters and less snow and ice cover will reduce the risk of spring floods in the future. An increase in the frequency and intensity of storms in the future could cause great damage to the economy, as well as adversely affect coastal erosion processes and the flooding of large coastal areas as a result of wind surges.

At present, Latvia has sufficient groundwater resources and by ensuring sustainable management of groundwater resources, it is not expected that the quantitative and qualitative status of groundwater could deteriorate. Nevertheless, due to climate change, droughts are increasing during the summer period, causing a seasonal decline in shallow groundwater (according to monitoring data). This problem mainly affects individual households (which use shallow aquifers for drinking water). Droughts also have a direct impact on agriculture, which could lead to an increase in water abstraction for irrigation purposes in the future.

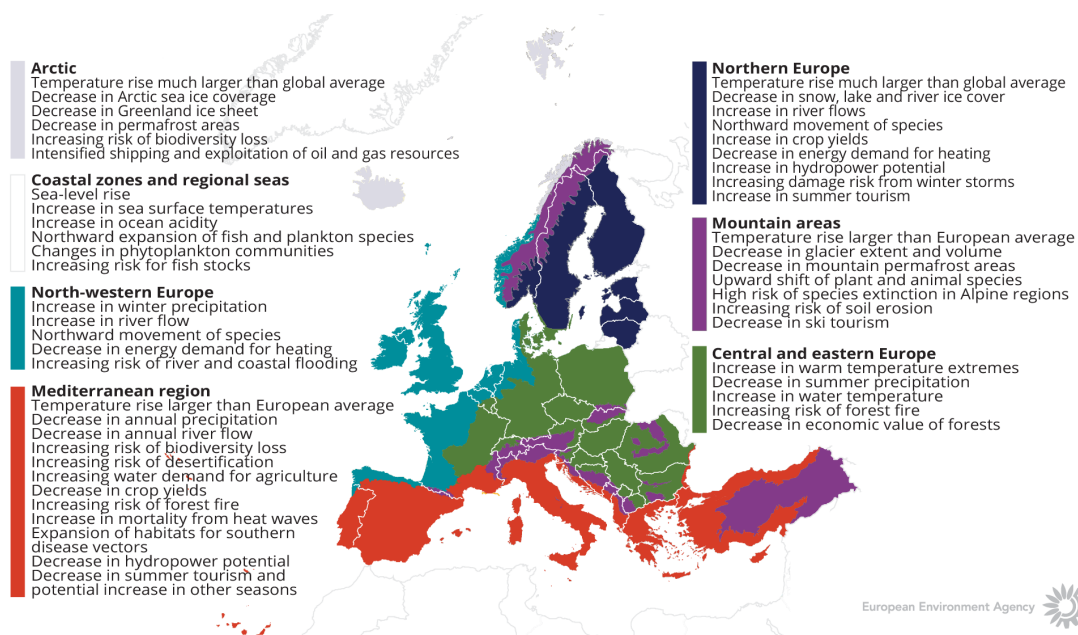


Figure 11. How is climate expected to change in Europe. The European Environment Agency map

4 METHODOLOGY

4.1 Methodology and climate data

4.1.1 Tools/ model description

Statistical analysis method, chloride ion concentration interpolated map development, as well as 3D hydrogeological modeling were used to assess seawater intrusion process.

Statistical analysis

Baena-Ruiz *et al.* (2018) suggested a methodology to quantitatively describe the sea-water intrusion in coastal freshwater aquifers. They suggest summarizing the available data about aquifer affected by saltwater intrusion in a proportionally scaled two-rectangle diagram (**Figure 12**). One rectangle represents the extent and depth of groundwater in its pristine (semi natural) quality and other – groundwater that had been polluted by seawater intrusion as indicated by above-background or above-threshold Cl^- ion concentration. The height and length of the rectangles represent the average depth and extent respectively of pristine and contaminated groundwater. In addition the mass of Cl^- ion intrusion per linear meter of coastline is suggested as measure of severity of contamination.

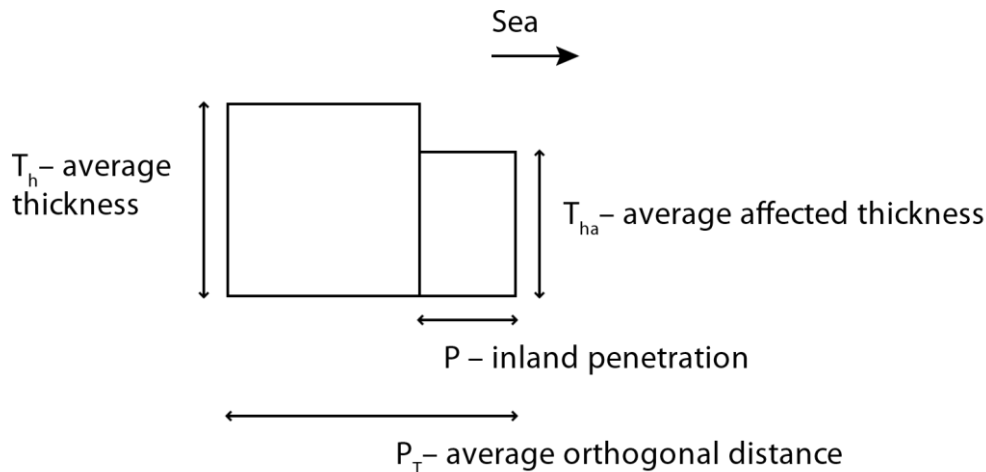


Figure 12 Conceptual visualization of proportion of the groundwater body affected by seawater intrusion as suggested by Baena-Ruiz *et al.* (2018)

Chloride ion concentration interpolated maps

Available observations of the groundwater chemical composition obtained from LEGMC were checked for quality as indicated by charge balance. Only observations where the ion balance error was less than 10% were used. Relatively loose charge balance criteria were selected as we

would be operating with average values thus slight uncertainties in chemical composition data would be smoothed-out.

In many historical observations, the concentrations of the Na^+ and K^+ ions often was expressed as a single aggregated value with unit mg/l. When calculating the charge balance, we used empirically established ratio of 0.276 between K^+ and Na^+ molar concentrations, calculated from the available data at the study region. Using this approach, we significantly increased volume of historical data with enabled charge balance control.

Available observations were selected for to time-intervals from 1975 to 1985 characterising situation in 80-ties of the 20th century and from 2010 to 2020 as modern situation. In total data from 81 and 38 wells respectively was selected in each case. In cases when more than one observation was available the median value of Cl^- concentration was used.

For the geostatistical interpolation of the chloride concentration kriging technique was chosen. With the use of available measurements the experimental variograms characterizing the spatial variability of chloride concentrations were constructed and applied to the ordinary kriging spherical model. Background Cl^- concentration was set as 3.6 mg/l – lowest reported concentration for the $\text{D}_{3\text{mr-}\check{\text{z}}\text{g}}$ aquifer in the study area.

3D hydrogeological modelling

Hydrogeological model was developed in MODFLOW environment using GMS software and steady state flow conditions. The transient solute transport was based on steady state flow solution using MT3DMS package.

Model was constructed with 7 geological layers, 4 aquifers and 3 aquitards (**Table 2**) and impermeable basal boundary condition. The infiltration from land surface groundwater recharge was constrained by data from regional hydrogeological model Spalviņš *et al.*, (2018), simplified into 4 recharges zones and adjusted during model calibration.

Table 2 Modelled hydrogeological units

Layer No.	Hydrogeological unit	Aquifer / Aquitard
1	Q_{3-4} sand or till	Aquifer or aquitard
2	Q_{2-3} moraine	Aquitard
3	$\text{D}_{3\text{fm}}$	Aquifer
4	$\text{D}_{3\text{kt}1}$	Aquitard
5	$\text{D}_{3\text{mr-}\check{\text{z}}\text{g}}$	Aquifer
6	$\text{D}_{3\text{ak}}$	Aquitard
7	$\text{D}_{3\text{jn-ak}}$	Aquifer

A two-step approach for modelling was devised: initial model calibration for regional model area followed solute transport calculations only for local model (**Figure 13, Table 3**). Regional model was the source of boundary conditions for local model. The two-step approach helped to capture regional flow patterns and reduce computing time for solute transport in local model.



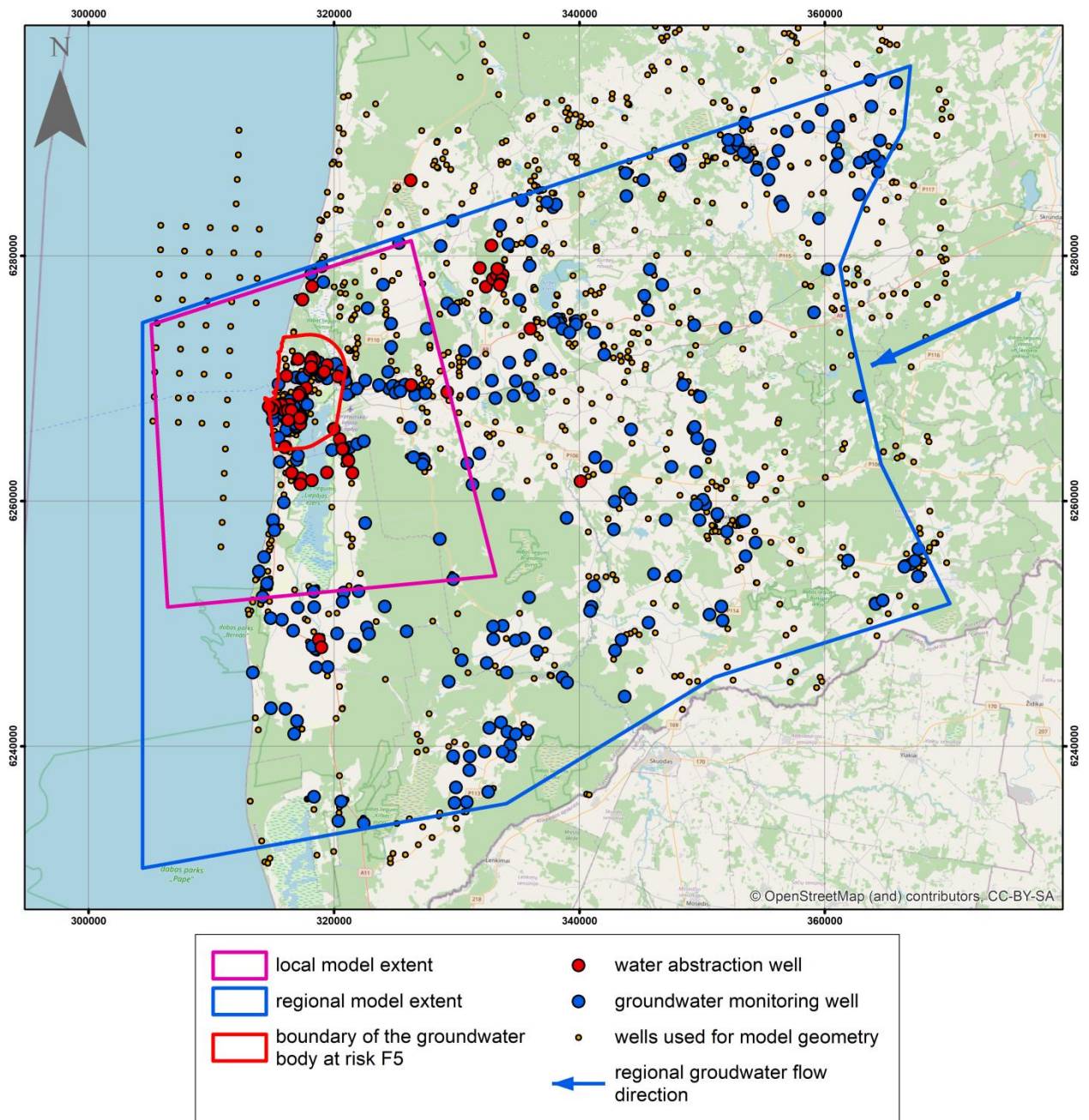


Figure 13 Area of the hydrogeological model for Liepāja seawater intrusion

Regional model area was selected to capture groundwater recharge and discharge areas and to be able to set no flow boundary conditions with no constraints on groundwater head at the model sides. General groundwater flow direction was from East to West. Recharge area was in West Kursa upland that is about 150 m above sea level while the ultimate groundwater discharge area was in the Baltic Sea. Model boundaries were pre-selected according to the regional hydrogeological model of Spalviņš *et al.* (2018). Eastern boundary was set along

groundwater divide in West Kursa upland. The North and South boundary approximately coincide with groundwater flowlines. Finally the western boundary is set under the Baltic Sea.

Table 3 Resolution and size of regional and local models

Parameter	Regional model	Local model
Model dimensions	80 x 54 km	30 x 30 km
Layer	7	7
Cell size	200 x 200 m	200 x 200 m
Rows	240	150
Columns	400	150
Total cells	756 000	157 500
Active cells	459 069	107 477

4.1.2 *Future scenarios. Climate and land use data*

Three model scenarios were defined (**Table 4**): Past (historical), Present and Future. Preliminary model runs showed that at modern conditions no seawater intrusion was likely as modelled groundwater heads were above the sea level. That would be true for Future scenario as well if the groundwater abstraction rate would remain the same, but groundwater recharge would increase significantly as is demonstrated below. Such a model would provide little new useful insight into seawater intrusion problem beside the facts that have been already established – gradual retreat of seawater intrusion (Bikše *et al.*, 2016). Therefore it was decided to explore how the seawater intrusion would develop if groundwater abstraction would increase threefold in the Future compared to Present.

Table 4 Summary of model scenarios

No.	Scenario name	Groundwater abstraction rate (m ³ /d)	Recharge	Transient solute transport	
				Time frame, years	Starting conditions Cl ⁻ concentration
1.	Past	57 688	Calibrated	up to 1990	Predefined
2.	Present	11 340	Calibrated	from 1990 to 2040	Output from Past scenario
3.	Future	34 020	Modified according to climate change scenario	from 2040 to 2100	Output from Future scenario

Standard climate change scenarios were provided by the GeoERA (<https://geoera.eu/> Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe) Tactic (Tools for Assessment of Climate change Impact on groundwater and adaptation Strategies) project WP3 by F. S. Weiland, B. van den Hurk and T. Kroon at Deltares, Netherlands. The climate change scenarios were selected from ISIMP climate data ensembles of 15 models (5 GCM's x 3 RCP's). From scenarios with global warming level of +3°C degrees and +1°C relative to a reference period (1980-2010) the 2nd highest and 2nd lowest scenario regarding precipitation change for each region of interest, based on annual mean change were



selected. Correction factors for monthly mean temperature, total precipitation and evapotranspiration was provided. The correction factors for temperature are additive, the correction factors for evaporation and precipitation was multiplicative. Only the scenario for +3°C degrees warming was selected for investigating Liepaja case study and is provided in **Table 5**

Table 5 The correction factors for Liepaja case study (WP5_LEGMC_17_Liepaja_pilot) as prepared by Deltares, Netherlands in scope of GeoERA TACTIC project WP3

scenario	Par	Deg	GCM	RCP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
minchange	PR	_3deg	hadgem2-es	rcp4p5	1.333	1.061	1.083	0.951	0.861	0.827	0.856	0.704	0.930	0.981	1.122	1.126
maxchange	PR	_3deg	miroc-esm-chem	rcp8p5	1.416	1.373	1.187	1.000	0.888	1.099	1.414	1.254	1.309	1.435	1.190	1.255
minchange	TAS	_3deg	hadgem2-es	rcp4p5	1.333	1.061	1.083	0.951	0.861	0.827	0.855	0.704	0.930	0.981	1.122	1.126
maxchange	TAS	_3deg	miroc-esm-chem	rcp8p5	1.417	1.373	1.187	1.000	0.888	1.099	1.415	1.254	1.309	1.435	1.189	1.255
minchange	PET	_3deg	hadgem2-es	rcp4p5	1.168	1.186	1.155	1.139	1.110	1.101	1.084	1.088	1.092	1.120	1.092	1.165
maxchange	PET	_3deg	miroc-esm-chem	rcp8p5	1.222	1.253	1.169	1.122	1.092	1.089	1.083	1.093	1.102	1.090	1.154	1.168
minchange	PR	_1deg	hadgem2-es	rcp6p0	1.190	0.994	0.903	0.951	1.131	0.863	0.995	1.031	0.910	0.868	0.981	1.105
maxchange	PR	_1deg	miroc-esm-chem	rcp4p5	1.245	1.119	1.087	0.950	1.007	1.099	1.134	1.199	1.030	1.316	0.953	0.962
minchange	TAS	_1deg	hadgem2-es	rcp6p0	2.56	2.35	2.14	2.87	3.21	3.42	2.90	3.02	2.76	3.08	2.08	2.71
maxchange	TAS	_1deg	miroc-esm-chem	rcp4p5	2.28	1.91	1.79	2.13	1.13	1.38	1.59	1.78	2.07	1.51	1.75	1.79
minchange	PET	_1deg	hadgem2-es	rcp6p0	1.165	1.148	1.116	1.126	1.112	1.1042	1.082	1.086	1.088	1.120	1.100	1.159
maxchange	PET	_1deg	miroc-esm-chem	rcp4p5	1.154	1.130	1.101	1.093	1.039	1.042	1.045	1.051	1.067	1.058	1.083	1.102

PR – Mean precipitation change per calendar month, multiplier

TAS – Mean temperature change per calendar month, additive

PET – Mean potential evaporation change per calendar month, multiplier

The correction factors for temperature are additive, the correction factors for evaporation and precipitation are multiplicative to avoid negative future precipitation.

The groundwater recharge is a function of local land surface conditions such as land use and soil type and hydrogeological regime of the local groundwater head in topmost aquifer. The later denotes distribution of groundwater recharge and discharge areas. In addition, the groundwater discharge would not be directly affected by climate change: any groundwater leaking to the land surface would be either consumed by evapotranspiration or removed as surface runoff. In contrast, the infiltration of the precipitation water to the groundwater would be affected by climate change: groundwater is recharged only by precipitation water that is not consumed by evapotranspiration or removed as surface runoff. We assumed that changes in balance of the precipitation and evapotranspiration would affect groundwater recharge however there is a site specific unknown partitioning coefficient (k) that controls the proportion of the excess precipitation that is directed towards groundwater and how much of it is removed as surface runoff. Thus, the ratio of groundwater recharge (R) to unknown partitioning coefficient (k) can be estimated by equation (1):

$$\frac{R}{k} = \frac{\sum (PR_i - PET_i, < 0 \Rightarrow 0)}{n}, \text{ where} \quad (1)$$

n – number of months,

PR_i – monthly precipitation,



PET_i – monthly potential evaporation.

Further we assume that value of the partitioning coefficient k in future conditions will remain the same while both precipitation RP and potential evapotranspiration PET will change. To describe present recharge conditions (R_p/k) we used monthly average precipitation and potential evapotranspiration data from ERA-5-land reanalysis (Copernicus Climate Change Service (C3S), 2019) of the model area for the time period from 1990-01-01 to 2019-12-31 calculating the R_p/k as a single average value.

To describe future recharge conditions (R_f/k) we used the scaling factors provided by GeoTACTIC to scale monthly-grid cell values of the PR and PET obtained from era-5-land reanalysis and calculate the future value of the groundwater recharge (R_f/k ; eq. 1) as the average across all the monthly values and grid cells.

As the next step we calculated scaling coefficient (k_R) for groundwater recharge due to climate change:

$$k_R = \frac{\frac{R_f}{k}}{\frac{R_p}{k}} = \frac{R_f}{R_p} \quad (2)$$

Finally we multiplied the calibrated groundwater recharge rate for the hydrogeological model with k_R to estimate the future groundwater recharge to be used as forcing for hydrogeological model.

We used monthly mean precipitation and potential evaporation from ERA5 land (Copernicus Climate Change Service (C3S), 2019) for model area from 1990 to 2020 as modern meteorological conditions. Future meteorological conditions were characterized by the same data set scaled according to delta-change methodology provide by Deltares for the *maxchange 3deg* scenario (WP5_LEGMC_17_Liepaja_pilot, GCM – miroc-esm-chem, RCP – rcp8p5). According to this scenario in future climate the groundwater recharge is expected to increase by factor of **1.52**. That is we expected around 50% increase in groundwater recharge in future.

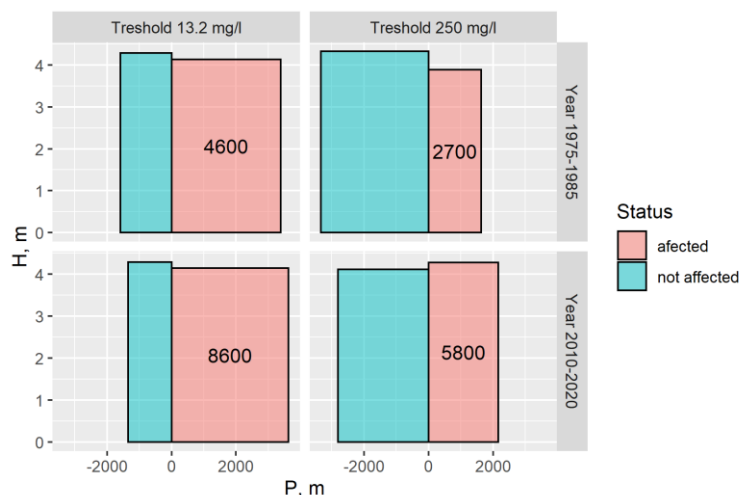


Figure 14 Conceptual representation of the state of the sea-water intrusion into groundwater body F5, Liepāja, Latvia, modified after (Baena-Ruiz *et al.*, 2018): vertical axis (H) is average aquifer thickness in m, horizontal axis (P) is average width of the aquifer affected by seawater intrusion, the number (positive values) and not affected by it (negative values), the number is the extra mas of Cl⁻ ion in the aquifer in kg due to seawater intrusion.

4.2 Tool(s) / Model set-up

Statistical analysis

We used a slightly modified methodology, where the left box represents the proportion of water in aquifer not polluted by seawater intrusion and right box – proportion affected by seawater intrusion (**Figure 15**). We used a subscript *a* to indicated indices considering part of the aquifer affected by seawater intrusion. To indicate parameters considering part of the aquifer not affected by seawater intrusion we used subscript *n*. The concentration of the Cl⁻ above a threshold value (C_R) was used to determine of the groundwater quality at a given location has been affected by seawater intrusion.



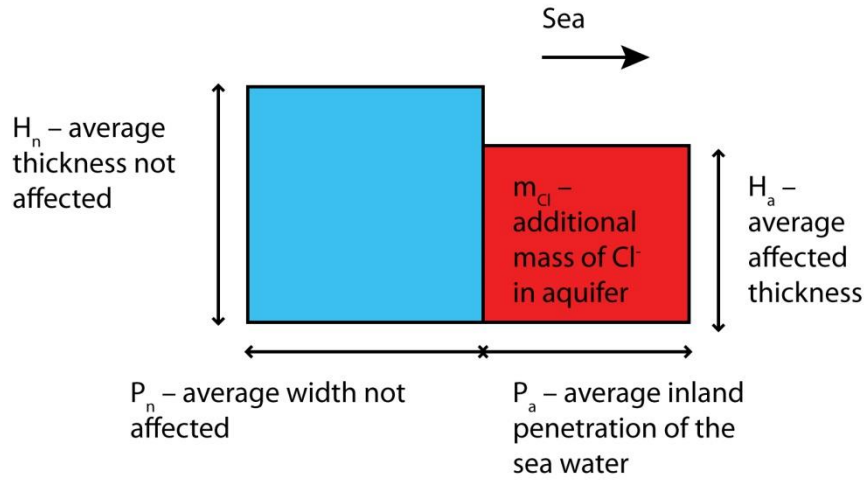


Figure 15 Modified conceptual visualization of proportion of the groundwater body affected by seawater intrusion as suggested by Baena-Ruiz *et al.* (2018)

Storage of water affected by seawater intrusion in grid cell i was calculated by equ. (1):

$$V_{i,a} = S_{i,a} b_i \quad (1), \text{ where}$$

$S_{i,a}$ – surface area of the grid cell i ,

b_i – saturated thickness of the grid cell i ,

α – active porosity (*storage coefficient* of Baena-Ruiz *et al.*, 2018).

Further the average thickness of the aquifer affected by seawater intrusion H_a and average inland penetration of the sea water P_a was calculated by equ. (2) and (3):

$$H_a = \frac{\sum V_{i,a}}{\sum S_{i,a}} \quad (2)$$

$$P_a = \frac{\sum S_{i,a}}{L_{coast}} \quad (3), \text{ where}$$

L_{coast} – coastline length.

The indices describing the average thickness of aquifer not affected by seawater intrusion H_n and its average width P_n were calculated by equations (4), (5) and (6):

$$V_{i,n} = S_{i,n} b_i \alpha \quad (4), \text{ where}$$

$$H_n = \frac{\sum V_{i,n}}{\sum S_{i,n}} \quad (5)$$

$$P_n = \frac{\sum S_{i,n}}{L_{coast}} \quad (6).$$

Finally, the average concentration of the chloride ion in the affected area C , increment of concentration I_C and mass of additional chloride ion $m_{Cl,a}$ was calculated by equ. (7), (8) and (9) as suggested by (Baena-Ruiz *et al.*, 2018):

$$C = \frac{\sum (C_{i,a} V_{i,a})}{\sum V_{i,a}} \quad (7)$$

$$I_C = C - C_R \quad (8)$$



$$m_{Cl,a} = P_a I_C H_a 10^{-3} \quad (9)$$

3D hydrogeological modelling

Geological information from 1492 wells and boreholes was used to construct the geological structure of the model. Groundwater head was constrained by data from 187 groundwater monitoring wells in historical and 163 in modern situation. Out of these wells 93 and 42 respectively were located in detailed model area. Finally 70 and 21 groundwater abstraction wells in the large model area and 65 and 12 in the detailed area for historical and modern situation respectively were considered. Wells with insignificant abstraction rates ($< 50 \text{ m}^3/\text{day}$) were excluded from the model.

Cl^- ion concentration defined for initial model setup is shown in **Table 6**. It was assumed that the first model layer – unsaturated zone and Quaternary sands – in model territory covered by Baltic Sea, was saturated with sea water. Further it was assumed that the groundwater in the rest of model territory had uniform background chemical composition.

Table 6 Cl^- ion concentration defined for initial model setup

No.	Cl^- (mg/l)	Reference	Description	Model units
1.	4100	monitoring data	Sea water	Baltic sea and first model layer Quaternary sands
2.	176	monitoring data	Lake Liepāja	Lake Liepāja
3.	13.2	Background groundwater composition in $D_3mr\text{-}\check{z}g$ aquifer (Retike and Bikše, 2018)	Groundwater	All geological units except where seawater was present
4.	3.6	Least observed Cl^- concentration in groundwater in model area, LEGMC data	Precipitation	Groundwater recharge

4.3 Tool(s)/ Model calibration/ test

After several preliminary and exploratory model runs best results were obtained calibrating the regional model against the historical situation and using this regional calibrated model as a basis for all further calculations (**Figure 16**). For present day and Future scenarios groundwater level distribution was re-calculated using respective values of groundwater abstraction and recharge imposed to the regional calibrated model. A local model area engulfing groundwater body at risk 5F, Otaņķi wellfield and Baltic Sea region where likely intrusion of seawater into aquifers was taking place was selected for solute transport – seawater intrusion – modelling. For each modelling scenario respective regional model was used to select the boundary conditions for the local model. Further, the transport modelling was performed sequentially running the three model scenarios and using the result – distribution of Cl^- concentration in groundwater – of one scenario as an input to the next scenario model.



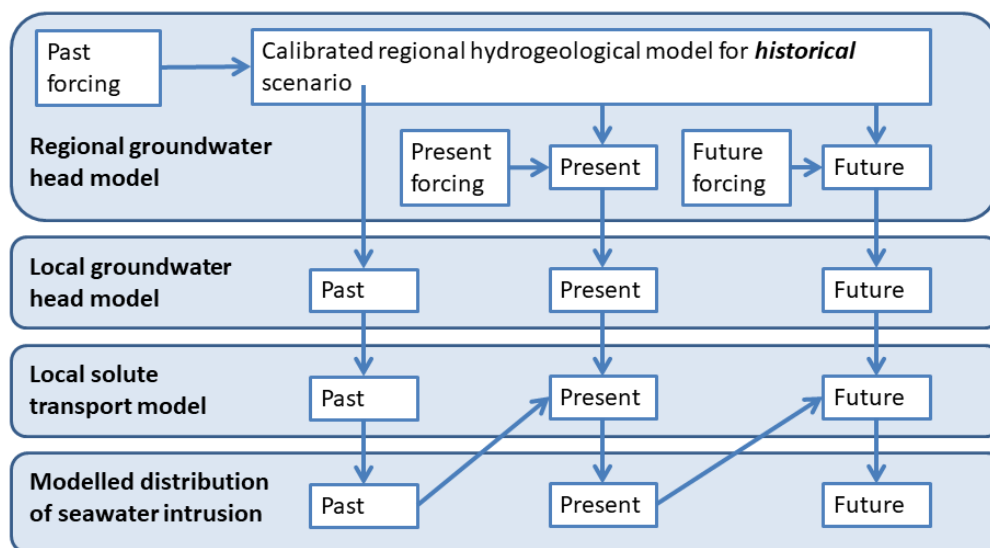


Figure 16 Modelling workflow

Calibrated hydrogeological model parameters are given in **Table 7** while the calibrated recharge values across recharges zones are in **Table 8**, future recharge was calculated by multiplying calibrated recharge with coefficient 1.52.

Table 7 Calibrated hydrogeological model parameters

Model layer No.	Material, formation	Horizontal hydraulic conductivity m/day	Anisotropy (Horizontal /vertical conductivity)	Porosity	Long. dispersivity
1.	Quaternary, aquitard upper glacial till	0.12	5	0.05	1
	Quaternary, aquifer sand	7.90	1	0.25	20
2.	Quaternary, aquitard lower glacial till	0.01	3	0.05	1
3.	Carboniferous, Permian and Devonian Famenian, aquifer dolomites and sandstones	1.05	2	0.15	20
4.	Devonian Ketleri Formation, aquitard dolomite marl and clay	7.73E-05	5	0.01	1
5.	Devonian Muri – Zagare, aquifer dolomites and sandstones	7.34	2	0.15	20
6.	Devonian Akmene Formation, aquitard marl and clay	3.00E-04	3	0.01	1
7.	Devonian Joniski - Akmene aquifer dolomites and sandstones	2.71	2	0.15	20



Table 8 Groundwater recharge values across recharge zones

Recharge zones	Recharge value, m/day	
	Past and Present	Future
Recharge zone 0 (sea)	0	0
Recharge zone 1	2.13E-08	3.23E-08
Recharge zone 3	1.11E-04	1.69E-04
Recharge zone 2	6.62E-06	1.01E-05

4.4 Uncertainty

Model uncertainties (errors) are summarized in **Table 9** and **Figures 17** and **18**. Positive mean error (ME) indicate that modelled groundwater head was higher than observed as the model errors are calculated as modelled head minus observed head. Mean absolute error (MAE) is a measure of average absolute deviation of modelled head from observed head. Relatively large errors were likely due to close proximity of observations wells and groundwater abstraction wells. Time-variable groundwater abstraction rates from individual wells and relatively coarse spatial resolution of our regional model preclude fine simulation of groundwater head near wells used for water extraction.

In addition it is likely that the groundwater flow in the 80-ties of the 20t century in Liepaja city were not at stationary state. That would explain the negative mean error of the local model for the Past scenario as well as positive mean error for the present scenario.

Table 9 Regional model uncertainties (errors) or residuals expressed as difference between observations and model: ME – mean error, MAE – mean absolute error; RMSE – root mean squared error.

Scenario	ME (m)	MAE (m)
Past, regional model	0.4	4.2
Past, local model	-2.2	3.4
Present, regional model	2.6	5.4
Present, local model	4.7	5.2

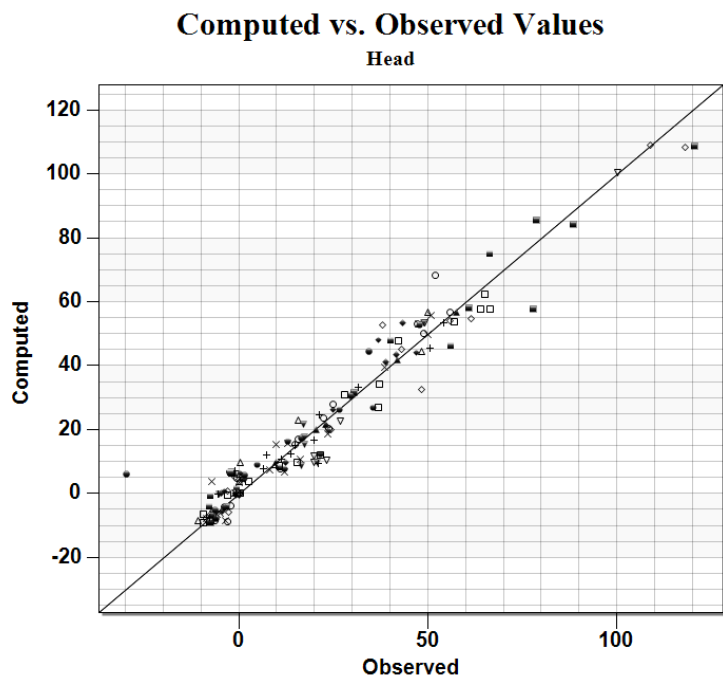


Figure 17 Comparison of the observed and modelled groundwater heads (m a.s.l.) Past scenario, full (regional) model, symbols non-uniquely indicate different groundwater observation wells.

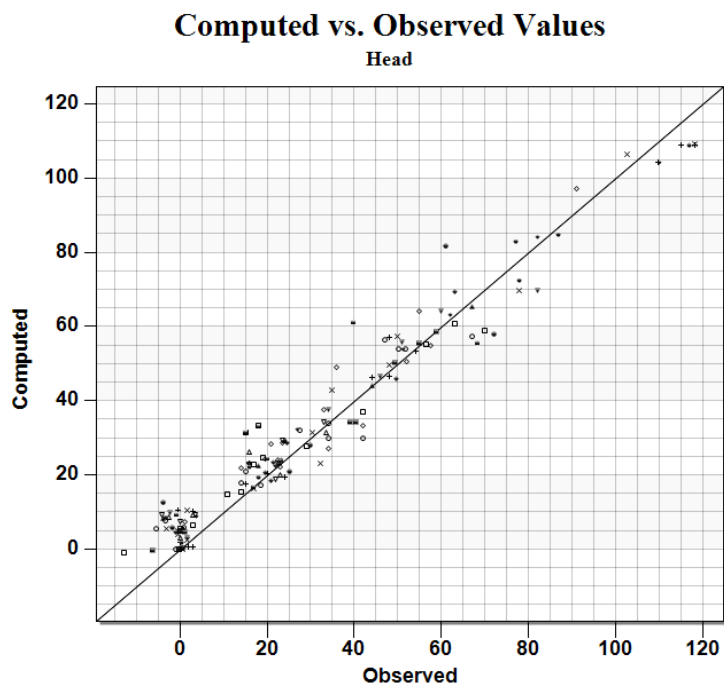


Figure 18 Comparison of the observed and modelled groundwater heads (m a.s.l.) present scenario, full (regional) model, symbols non-uniquely indicate different groundwater observation wells.

5 RESULTS AND CONCLUSIONS

5.1 Statistical analysis

The extrapolated Cl^- ion concentration in D₃mr-žg aquifer in the 80-ties of the 20th century and modern situation is shown in **Figures 19**. Interestingly we found that the apparent seawater intrusion extent and volume was greater in modern situation rather than in the past when groundwater abstraction was at its peak (**Figure 14**). In part that might be due to methodological reasons: for the past conditions data about groundwater salinity was available for more wells (81 wells) than in modern situation (38 wells). In addition the wells used for interpolation in past and modern situation overlap only partly. Thus the current representation cannot be used to directly assess the evolution of the seawater intrusion, however it is useful for examining the proposed methodology (Baena-Ruiz *et al.*, 2018).

The Baltic coastline in the study region is trending in N-S direction and forms the Western boundary of the F5 groundwater body. Therefore we have taken the N-S extent of the F5 groundwater body as a good approximation for the coastline length (L_{coast}), that was needed to calculate the indices describing seawater intrusion along the methodology adopted from (Baena-Ruiz *et al.*, 2018). Thus the value of L_{coast} was found to be 9343 m.

Guidance document elaborated by LEGMC (LVGMC, 2018) suggests that the active porosity (α) for the Upper Devonian Mūri-Žagare aquifer ranges from 0.08 to 0.12, for our calculations we used value 0.1.

As noted by Retike and Bikše (2018) in two adjacent wells data base No 2645 and 2647, contrasting Cl^- concentrations were observed: median Cl^- concentration from 2010 to 2020 was 8.6 and 2000 mg/l respectively. They explained that two wells tap different depths intervals of the Mūri-Žagare aquifer. Similar contrast in these wells was observed for Cl^- concentration measured from 1975 to 1985. Therefore, to avoid obtaining geologically unreasonable concentration gradients we exclude the well No 2645 from interpolation of the Cl^- load.

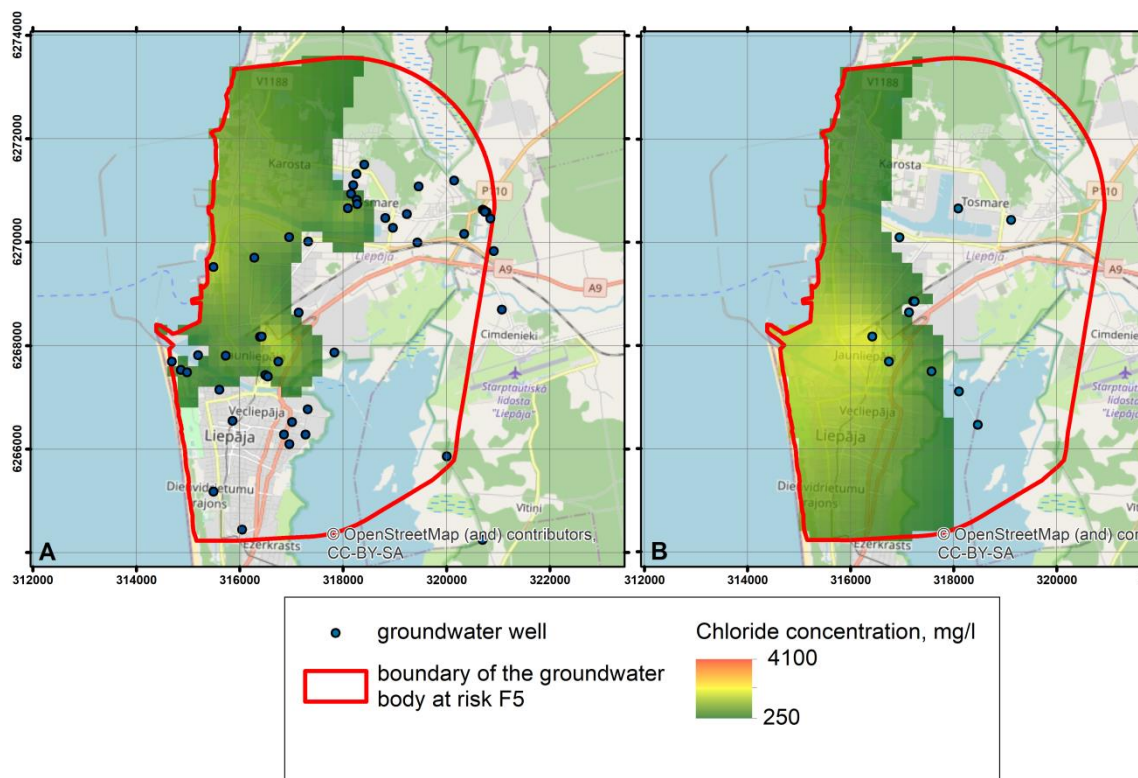


Figure 19 Interpolated Cl^- concentration in the groundwater of the Mūri-Žagare Upper Devonian aquifer, median values for observations from 1975 to 1985 (left) and from 2010 to 2020 (right).

5.2 Modelling results

Modelled groundwater head distribution and extent of the seawater intrusion as illustrated by Cl^- concentration in D_3mr -žg aquifer for the Past, Present and Futures scenarios are presented in **Figures** from **20** to **27**.

Results for Past scenario demonstrated that groundwater depression cone clearly extended below the Baltic Sea (**Figure 20 and 21**) indicating significant potential for sea water intrusion. That was confirmed by solute transport model. Albeit, with provided model setup, it was found that about 250 years of water abstraction was necessary for development of the seawater intrusion similar to one that was historically observed. This apparent discrepancy most likely was due to necessary model initiation time to achieve realistic starting conditions. Further it was considered that the model still provides valuable insights into development of seawater intrusion and is further elaborated in discussion chapter. Further transient solute transport simulation results were considered to be consistent with observations. We have elaborated the question in discussion section.

For the Present scenario only insignificant depression of groundwater head due to groundwater abstraction for steady state situation was modelled (**Figure 22 and 23**). Groundwater depression cone had not developed around groundwater abstraction sites within detailed model area. Thus



it can be concluded that any remaining seawater intrusion was inherited from the peak of groundwater abstraction during 20th century, indicating that the seawater intrusion was no longer. This is in line with this previous finding, that the groundwater heads in last decades had rebounded and the Cl⁻ concentration in the aquifer was declining (Bikše and Retike, 2018). Furthermore we examined the modelled state of the seawater intrusion for year 2027 when next planning cycle for water management was due to start. A slight reduction of the modelled extent of the seawater intrusion was expected (**Figure 24 and 25**) however generally it was expected to change negligibly.

Steady state groundwater head simulation for Future scenario – 3-fold increase of present groundwater abstraction rate and 1.52-fold increase in groundwater recharge – indicate that depression cone had developed around Otaņķi wellfield (**Figure 26 and 27**). However the groundwater head in D₃mr-žg aquifer remains above the sea level and no significant sea-ward extension of groundwater depression cone within F5 groundwater body and Otaņķi wellfield next to it was detected. These model results indicate that renewed seawater intrusion in Liepāja city even for increased groundwater consumption was unlikely.

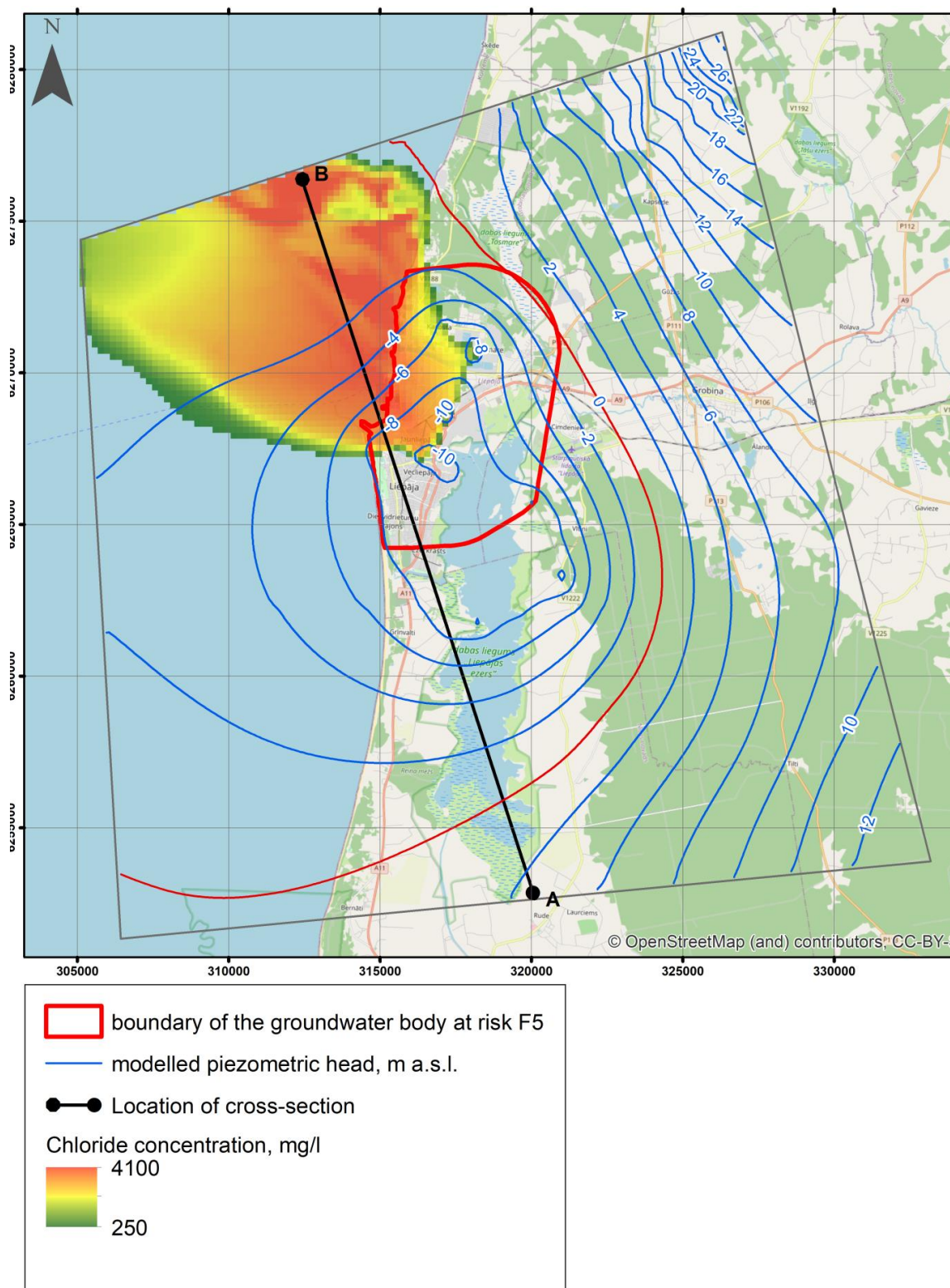


Figure 20 Modelled groundwater head (m a.s.l.) and Cl^- concentration (mg/l) distribution in $D_{3mr-žg}$ aquifer around 1980, Past scenario



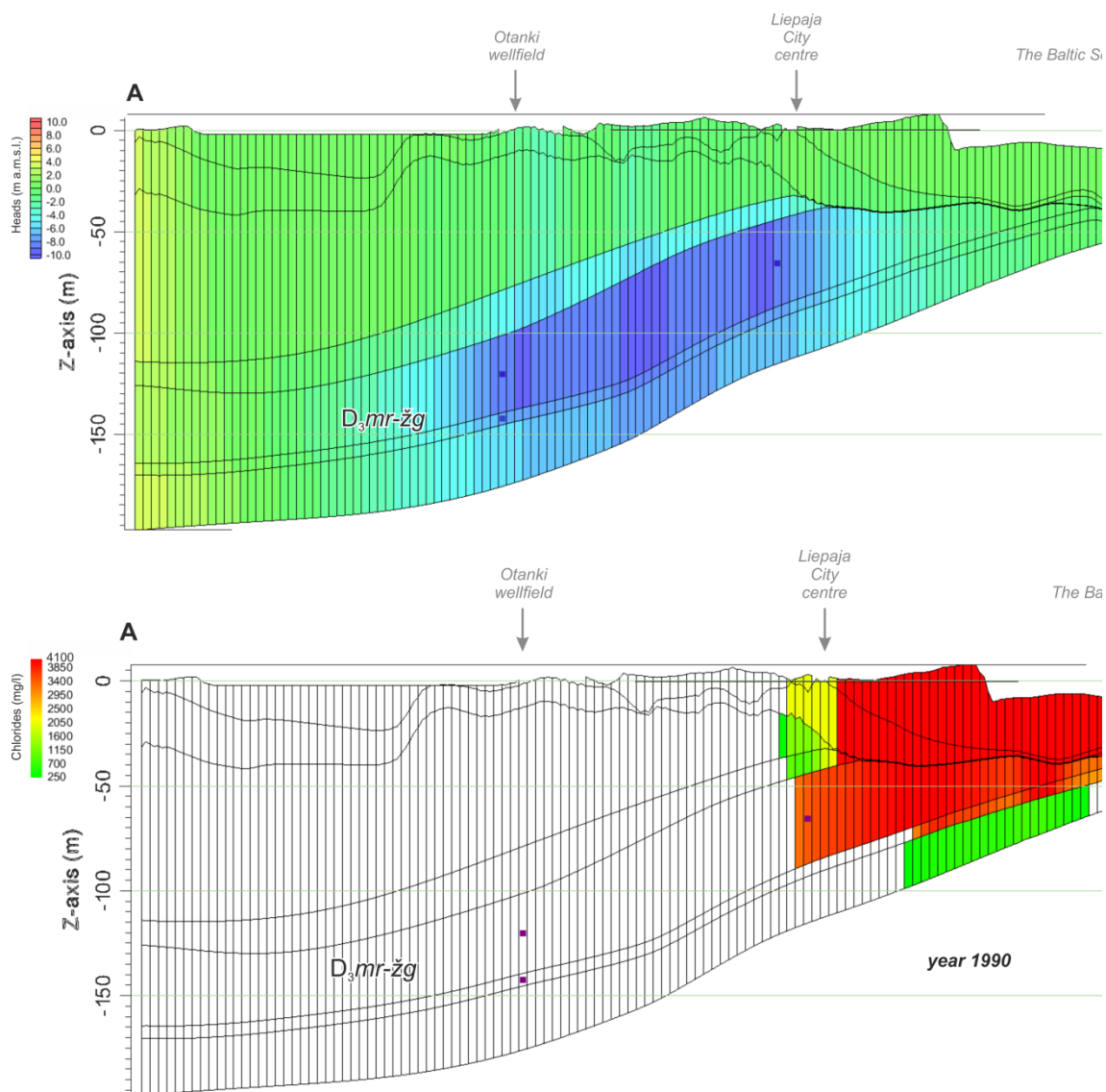


Figure 21 Vertical cross-section along A-B line (**Figure**): top – groundwater head (m a.s.l.); bottom - Cl⁻ concentration (mg/l) around 1980, Past scenario

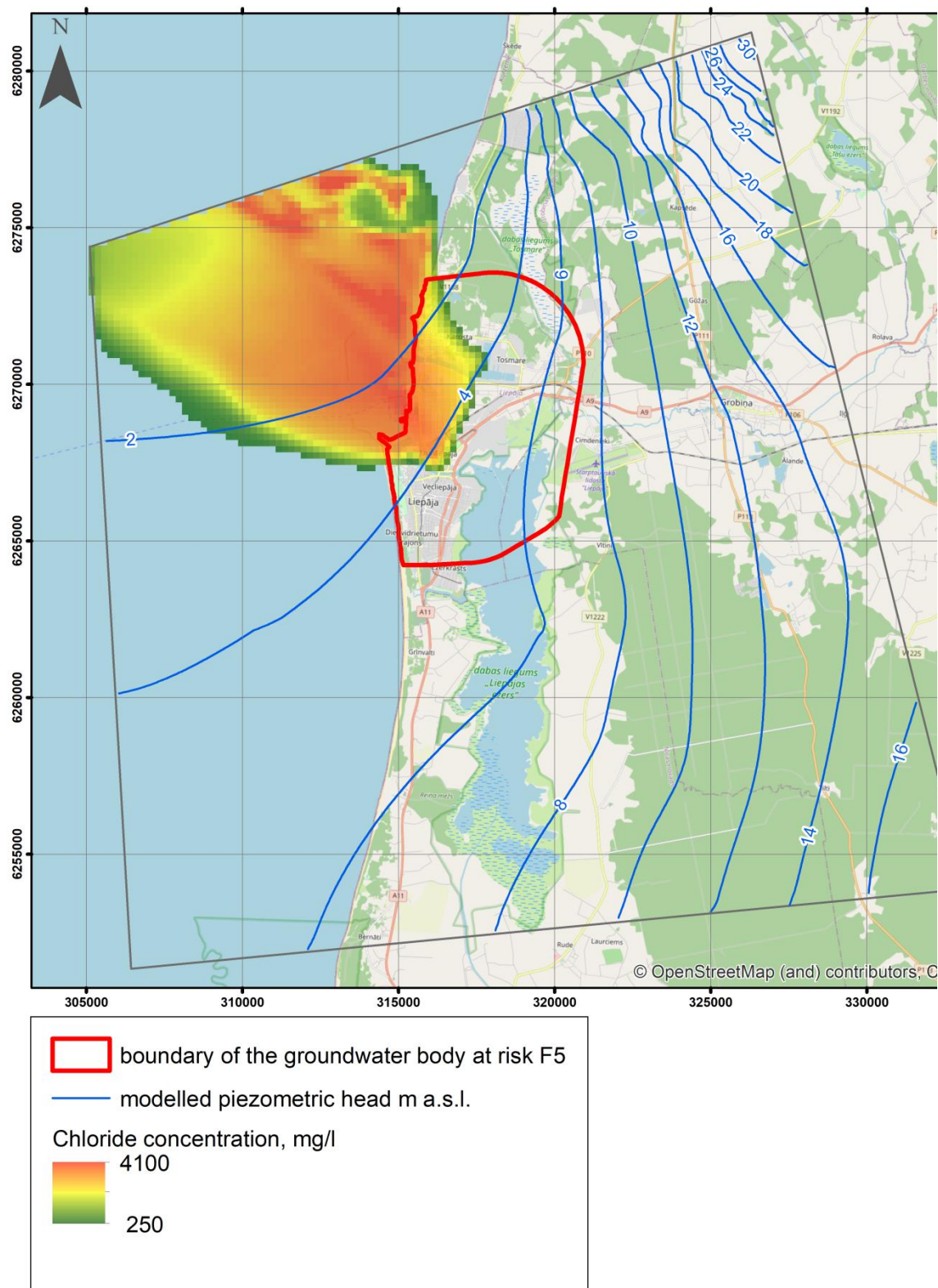


Figure 22 Modelled groundwater head (m a.s.l.) and Cl^- concentration (mg/l) distribution in $\text{D}_3\text{mr-}\check{\text{z}}\text{g}$ aquifer around 2015, Present scenario



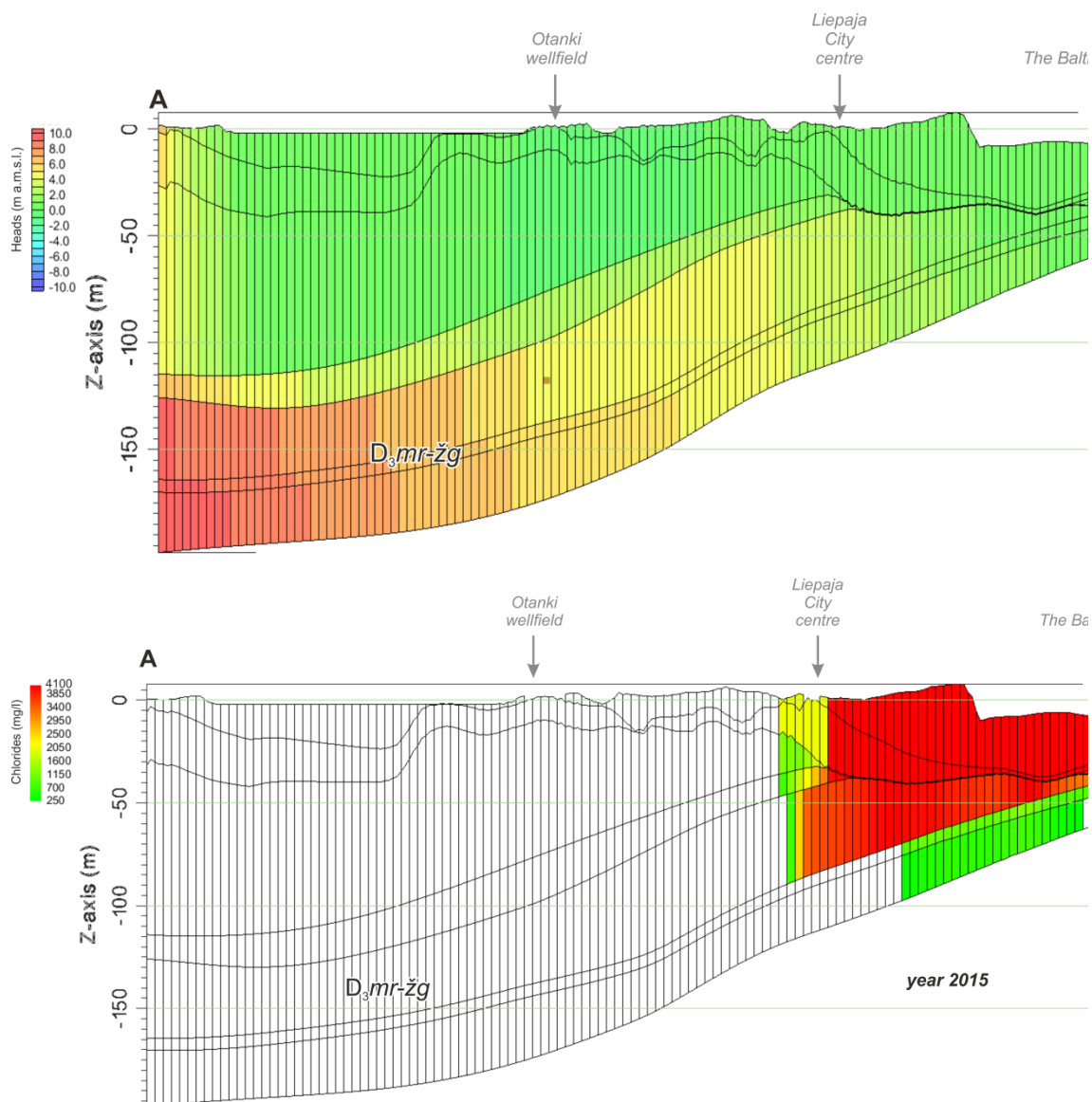


Figure 23 Vertical cross-section along A-B line (**Figure 20**): top – groundwater head (m a.s.l.); bottom - Cl⁻ concentration (mg/l) aquifer around 2015, Present scenario

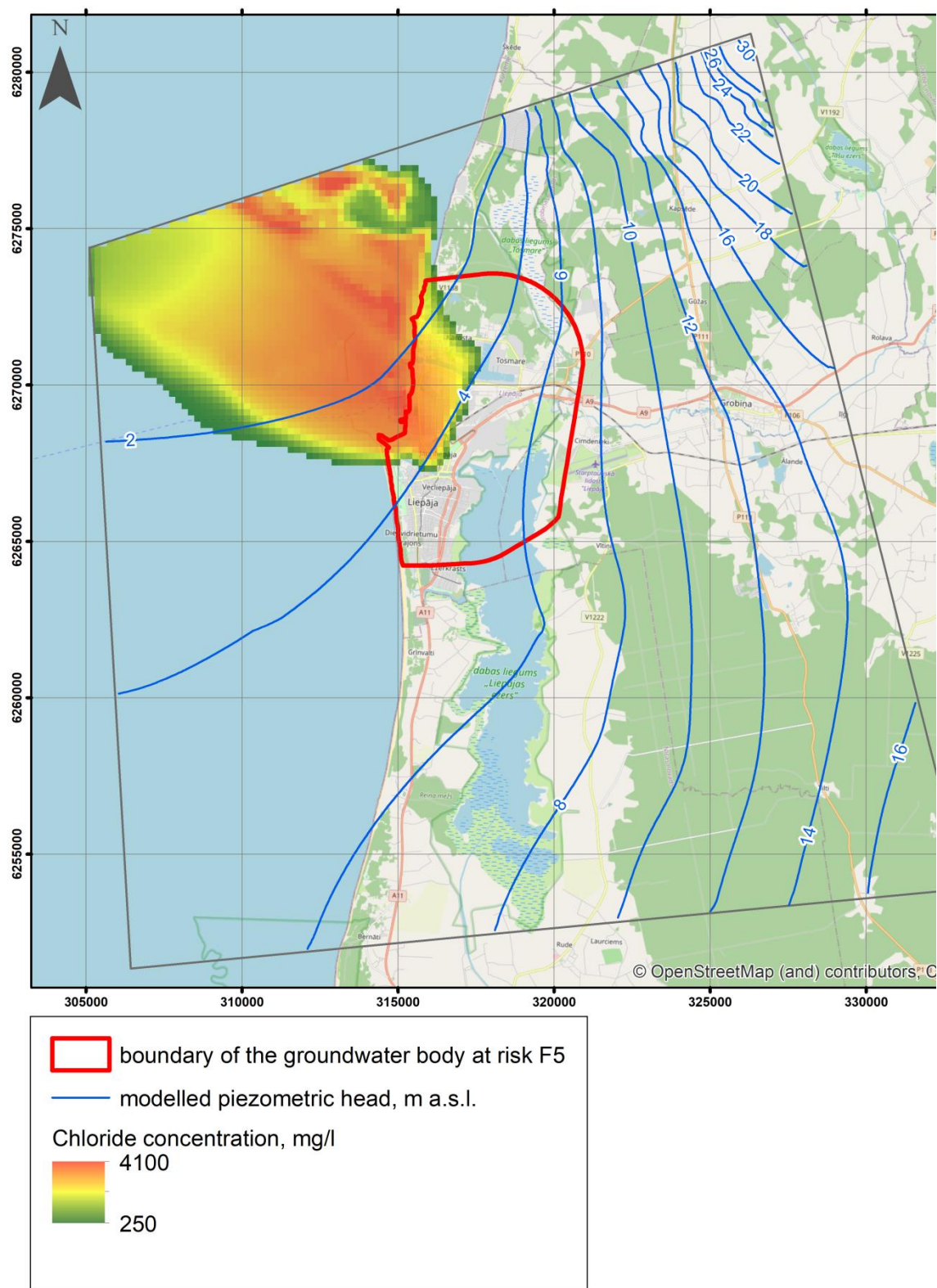


Figure 24 Modelled groundwater head (m a.s.l.) and Cl^- concentration (mg/l) distribution in $\text{D}_{3mr}\text{-}\check{z}g$ aquifer around 2027



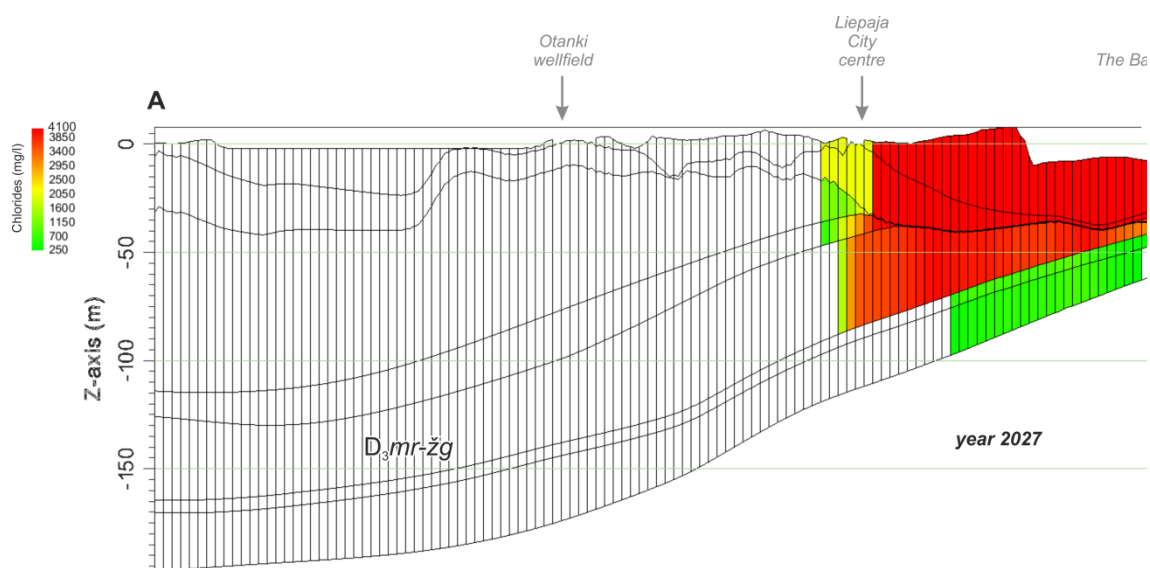


Figure 25 Vertical cross-section along A-B line (Figure 20): Cl^- concentration (mg/l) around 2027

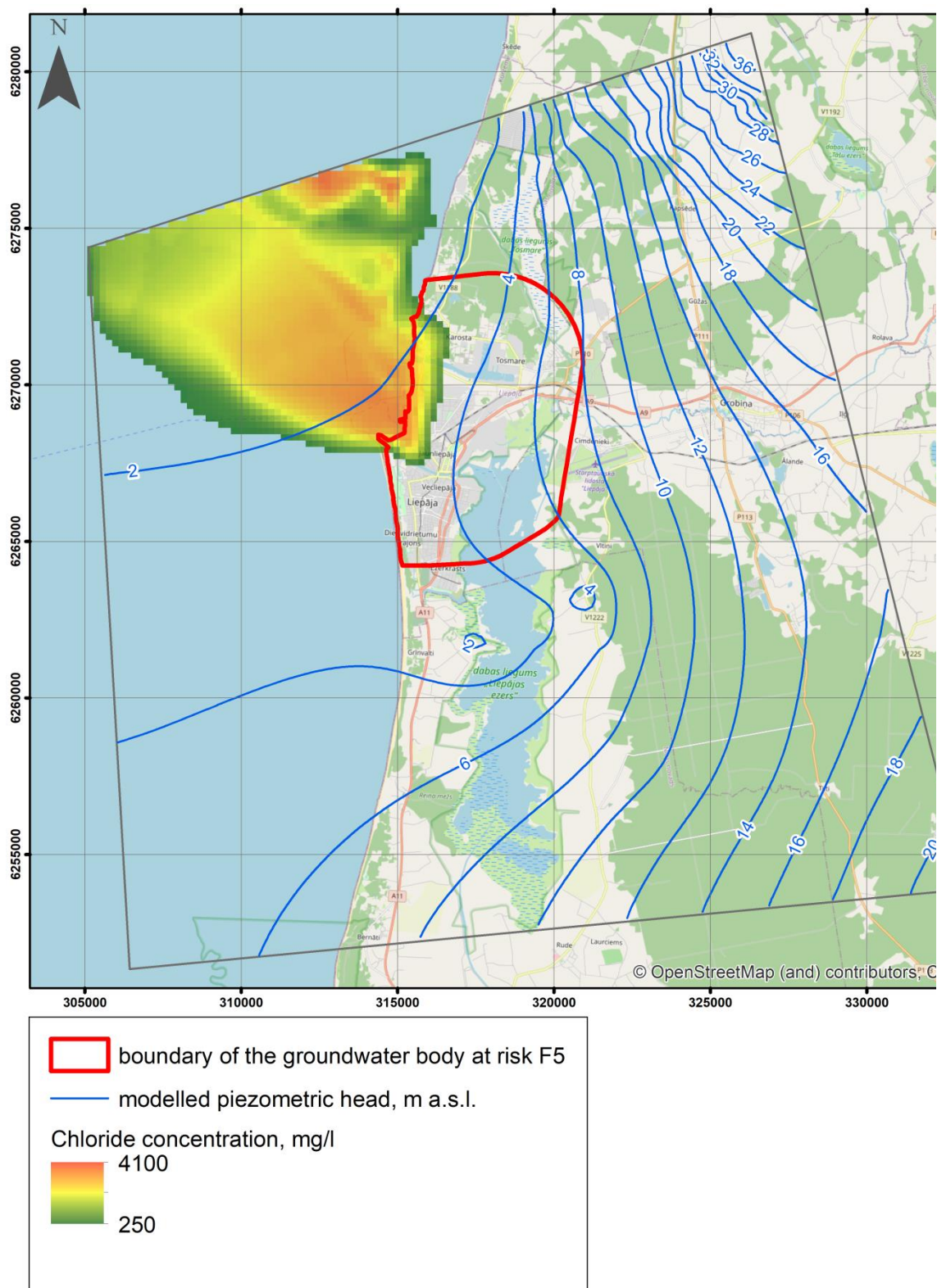


Figure 26 Modelled groundwater head (m a.s.l.) and Cl^- concentration (mg/l) distribution in $\text{D}_{3\text{mr-}\dot{\text{z}}\text{g}}$ aquifer around 2100, Future scenario



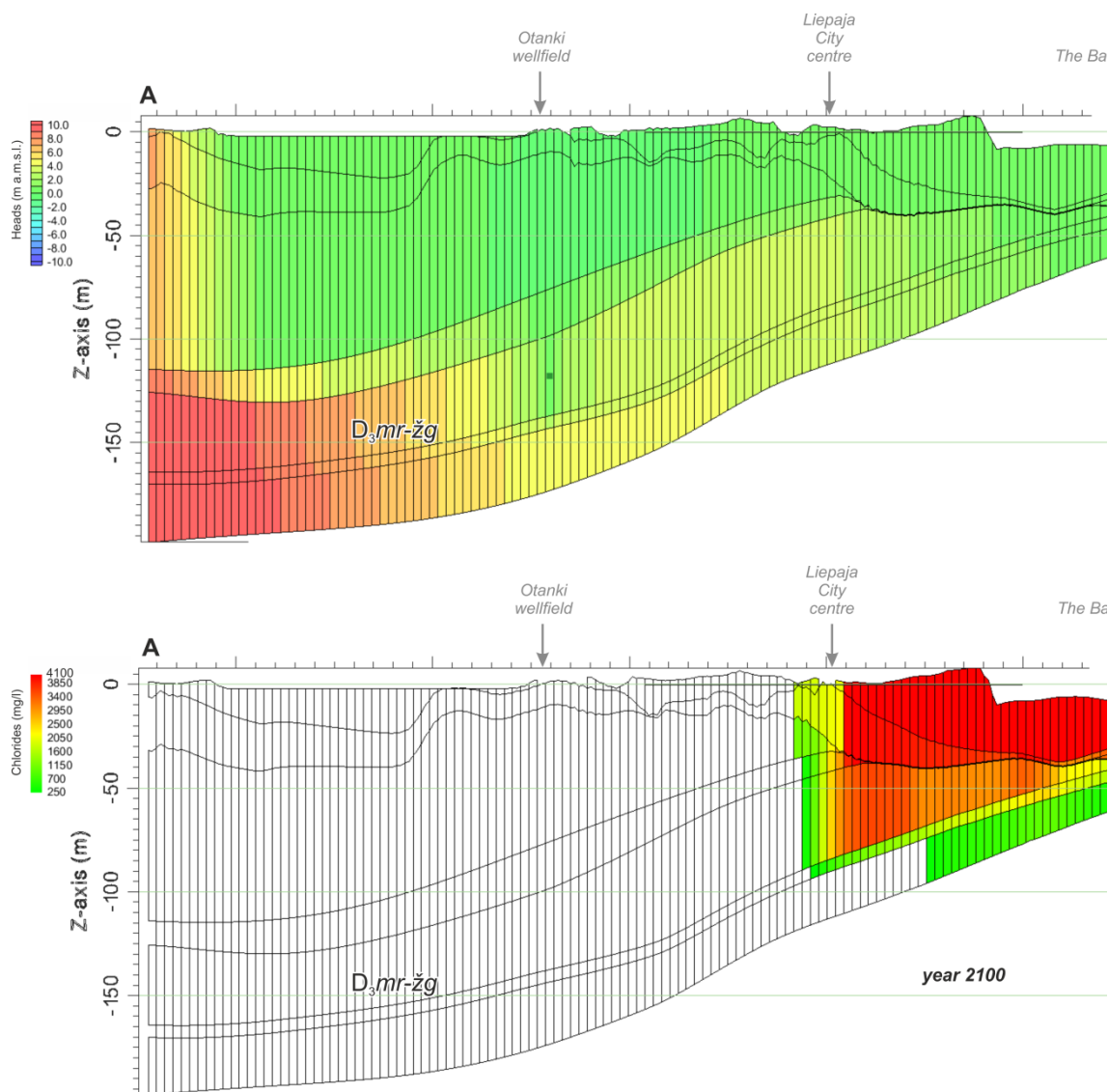


Figure 27 Vertical cross-section along A-B line (**Figure 20**): top – groundwater head (m a.s.l.); bottom - Cl⁻ concentration (mg/l) around 2100, Future scenario

5.3. Conceptual representation of the state of seawater intrusion

Results of the conceptual representation of the state of seawater intrusion according to modified methodology by Baena-Ruiz *et al.*, (2018; **Figure 28**) show gradual retreat from its peak in late 20th century. However, despite significantly increased groundwater recharge, even by the end of 21st century the tracer of historical seawater intrusion was expected to be found in groundwater body F5.



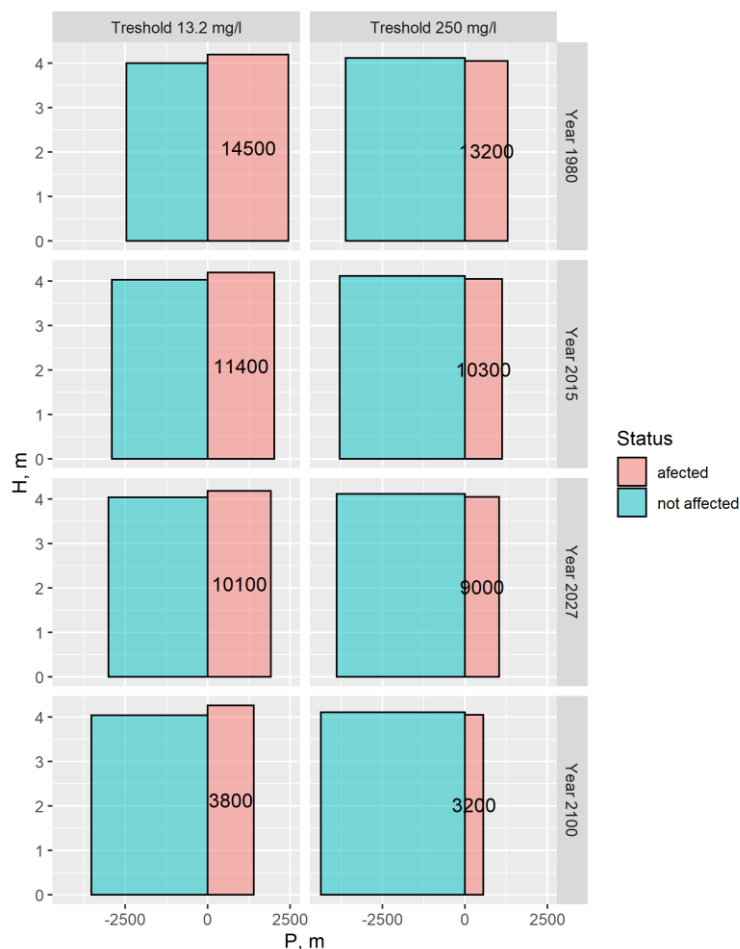


Figure 28 Conceptual representation of the state of the sea-water intrusion into groundwater body F5, Liepāja, Latvia, modified after (Baena-Ruiz *et al.*, 2018), see symbol explanation in Figure 15

5.4. Performance to historical data

3D hydrogeological modelling

Simulation of the seawater intrusion into D₃ Mūri-Žagare aquifer yielded controversial results: at least 250 years of historically high groundwater abstraction was needed to have the state of seawater intrusion as historically observed. However the modelled retreat of the seawater intrusion after decrease of abstraction rate largely followed the observations. This indicate that either assumptions of initial chloride distribution in aquifer was inaccurate or model setup does not satisfactory reflect actual geological situation.

In literature (Semjonovs *et al.*, 1997) there were indications about groundwater salinization already in 30-ties of the 20th century. If this is the case, then it is likely that at natural state significant portion of aquifers bellow the Baltic Sea were saturated with saltwater rather than



freshwater. In our model setup we have assumed that the brackish (salinity of about 10‰) water of Baltic Sea has the same density as fresh water, therefore little or no natural penetration of seawater into aquifers would take place. In model initiation only the topmost layer was marked as saturated with seawater. Much earlier inland penetration of seawater in $D_3mr\text{-}\check{z}g$ aquifer would be modeled if on model initiation saltwater would be present in the aquifer under the Baltic Sea.

$D_3mr\text{-}\check{z}g$ aquifer is made of both sandstones, dolomites and impervious interlayers of fined grained sediments (Lukševičs *et al.*, 2012), however in model setup it was represented as uniform aquifer. Thus actual configuration of locally significant aquitards could significantly influence the propagation rate of seawater intrusion into aquifer. In addition carbonate aquifers are known to have a dual porosity: water movement in fissures and cracks are much faster than in fine pores in blocks separated by the fissures. Thus actual penetration of intrusion in fissured rocks would be faster compared clastic sediments.

Furthermore both more heterogeneous geological structures of the study site as well as speculated antecedent sea water in sedimentary formations below Baltic Sea would result in development of more dispersed sea water intrusion. Configuration of observed seawater intrusion actually was more complex and dispersed compared to our model output. Both hypotheses deserve further attention, but are outside the scope of current work.

Conceptual representation of the state of intrusion

Interpolated results of the Cl^- concentration in $D_3mr\text{-}\check{z}g$ aquifer clearly did not adequately illustrated the state of the seawater intrusion. That was evident by overall smoothing and patchiness of the maps. Consequently conceptual representations are equally uncertain. However the rather wide distribution of low-level Cl^- contamination (**Figure 19**) might be rather realistic, particularly if compared to the modeled sharp gradients of Cl^- concentration.

Conceptual representation of the statistically interpolated state of intrusion have greater extent but leaser total mass of above-threshold Cl^- intruded into aquifer (**Figure 14**) if compared to the modeled one (**Figure 28**). Arguably the area of the aquifer affected by intrusion was better represented by the 3D hydrogeological model, despite some of regions (near lake Liepāja, **Figure 19 and 20**) know to have elevated Cl^- concentration does not show up in modeled maps. That might be due to simplification of geological complexity in geological model or inaccurate representation of the actual groundwater abstraction.

In contrary it is likely that the total mas of extra Cl^- ion in $D_3mr\text{-}\check{z}g$ aquifer were more closely represented by the interpolated observations as generally higher concentrations were calculated by modeling compared to actual observations. This discrepancy between modeling results and observation very likely was due to simplified representation of complex geological stricter in the model.

Interpolation of the observed Cl^- concentration in $D_3mr\text{-}\check{z}g$ aquifer gives an impression that the intrusion has spread since the 80-ties of the 20th century. Most likely that was not the case as groundwater abstraction rates had decreased and observed levels of Cl^- concentration are decreasing (Bikše *et al.*, 2016). Non-overlapping observation wells were the source of this misleading result, demonstrating the need for continuous and consequent monitoring. It is unlikely that the geology will experience similar explosion of high resolution, near-continues

availability of remote sensing data, like some other earth sciences had in recent decades year. Lack of knowledge about detailed structure of the geological environment will remain a major challenge in hydrogeological modeling. Thus continuation of ongoing monitoring work is important as ever ensuring that the same parameters are being observed at the same locations.

5.5 Results of assessments

1. Using 3D stationary groundwater flow model we did not find any evidence of ongoing seawater intrusion into D₃mr-žg aquifer, thus we conclude that elevated Cl⁻ concentration in this aquifer was the historical pollution that is gradually removed by natural groundwater flow.
2. Results of hydrogeological modelling demonstrated that present groundwater abstraction rates in Liepāja city were sustainable, and gradual recovery of freshwater D₃mr-žg aquifer affected by seawater intrusion was expected to continue confirming previously observed trends in water levels and quality.
3. It was found that in future climatic conditions increased groundwater recharge was to be expected. As a result even three-fold increase of present groundwater abstraction and preserving present configuration of abstraction wells was not likely to trigger renewed seawater intrusion.
4. Unrealistically long initiation period of historically high groundwater abstraction rates was necessary to model state of seawater intrusion similar to observations, however modelled retreat of intrusion after reduction of groundwater abstraction reflected observations satisfactory. It is likely that already at natural state seawater was penetrating sedimentary rock below Baltic Sea near Liepāja, resulting in fast development of inland intrusion when intensive groundwater abstraction was initiated in early 20th century. In addition geological heterogeneous and possibly fissured, dual-porosity layers within D₃mr-žg aquifer would have contributed in faster than expected inland penetration of seawater. Both these aspects deserve further investigation.
5. In a case of climate change scenario with expected 3°C average temperature rise, increased groundwater recharge (by up to 50%) was expected. As a result even threefold increased groundwater abstraction compared to modern situation with current configuration of abstraction wells was not likely to result in renewed seawater intrusion into Upper Devonian Mūri-Žagare aquifer within groundwater body F5 and its surrounding.
6. The inherent difficulties in using simple statistical interpolation to represent the state of seawater intrusion in a complex geological environment underlain the need for continued monitoring of the same groundwater parameters at the same locations.

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