Effects of karst processes on surface water and groundwater hydrology at Skaistkalne Vicinity, Latvia

Aija Delina, Alise Babre, Konrads Popovs, Juris Sennikovs
and Baiba Grinberga

ABSTRACT

The Skaistkalne area in Latvia is one of the places where karst processes in gypsum strata occurs. The Iecava and Memele rivers border the area with extensive surface karst features such as sinkholes and karst lakes. Earlier investigations suggested a hydraulic connection between the Iecava and Memele rivers exists via the karst conduits due to the water level (WL) difference in the rivers. A set of methods was performed to study the possible connection: dye tracer was applied in the Iecava river and its occurrence was visually observed at the karst lakes and Memele river; the current velocity was measured and discharge of rivers calculated at several profiles; surface water and groundwater composition was studied involving *in situ* measurements of water pH and electrical conductivity, water sampling and chemical analysis of the water samples on the content of sulphates, calcium and magnesium ions. A numerical finite element 3D groundwater flow model was developed to assess the impact of WL changes in rivers to groundwater flow. The study showed that there is direct hydraulic connection between the rivers – water from the Iecava river flows to the Memele river. The groundwater discharge to the Memele river varies seasonally, and more intensive groundwater discharge is observed during the high season.

Key words | gypsum aquifer, numerical modelling, sulphates, tracer test

Aija Delina (corresponding author)
Alise Babre
Konrads Popovs
Baiba Grinberga
University of Latvia,
Faculty of Geography and Earth Sciences,
Alberta Street 10,
Riga, LV 1010,
Latvia
E-mail: *aija.delina@lu.lv*

Juris Sennikovs
University of Latvia,
Laboratory for Mathematical Modelling of Environmental and Technological Processes
Zellu Street 8,
Riga, LV 1002,
Latvia

NOMENCLATURE

EC	electric conductivity, μS/cm
Q	discharge, m^3/sec or m^3/day
T	temperature, °C
LMMETP	Laboratory for Mathematical Modelling of Environmental and Technological Processes of University of Latvia
LEGMC	Latvian Environment, Geology and Meteorology Centre
WL	water level, m
R^2	square of correlation coefficient
K	hydraulic conductivity, m
H	water level (head), m

INTRODUCTION

Several rocks are referred to as karst rocks – gypsum, anhydride, salt, limestone, dolomite, but karst processes commonly take place in carbonate rocks (Derek & Williams 2007) forming different surface and sub-surface karst features such as caves, karrs, sinkholes and tunnels which develop unusual subsurface hydrology. Gypsum is so soluble that its layers can be completely dissolved and the protective insoluble cover strata may collapse and subside. Derek & Williams (2007) use the term intrastratal karstification to refer to the preferential dissolution of a particular bed within a sequence of soluble rocks.

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Karst rocks such as dolomite, gypsum and limestone occur in the geological section of Latvia in the Upper Devonian and Permian sediments. Dolomite is the most abundant karst rock in Latvia, found in a number of Upper Devonian formations. Gypsum is mainly found in the Salaspils formation of Upper Devonian, but limestone is more typical for the Upper Permian formations. Karst processes are observed in carbonate and sulphate rocks in the central and southern part of Latvia, but in some areas surface features of the karst such as sinkholes and land subsidence are found (Figure 1).

The intrastratal karst processes area in southern Latvia around Skaistkalne town (Figure 1) is where gypsum layers of Upper Devonian Salaspils formation are partially dissolved forming underground fractures, channels and caves, as well as sinkholes, when overlying glacial deposits have collapsed. There are two rivers, the Iecava river and the Memele river, running from east to west, and their valleys cut the deposits of the Salaspils formation. Earlier studies (Narbutas *et al.* 2001) have shown that there should be an underground hydraulic connection between the Iecava and Memele rivers about 5 km upstream of Skaistkalne town. To study the effect of karst processes on surface water and groundwater hydrology in the Skaistkalne vicinity, the data on water levels (WLs), river discharge, tracer test results and analysis of water chemistry data were evaluated and processed. The numerical hydrogeological model of the area was built in order to simulate groundwater and surface water interaction in high and low water seasons, and to check the validity of Darcy's law to describe the groundwater flow in the karst environment.

GEOLOGY AND HYDROLOGY OF THE STUDY AREA

The study area is located in the Upmale hillock plain of the Middle Latvia lowland. The land surface is slightly undulated, gently sloping from east–northeast to west–southwest and its altitude is 40–50 m a.s.l. (Figure 2), but the relative height of the hills is from 2–5 to 8–10 m. Several rivers cross the Upmale hillock plain, and the main ones are the Iecava and Memele rivers. The Iecava river flows along the northern border of the study area, and the Memele river along its southern border (Figure 2). The Iecava river valley is 2–3 m deep, mainly cut in the Quaternary deposits, but sediments of Upper Devonian Salaspils Formation are found at the river bottom in places. The Iecava river flows from northeast to southwest, the mean WL changes from 25.5 to 43.1 m a.s.l. and the flow gradient is 0.5 m/km on average, and in the study area it is 0.46 m/km. The Memele river is the largest river in the study area and it flows in the deep valley, which is cut in Quaternary and Devonian sediments (Figure 3). The river valley depth varies from 2–5 to 10–12 m, and outcrops of the Devonian carbonate and sulphate rocks are found in the deepest stretches of the valley. The Memele river flows from northeast to southwest, the mean WL changes from 21.2 to 46.6 m a.s.l., flow gradient in the study area is 0.5 m/km

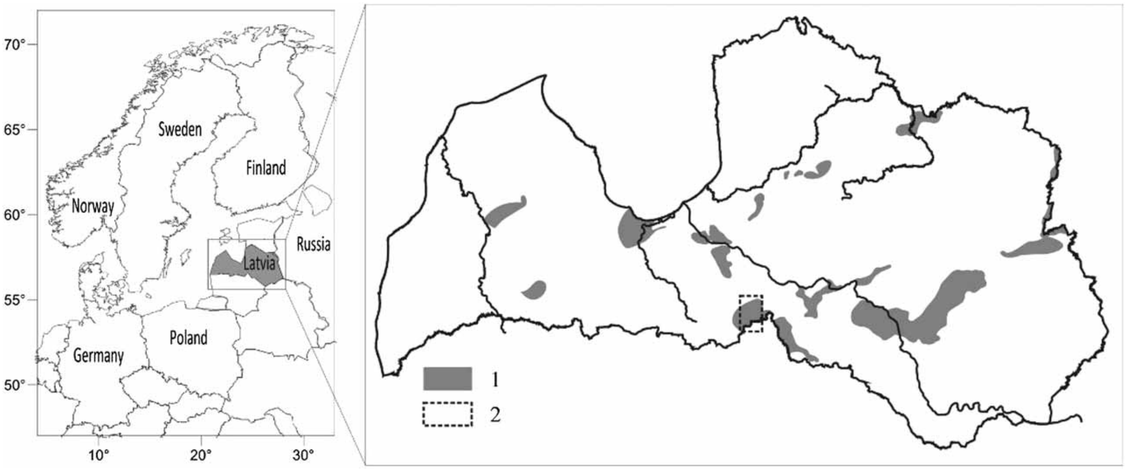

Figure 1 | Distribution of surface karst features in Latvia (Levins & Buzajevs 1999). 1 – carbonate and sulphates karst distribution areas; 2 – study area at the Skaistkalne vicinity.

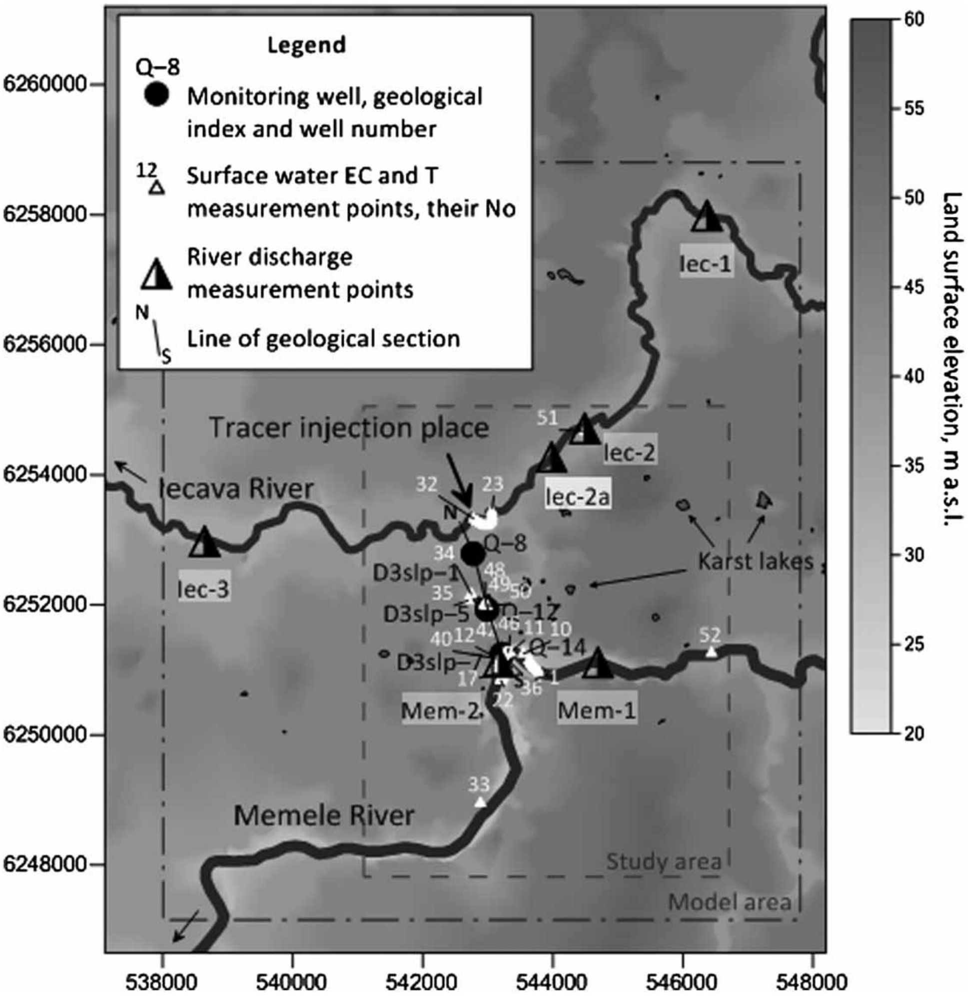

Figure 2 | Location of investigation points.

on average, and in the study area it is 0.17 m/km. The mean annual WL change in both rivers is 1–1.5 m, rarely reaching 2 m (Pastors 1987). The high WL is typical for spring and late autumn, and the low WL is in late summer and winter. There is a difference in WL altitude in both rivers; the WL altitude in the Iecava river is constantly 5–7 m higher than in the Memele river, causing a hydraulic head difference in the Salaspils Formation.

Quaternary and Devonian sediments form the upper part of the geological section in the study area (Figure 3). The thickness of the Quaternary sediments varies from a few metres in the river valleys and around Skaistkalne town west of the study area to 10–15 m in the study area. Quaternary cover formed during the Late Weichselian glaciation and in post-glacial time, and consists of glaciolacustrine deposits (lgQ_3ltv) – sand, fine and silty, thickness 0–5 m and clay, silty clay and sandy clay, thickness 0–5 m, which were deposited in the glacial lake environment. The sand and silt sediments are found on the ground surface in almost the whole study area, apart from some islets where underlying glacigene till (moraine) outcrops. The base of the Quaternary cover was formed during the Late Weichselian glaciation and consists of glacigene deposits (gQ_3ltv) – till loam with gravel and pebbles, the thickness of the till deposits varies from a few to about 10 m. Devonian sediments lie below the Quaternary deposits, the surface of the pre-Quaternary rocks is gently sloping to northwest, the absolute height of the pre-Quaternary sediments surface changes from 42 to 45 m a.s.l. in the centre of the study area to 34–36 m a.s.l. in the periphery. The

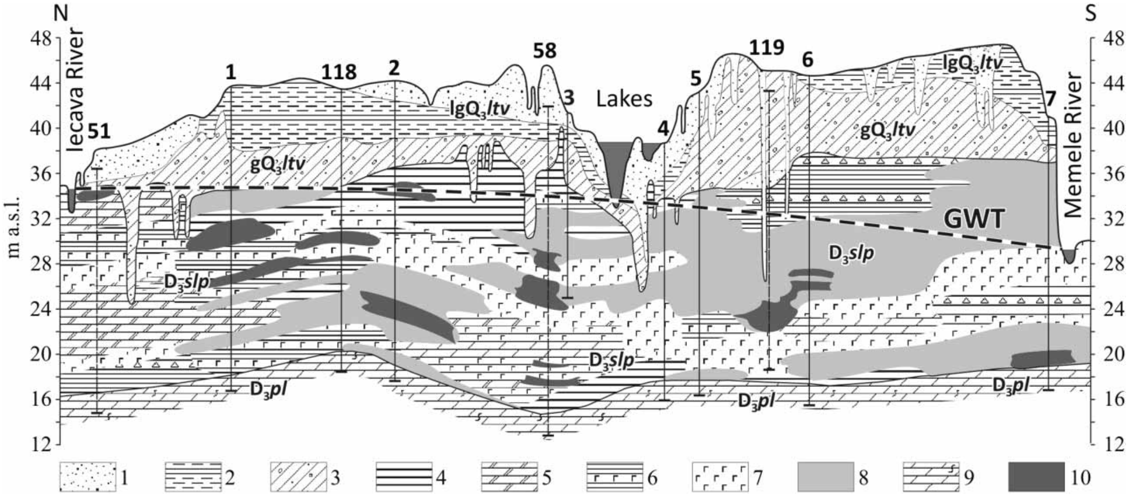

Figure 3 | Geological section of the study area along the line of sampled wells, the length of the section is 2.6 km (Tracevska *et al.* 1986). 1 – sand, 2 – silt, clayey silt, 3 – till loam, 4 – carbonate clay, 5 – marl, dolomite marl, 6 – clayey gypsum, 7 – gypsum, 8 – dissolved gypsum strata with clay and dolomite flour, 9 – dolomite, fractured dolomite, 10 – karst cavities, partially filled with dolomite flour; GWT – groundwater table; lgQ$_3$ltv – glaciolacustrine sediments, gQ$_3$ltv – glacigene till deposits, D$_3$*slp* – Upper Devonian Frasnian stage Salaspils Formation sediments, D$_3$pl – Upper Devonian Frasnian stage Plavinas Formation.

pre-Quaternary surface is dissected by a number of sinkholes up to 8–10 m deep filled with Quaternary deposits. Some of the sinkholes are filled with water forming small karst lakes. These lakes are recharged from precipitation and confined groundwater, the recharge type can be identified based on the chemical composition of water in the lakes; there are significantly higher values of electric conductivity (EC) and sulphates content in the lakes where confined groundwater discharges.

The Upper Devonian Frasnian stage Salaspils Formation (D$_3$slp) sediments lay below the Quaternary deposits within the study area (Figure 3), and only in the periphery are they are covered with the dolomites of Upper Devonian Frasnian stage Daugava Formation (D$_3$dg), the Daugava Formation deposits are eroded at the study area. The thickness of Daugava Formation dolomites varies from 0.2–0.5 m near the distribution border to 3–5 m further from it. Salaspils Formation sediments formed during the regression stage of the sedimentary basin, when lagoon conditions prevailed, facilitating sedimentation of evaporites such as gypsum (Birger *et al.* 1979). Three substrata are divided in the Salaspils Formation: (1) carboniferous clay layer, 0.5–3.5 m thick, lay in the bottom of the formation; (2) the middle strata consists of carbonate and sulphate rocks – dolomite, gypsum, dolomite marl and dolomite flour, the total thickness of this strata is from a few metres to 10–12 m in areas where gypsum layers are present, the thickness of the gypsum beds is 3–9 m; and (3) the upper layer is mainly carboniferous clay with 1–1.5 m thick interbeddings of dolomites, the thickness of the layer is 5–8 m. The karst processes are bound to the gypsum-containing strata, but sinkholes, caverns and fractures have also formed in the layers above due to the dissolution of gypsum layers and collapse of the overlaying strata. Upper Devonian Frasnian stage Plavinas Formation (D$_3$pl) fractured dolomites lay below the Salaspils Formation, their thickness is 20–23 m.

Hydrogeologically, the geological section is divided in three aquifers separated by the aquitards: (1) water table aquifer, bound to the Quaternary sand deposits; (2) Salaspils semi–confined aquifer, bound to the middle part of the formation, is the karst aquifer where groundwater flow occurs along the karst conduits; and (3) Plavinas confined aquifer bound to the fractured dolomites. Groundwater recharges from precipitation and discharges in the deeper river valleys. However, it was found (Narbutas *et al.* 2001) that there is a water loss of about 15% (compared with the river discharge upstream from the karst area) in the Iecava river showing that groundwater recharge from the rivers occurs. The groundwater table in the unconfined Quaternary aquifer is 0.5–2 m below the ground surface and 4.5–18 m below the ground surface in the semi-confined

Salaspils aquifer. Hydraulic conductivity of the Salaspils aquifer sediments is 30–100 m/day in the areas of intensive karst (Tracevska *et al.* 1986).

MATERIALS, METHODS AND RESULTS

River discharge measurements

River discharge is one of the elements in water balance, where estimations are one of the steps in the karst hydrology studies (Derek & Williams 2007). However, only the water discharge of the Iecava and Memele rivers was measured in six locations (Figure 2) in low season. The discharge measurements included river profile measurements at each location and stream velocity measurements with current velocity metre RICKLY 1210 and impulse counter AQUAPULSE 5210. Each profile was divided into three sections, and stream velocity was measured at several depth intervals. The total discharge was calculated (Table 1) by summing the individual velocities and multiplying the result by the respective cross-sectional areas (Weight & Sonderegger 2001)

$$Q = \sum_{i=1}^{n} v_i A_i \tag{1}$$

where Q= river discharge, m^3/sec; v_i= stream velocity at each profile section, m/sec; A_i = area of the profile section, m^2.

Tracer test

Tracer tests are used in karst hydrology studies to trace the water flow paths, flow velocity and hydraulic parameters (Derek & Williams 2007), and dye tracers are most commonly used (Aley 2008). The tracer test was performed in the Skaistkalne area to prove the subsurface hydraulic connection between the Iecava and Memele rivers. Dye tracer fluorescein $C_{20}H_{12}O_5$ was used. The tracer test was designed so that the tracer occurrence in possible discharge locations (karst lakes, Memele River) could be visually detected. The tracer (1 kg) was applied in the Iecava river (Figure 4) on 6 December 2008 at 14:30 in a stretch of river where water loss was reported. The whole amount of the dye was diluted in 5 L of water and poured in the river at one spot all at once. Tracer was visually observed in the karst lakes after 22 h and in the Memele river after 65.5 h (2.7 days) and after 4.7 days the tracer was observed for a short period (2 h) in the spring (Figure 4). The tracer residence time in the karst lakes and Memele river was not registered.

The tracer travel time was used to calculate water flow velocity via the karst conduits – the water flow velocity is 1,290 m/day near the Iecava river (tracer reached A in Figure 4) and about 800 m/day closer to the Memele river (tracer reached B in Figure 4).

Surface water and groundwater sampling and analysis

The karst processes in sulphate rocks dissolves gypsum strata, and the sulphate content in water is increased so it could be used as a natural tracer. Surface water EC, pH and temperature (T) was measured in the Iecava and Memele rivers and karst lakes (Figure 2, Table 2) at 52 measurement points in total to locate the discharge areas of sulphates containing groundwater. Measurements were made and samples taken on November 2008 and July 2010. Surface water sampling locations were selected based on these measurements to represent background

Table 1 | Measured river discharge at study area on 09/07/2008 (discharge data from Grinberga 2009)

River	Post	Discharge Q, m^3/s	Discharge Q, $n \times 10^3$ m^3/day	Difference in discharge between measurement posts ΔQ, $n \times 10^3$ m^3/day	Discharge increase (+) or decrease (–) in %
Iecava	Iec–1	1.68	145		0
	Iec–2	1.54	133	−12	–8
	Iec–2a	1.16	100	−33	–25
	Iec–3	1.42	123	+23	+23
Memele	Mem–1	5.93	512		0
	Mem–2	22.48	1,942	+1,430	+279

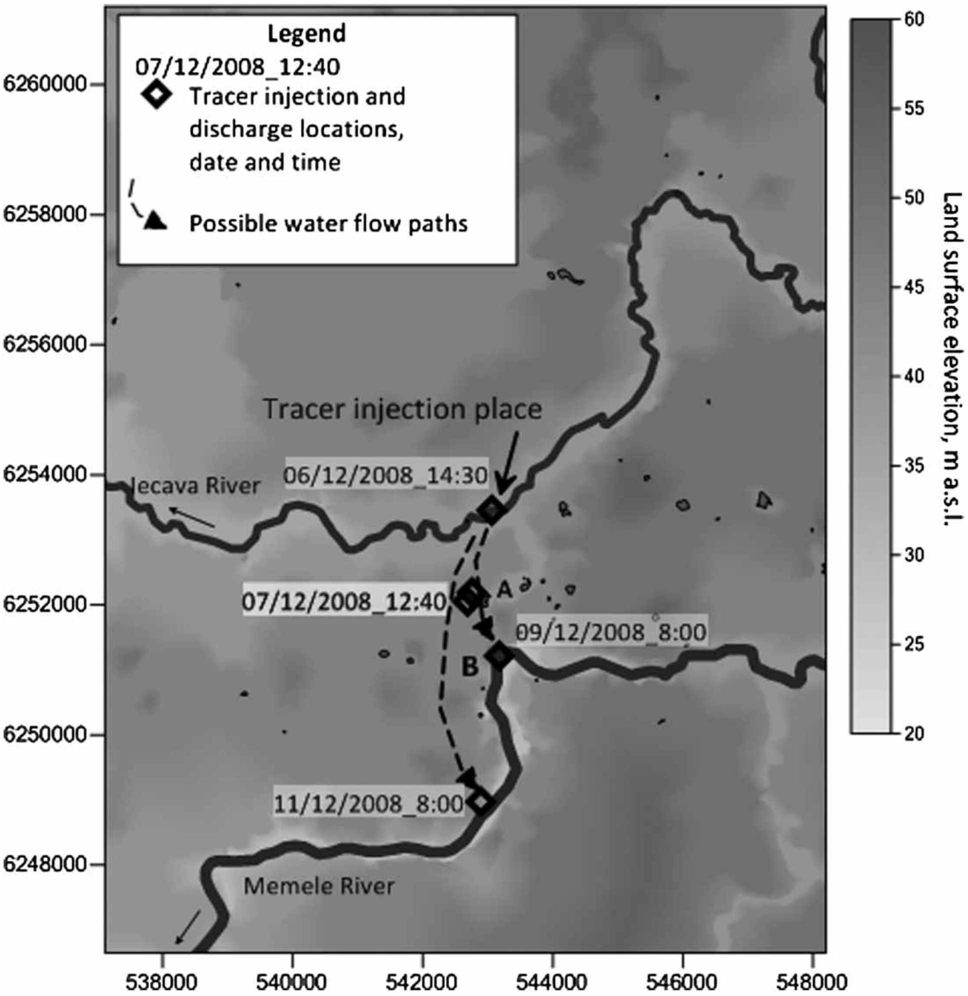

Figure 4 | Tracer test injection and observation points and possible flow paths.

values of surface water chemical composition and the chemical composition of surface water recharged by sulphates containing groundwater. Seventeen samples were taken.

Six groundwater samples were taken from pairs of wells installed in the Quaternary aquifer (depth 5–6 m) and Salaspils aquifer (depth 25–26 m) on July 2010; two wells were located near the Iecava river (Figure 2 – wells 1 and 8), two wells are near the karst lakes (Figure 2 – wells No. 5 and 12) and two wells are on the bank of the Memele river (Figure 2 – wells No. 7 and 14). Wells were pumped with a submersible pump MP-1 (yield 1.1 L/s) for 20–30 min before the sampling in order to replace the water volume in the well several times. Groundwater pH, EC and T was measured continuously using a portable WTW multi-parameter metre P4 with electrodes SenTix 41 (pH, T) and TetraCon 325 (EC, T). Sulphates, calcium and magnesium content was analysed in the surface water and groundwater samples (Table 3). The sulphate content was analysed by the turbidity method and titration methods were used to analyse calcium and magnesium content during the first stage of analysis in 2008. During the second stage of analysis in 2010, mass spectrometry was used for all ions.

Numerical modelling of groundwater flow

A numerical 3D hydrogeological model of the study area was created in order to analyse groundwater flow, hydraulic connection of the Iecava and Memele rivers and to simulate

Table 2 | Physical–chemical properties of surface waters at Skaistkalne area

ID	pH	EC, μS/cm	*T*, °C	Date	ID	pH	EC, μS/cm	*T*, °C	Date
Memele river									
M–1	8.14	840	2.3	Nov-08	M–19	8.14	823	2.3	Nov-08
M–2	8.17	852	2.5	Nov-08	M–20	8.44	835	2.3	Nov-08
M–3	8.21	860	3.1	Nov-08	M–21	8.21	830	2.3	Nov-08
M–4	8.15	872	2.8	Nov-08	M–22	8.32	840	2.5	Nov-08
M–5	8.16	877	2.7	Nov-08	M–36	7.78	414	26.3	Jul-10
M–6	8.32	895	2.7	Nov-08	M–37	7.78	413	26.3	Jul-10
M–7	8.44	920	2.8	Nov-08	M–38	7.79	413	26.3	Jul-10
M–8	8.14	910	2.5	Nov-08	M–39	7.78	420	26.3	Jul-10
M–9	9.32	1,250	2.4	Nov-08	M–40	7.79	420	26.4	Jul-10
M–10	9.3	1,145	2.5	Nov-08	M–41	7.6	462	26.6	Jul-10
M–11	8.6	1,098	3.2	Nov-08	M–42	7.79	452	26.1	Jul-10
M–12	8.64	1,123	2.8	Nov-08	M–43	7.76	402	26.5	Jul-10
M–13	8.55	955	2.6	Nov-08	M–44	7.82	402	26.5	Jul-10
M–14	8.54	920	2.4	Nov-08	M–45	7.79	404	26.4	Jul-10
M–15	8.48	884	2.5	Nov-08	M–46	7.8	405	26.4	Jul-10
M–16	8.35	868	2.6	Nov-08	M–47	7.78	413	26.3	Jul-10
M–17	8.38	854	2.1	Nov-08	M–52	7.71	388	27.8	Jul-10
M–18	8.2	834	2.4	Nov-08					
Iecava river					*Karst lakes*				
Iec–23	6.42	630	2.2	Nov-08	KL–34	9.48	1,334	3.2	Nov-08
Iec–24	6.61	643	2.1	Nov-08	KL–35	9.65	1,356	3.1	Nov-08
Iec–25	6.64	645	2.2	Nov-08	KL–48	7.37	73	26.1	Jul-10
Iec–26	6.83	620	2.5	Nov-08	KL–49	7.02	72	25.8	Jul-10
Iec–27	6.77	625	2.5	Nov-08	KL–50	6.96	72	26	Jul-10
Iec–28	6.64	630	2.6	Nov-08					
Iec–29	6.21	632	2.4	Nov-08					
Iec–30	6.44	626	2.3	Nov-08					
Iec–31	6.45	624	2,3	Nov-08					
Iec–32	6.62	634	2,3	Nov-08					
Iec–51	7.59	241	25,1	Jul-10					

the effect of low and high flow in the rivers on ground WLs, as well as to check the validity of Darcy's law to describe the groundwater flow in the karst environment.

Model structure and lithology

The 3D geological model covers an area of 120 km^2, its latitude is 10 km and longitude is 12 km. The horizontal resolution of the model structure is given by the regular mesh step 75 × 75 m based on cartographic map data and it was further refined with irregular point clouds in areas of river valleys. The vertical resolution is given by the log resolution of about 0.5 m and five stratigraphic units, separated in eight layers (Table 4).

Land surface elevation data are taken from a cartographic map at a scale of 1:50,000 and detailed in areas of river valleys with digitised data from a cartographic map at a scale of 1:10,000. Geological data were taken from

Table 3 | Surface water and groundwater chemical composition

Sample ID	Date	pH	EC µS/cm	*T* °C	Ca^{2+} mg/L	Mg^{2+} mg/L	SO_4^{2-} mg/L
M1	Nov-08	8.14	840	2.3	177.2	70.5	35
M5	Nov-08	8.16	877	2.7	178.3	72.4	43
M9	Nov-08	9.32	1,250	2.4	193.3	72.5	45
M10	Nov-08	9.3	1,145	2.5	185.5	68.1	55
M11	Nov-08	8.6	1,098	3.2	175.3	67.4	64
M12	Nov-08	8.64	1,123	2.8	190.4	67.4	65
M16	Nov-08	8.35	868	2.6	173.1	74.3	36
M22	Nov-08	8.32	840	2.5	164.4	75.4	38
Iec23	Nov-08	6.42	630	2.2	64.3	25.4	18
Iec32	Nov-08	6.62	634	2.3	78.2	23.1	21
Spr33	Nov-08	8.45	780	3.1	92.4	30	43
KL34	Nov-08	9.48	1,334	3.2	194.1	107.4	72
KL35	Nov-08	9.65	1,356	3.1	188.1	100.3	78
M42	Jul-10	7.79	452	26.1	70.7	14.1	23.3
KL49	Jul-10	7.02	72	25.8	9.2	3.3	0.15
Iec51	Jul-10	7.59	241	25.1	39.9	8.1	2.9
M52	Jul-10	7.71	388	27.8	64.8	14.0	11.3
W–D3slp–1	Jul-10	7.27	680	9.1	98.5	28.0	57.3
W–D3slp–5	Jul-10	7.29	1,920	8.9	523	20.8	1,100
W–D3slp–7	Jul-10	7.14	1,984	8.5	528	24.2	1,130
W–Q–8	Jul-10	7.17	590	15.7	78.2	23.3	11.7
W–Q–12	Jul-10	7.28	519	15.3	102	21.1	72.7
W–Q–14	Jul-10	7.1	778	16.5	114	30.2	17.9

Sample ID description: M – Memele river, Iec – Iecava river, Spr – spring, KL – karst lake, W – well and aquifer identification.

Table 4 | Model layers and their hydraulic properties

Stratigraphic unit	Layer name	Lithology of the layer	Horizontal hydraulic conductivity, m/day	Vertical hydraulic conductivity, m/day
lgQ3ltv	lgQ3ltv	Sand, water	15	15
gQ3ltv	gQ3ltv	Moraine	0.03	0.03
D3dg	D3dg	Dolomite	50	50
D3slp	D3slp1	Gypsum	320	100
	D3slp2	Dolomite	50	50
	D3spl3	Dolomite cavernous	75	75
	D3slp4	Clay	0.003	0.003
D3pl	D3pl	Dolomite	30	30

the Latvian Environment, Geology and Meteorology Centre (LEGMC) borehole database, where 72 boreholes were found in the modelled territory.

Model layers were interpolated in MeshEditor (Bethers *et al.* 1998a) using the kriging interpolation algorithm from borehole data. Further step layers were smoothed to eliminate overlapping between underlying and overlying surfaces, which might form from different dispersion of data used in the generation of each surface. Due to very complex lithology of D_3slp and uncertainty of local fault zones, this stratigraphic unit was divided into four subunits with equal thickness, interpolated between the bottom surface of D_3dg and the top surface of the D_3pl stratigraphic unit. Model layers were combined into one structure in HiFiGEO software for the creation and visualisation of 3D geological structures and modelling groundwater flows by 3D finite elements method (Bethers *et al.* 1998b; PAIC 2002) developed by the Laboratory for Mathematical Modelling of Environmental and Technological Processes of University of Latvia (LMMETP). There is a need to correct interpolation errors and to specify geologic structure when mesh is generated and compiled as the geologic uncertainty is great. Surface altitude was verified at borehole heights and corrected manually using a MeshEditor application built-in tool. This is essential during the calibration stage as mismatch can lead to calibration on incorrect data. The geologic structure was corrected by comparing three cross sections from the generated model and those made by geophysical methods earlier (Tracevska *et al.* 1986). The structure verification process was complete when satisfactory resemblance was achieved. Some layers were pinching out at local areas and their thickness was defined as 10 cm as it was not possible to cut them out at all.

Two large rivers flow through the model territory. Their impact on groundwater flow is very important as river bottoms come into contact with confined aquifer D_3slp and represent a significant inflow and outflow volumes of water through this aquifer. As river bathymetry for these rivers is not available, constant depth was defined from WL, and it was 1.5 m for the Iecava river and 2 m for the Memele river. The thickness of the surface layer was changed downwards in the river valleys. The outlying area within a distance of 10 m for the Iecava river and 20 m for the Memele river valleys were defined using the 'Buffers' tool in ArcMap version 9.3.

Several material types were used to represent geologic structure, and initially they were assigned constant to each layer. Material properties are summarised in Table 4; anisotropy of the hydraulic conductivity was applied for some materials, especially gypsum, which has a clay interlayer reducing hydraulic conductivity in vertical direction.

Boundary conditions

Boundary conditions were set for the Iecava and Memele rivers and larger karst lakes (Figure 5), model margins and

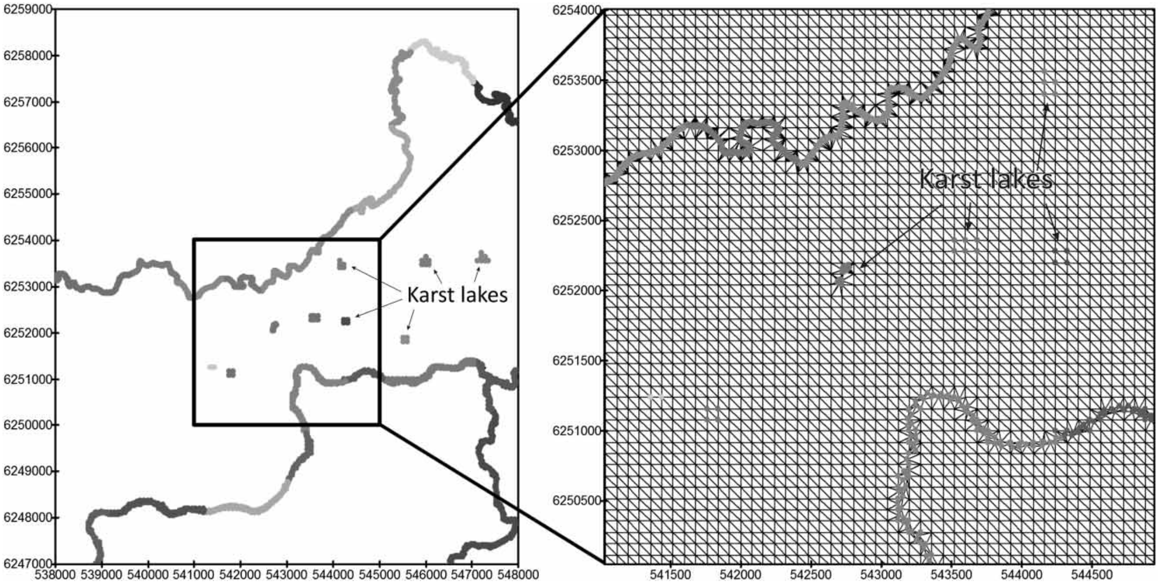

Figure 5 | Constant head boundary conditions location in the model area. Hues of grey indicate variations in constant head values in rivers and karst lakes. The left-hand figure shows the model mesh and location of boundary conditions on element vertexes.

model surface. Cauchy boundary conditions were set on every aquifer margin, with regional impact coefficient $\alpha = 0.6$ according to the equation (PAIC 2002):

$$k\frac{\partial h}{\partial n} = \alpha(h - h_0) \qquad (2)$$

where k = hydraulic conductivity, m/day; h = WL on margin, m; h_0 = regional WL (Tracevska *et al.* 1986), m; n = normal to the outside margin; α = regional impact coefficient.

A Dirichlet boundary condition (constant head) was omitted to rivers and each river was divided into nine parts; WLs were set for these parts taken from topographic maps to a scale of 1:10,000, which represents the long-term average WL in the river. Several karst lakes were also set as constant head boundary conditions. The recharge from atmospheric precipitation was set as 0.000005 mm/s on materials exposed to the ground surface, which is an approximate infiltration rate for the country as a whole. Recharge was not adjusted for seasons of high and low water. The low and high water conditions in rivers were simulated by changing the boundary conditions of the rivers, −1 m from mean WL was applied for low water and +1 m for high water, based on long-term data that the average WL change is 1.5–2 m (Pastors 1987).

Model calibration and sensitivity assessment

The model was calibrated for steady state conditions by the trial-and-error method, and the WL in monitoring wells (Figure 6) was used as the calibration target. Material properties were adjusted during the calibration until the difference between measured and modelled WLs was less than 1 m.

Several model conditions were simulated to determine sensitivity of the groundwater model to various parameters: hydraulic conductivity, water table of the rivers and recharge. Modelled WLs in monitoring wells were correlated to the reference levels from calibrated model, differences in average WL and squared correlation coefficient (R^2) were assessed (Table 5). The model sensitivity

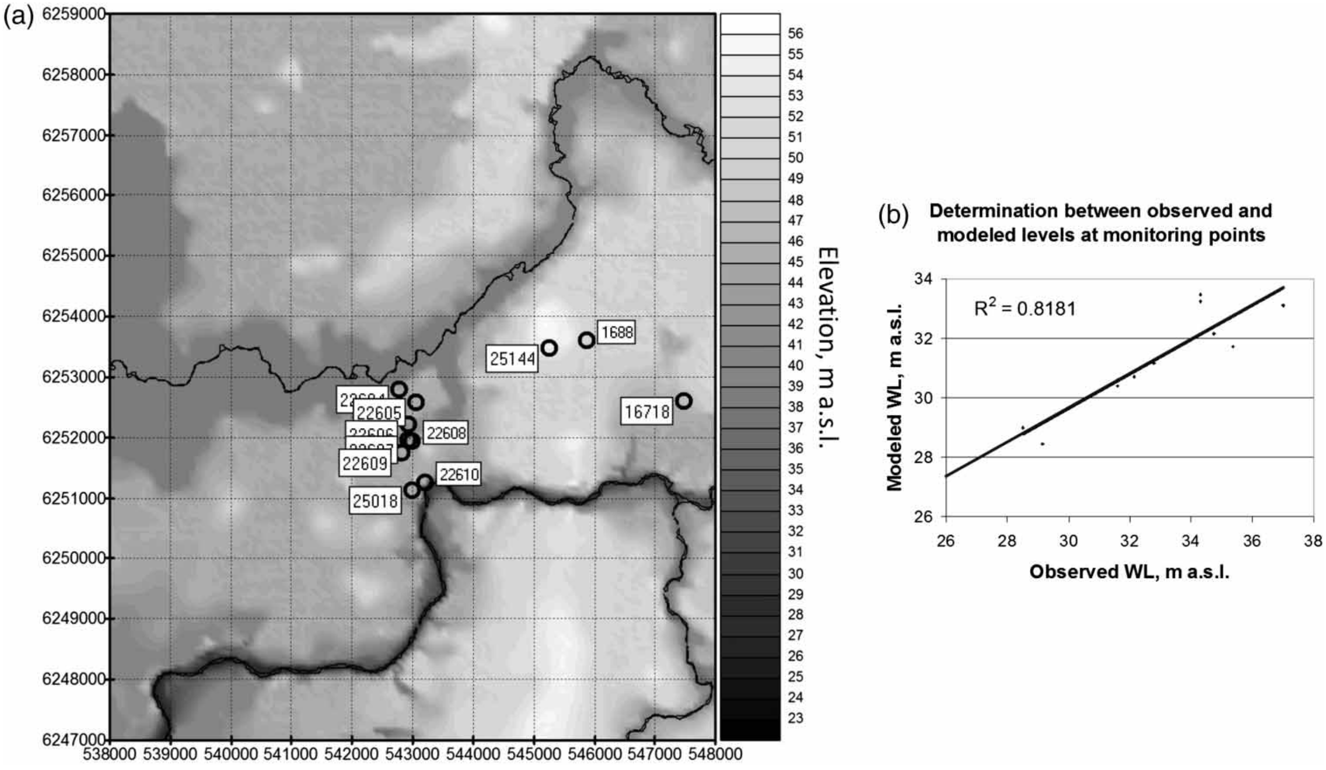

Figure 6 | Location of monitoring wells used in model calibration (a) and calibration results (b).

Table 5 | Model sensitivity assessment results

Parameter, changes applied	Average change of WL in monitoring wells, m	R^2 between observed and modelled WL
Hydraulic conductivity increased, aquifer D3slp1	−0.51	0.8145
Hydraulic conductivity decreased, aquifer D3slp1	+0.10	0.8078
Hydraulic conductivity increased, aquitard gQ3ltv	−0.18	0.8067
Hydraulic conductivity decreased, aquitard gQ3ltv	−0.35	0.8143
River WL increased by 1 m	+0.47	0.7716
River WL decreased by 1 m	−0.60	0.8124
Recharge increased by 100 mm/y	+0.18	0.7978
Recharge decreased by 100 mm/y	−0.79	0.8317

analysis showed that the reduction of recharge had a distinct impact on WLs, but a reduction of hydraulic conductivity of aquitard or increase of hydraulic conductivity of aquifers, as well as increased recharge, resulted in less impact on model results.

Modelling results

The model shows that groundwater flow in the study area is directed to the Memele river valley, the sub-regional sink of the upper aquifers (Figure 7). The Iecava river recharges the upper part of the Salaspils aquifer (Figure 7(a)), but it has an insignificant effect on regional piezometric head distribution (Figure 7(c)). The aquitard between the Salaspils and Plavinas aquifer is semi-confined and a hydraulic connection between these two aquifers exists (Figure 7(a)).

The seasonal changes in WLs in rivers affect the sub-regional flow system in the Salaspils aquifer. During the high season the hydraulic gradient is larger (Figure 8(a)) and the groundwater flow is faster, but in the low season the hydraulic gradient is smaller (Figure 8(b)) and the flow is slower.

The modelled water discharge in approximately 1 km sections (Figure 8(a)) on the both banks of the Iecava river (Iecava north and south) and on the right-hand bank of the Memele river (Memele north) shows that the main groundwater discharge to the rivers occurs during the low season (Table 6). The modelled Iecava river loss could be calculated as the difference between the discharge south of the Iecava river and north of the Iecava river, and it is about 1,900–2,500 m^3/day in a 1 km stretch.

DISCUSSION

The hydraulic connection between the Iecava and Memele rivers was observed by E. Klivs in 1999 (Narbutas *et al.* 2001) based on river discharge measurements, and it was assumed that the karst conduits in gypsum and dolomite strata of Salaspils Formation could be the ones causing this effect.

Our complex study proved this hypothesis. First of all, the tracer test results provided visible proof that there is a hydraulic connection between the rivers. The calculated groundwater flow velocity based on tracer test results is great, 800–1,290 m/day, on average 1,050 m/day. In comparison, if the groundwater flow velocity is calculated based on basic flow equations (Equations (3) and (4)), the results differ significantly. Initially, Darcy velocity of the groundwater flow is calculated from (Todd & Mays 2005)

$$v_D = ki \tag{3}$$

where v_D is the Darcy velocity of groundwater flow, m/day; k is hydraulic conductivity, m/day; i is the hydraulic gradient of the groundwater flow. The hydraulic gradient (i) is about 0.003 in the area between the rivers, hydraulic conductivity of the whole Salaspils aquifer is 30–100 m/day, and the Darcy velocity is only 0.1–0.3 m/day. Assuming that porosity of the dolomites and gypsum strata is 0.3 (Todd & Mays 2005), the actual flow velocity could be calculated (Todd & Mays 2005)

$$v = \frac{v_D}{n_e} \tag{4}$$

where v is actual groundwater flow velocity, m/day and n_e is effective porosity of the aquifer; and the groundwater

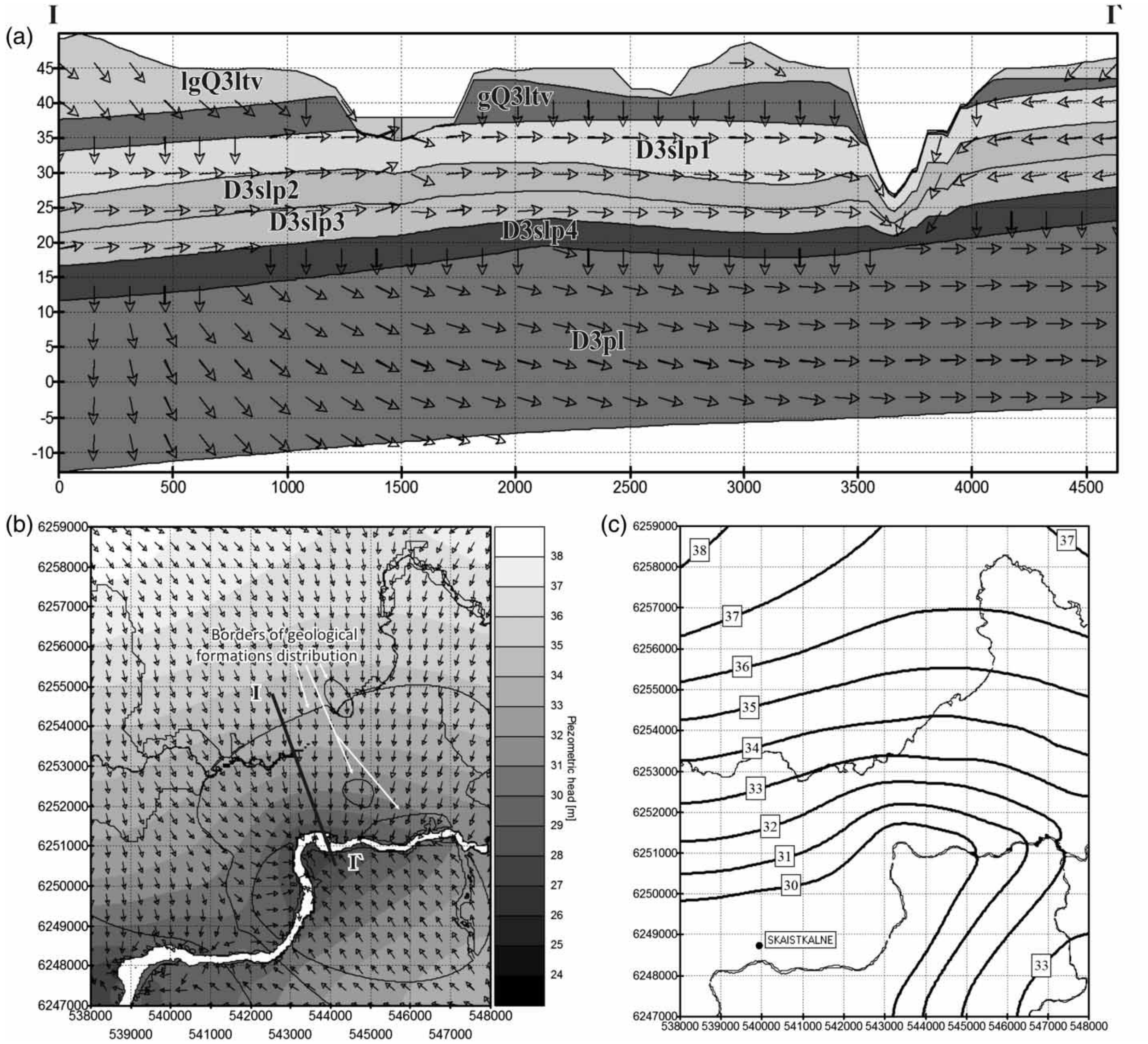

Figure 7 | Model results for long-term average boundary conditions: (a) water flow directions in cross–section I–I′, (b) water flow directions and piezometric head distribution in horizontal section $z = 35$ m a.s.l., location of cross-section I–I′ shown, (c) piezometric head distribution in Salaspils Formation. Circular lines on Figure 7(b) show borders of distribution of geological formations at the elevation 35 m a.s.l.

flow velocity there is just 0.3–1 m/day. These values are several orders lower than those obtained from the tracer test (1,050 m/day on average), but they could be valid for groundwater movement in the porous environment. The tracer had travelled with the preferential flow, thus the maximum velocity of the groundwater flow through karst conduits was detected. This finding leads to the conclusion that large fractures, or even channels, should be present in the area between both rivers. Hydraulic conductivity values lower than those calculated based on tracer test results used in the model indicate that some modifications are needed in the groundwater flow calculations at the karst environment. Darcy's law cannot simply be applied to the karst aquifers due to the karst conduits present in the system, where turbulent flow might occur. Another issue that could impact on the model results is the dual porosity effects, which are not taken into account in our model.

The groundwater model shows that groundwater recharge from the Iecava river and discharge to the

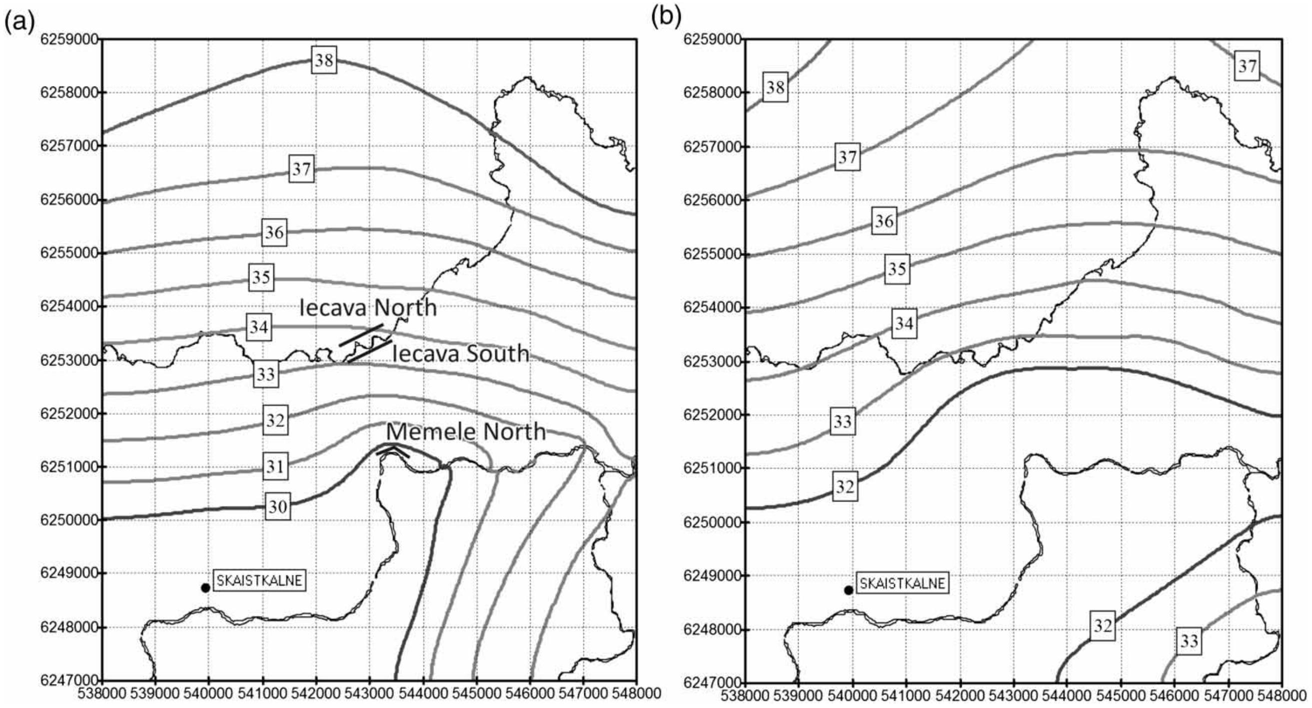

Figure 8 | Modelled WLs in Salaspils aquifer. (a) Piezometric head in D3slp aquifer at high WL in rivers, (b) Piezometric head in D3slp aquifer at low WL in rivers. Sections where water discharge in Salaspils aquifer is calculated are shown as lines on Figure 8(a).

Table 6 | Modelled water discharge (*Q*)

	***Q*, m³/day**		
Water discharge section	**Long-term average**	**Low season**	**High season**
Iecava south	5,167	5,788	5,105
Iecava north	3,011	3,256	3,173
Memele north	12,159	13,121	10,876
GW recharge from the Iecava river	2,156	2,532	1,932

Memele river increases during the low season. The surface water EC measurement results gave the same pattern. Significant groundwater discharge to the Memele river was observed, based on the high EC values (Figure 9(a)), during late autumn 2008 when the WLs in the rivers was low, and poor discharge in July 2010, when the WL in the Memele river was high due to the heavy rains (based on LEGMC observation data in Lielupe River Bauska post, downstream study area). The location of points with the highest EC values in the Memele river corresponds to the places where tracer occurrence was observed. The results of sulphates content in the Memele river in low season is 1.5–2 times higher (Figure 9(b), samples M 1–22) than during the high season (sample M 42), showing that the groundwater ratio in the river water is smaller than during low season.

Tracevska *et al.* (1986) suggested that some of the karst lakes have hydraulic connection to the Salaspils aquifer, but some are isolated by the glacigene till layer. The tracer test performed in 2008 proved that there is hydraulic connection between the Salaspils aquifer and some karst lakes (Figure 4), and chemical analysis proved that groundwater discharge occurs in these lakes, but there are also lakes formed in the sinkholes lined with glacigene till deposits which have no connection to Salaspils aquifer. The results of the EC measurements and sulphate content analysis in karst lakes were very different. The karst lakes (KL 48–50) near the wells No. 5 and 12 have typical atmospheric water with EC values below 100 μS/cm, but the lakes (KL 34–35) next to them to the west have EC values of about 1,300 μS/cm which is typical for the sulphates containing groundwater (Tables 2 and 3, Figure 9).

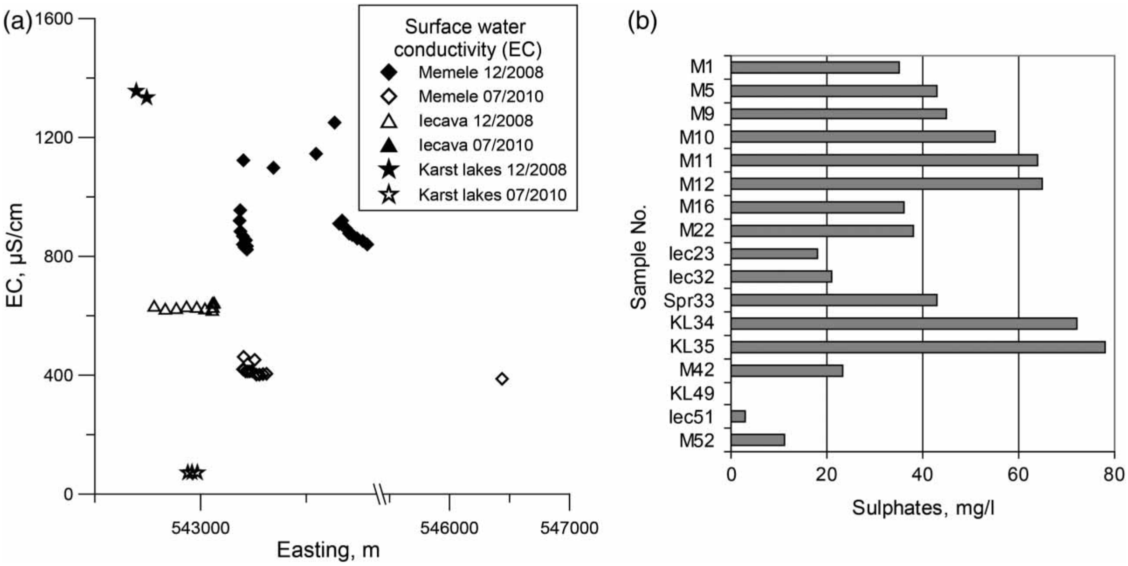

Figure 9 | Surface water conductivity (EC) values plotted by measurement point projection on Easting axis (a) and sulphate content in surface water samples (b).

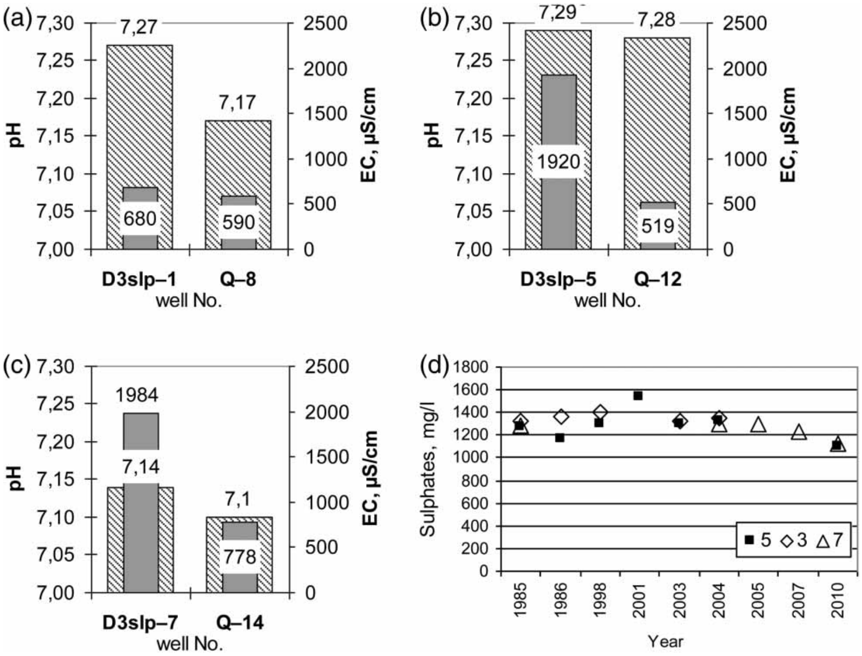

Figure 10 | Changes of groundwater composition in space and time. (a) Groundwater pH and EC values in wells located 400 m from the Iecava river, (b) groundwater pH and EC values well located 1,300 m from the Iecava river, (c) groundwater pH and EC values at the Memele river, 2,000 m from the Iecava river, (d) sulphate content variations in wells No. 3, 7 and 5 during 1985–2010. Columns of pH values are hatched, columns of EC values are tinted.

The dissolution of gypsum strata still takes place at the study area as it is described by the groundwater composition in monitoring wells (Figure 10). The groundwater EC value is just 680 µS/cm in Salaspils aquifer well No. 1 close to the Iecava river, and could be compared with the EC value of shallow groundwater (Figure 10(a)), but during the travel through the gypsum containing strata the groundwater is enriched with sulphates, and EC values increase three-fold

(Figure 10(b) and (c)) and stabilise at around 1,900–2,000 μS/cm.

The sulphate content in the wells in Salaspils aquifer varies from 1,100 to 1,600 mg/L (Figure 10(d)), and the values are high all the time, showing that karst processes are still active there. The minor variations of the sulphate values could be caused by the different solving intensity of the gypsum strata, fluctuations of WLs in rivers and the aquifer recharge volumes.

CONCLUSIONS

- A tracer test proved that there is underground hydraulic connection between the Iecava and Memele rivers.
- The Iecava river discharge loses 10–25% from the river discharge upstream karts area, but the Memele river discharge increases by 200% compared with the upstream discharge due to the flow from the Iecava river and massive groundwater inflow, characterised by the increased sulphate values in the river's water.
- Huge difference between calculated (10–30 m/d) and observed (800–1,300 m/d) water flow velocity shows that large karst conduits should be developed in the Iecava–Memele water divide area. Therefore, another numerical model should be developed for proper representation of the karst environment including turbulent flow in the large conduits and dual porosity effects of the geological strata.
- The numerical model shows that groundwater discharge to the Memele river should vary by seasons. Little discharge is characteristic for high season and intensive discharge for low season.

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