Drinking water extraction facilities at risk of flooding from rivers and groundwater – flood impact assessment for water extraction facilities in Ljubljana area

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Abstract In this paper, risk to the Brest drinking water facility due to an extreme hydrological event in September 2010 is analysed. Groundwater is pumped from the Iška River fan gravel aquifer, which drains mountains in the south. When reaching its fan gravel aquifer, the Iška River starts to infiltrate the aquifer. Its flow decreases to a minimum and increases at geomorphological break between torrential fan and flat Ljubljana Moor surface. The water works at Brest are therefore at risk of flooding from surface water. In September 2010 Ljubljana Moor was flooded for five days. The specific phenomena happened due to Iška River. It overflowed its banks upstream of the Brest water field. It was the first time that the Brest field was also flooded. On the fifth day Iška River disappeared for two days into the groundwater. The operation of drinking water extraction facilities was stopped in the succeeding days.

Key words flood risk; groundwater; drinking water; gravel fan

INTRODUCTION

There are five main drinking water extraction facilities in the Ljubljana area (0.35 million inhabitants, the capital of Republic of Slovenia, Europe). Four of them are located north of Ljubljana city, along the Sava River (Ljubljansko polje aquifer). The fifth, Brest water field, is located south of Ljubljana, on the southeast part of Ljubljana Moor. Brest has 200 L/s capacity with 12 pumping wells. It was been opened at the beginning of the 1980s. Here groundwater is pumped from the fan gravel aquifer. Groundwater is recharged from the Iška River, the Ljubljanica tributary. The Brest drinking water extraction facility is situated 300 m away from the Iška River and is at risk of flooding. Historical and recently produced flood hazard maps declare the area has less than 1% probability of flooding.

However, the flood event in September 2010 showed this assumption was wrong. Precipitation from 16 to 19 September 2010 caused a flood in the 250 km^2 Ljubljana Moor valley. The flood began in the night from 18 to 19, and lasted until 23 September. The flooding was caused by the River Ljubljanica and its streams and springs that drain a 1725 km^2 karstic area in the south. It was the first time that the Brest drinking water extraction facility was flooded since it started operating. In this paper we analyse causes for the flood with quantitative and qualitative methods.

MATERIALS AND METHODS

Ljubljana Moor lies in the central part of Slovenia. In the northeast it stretches toward Ljubljana, the capital. In the south it is surrounded by the Krim-Mokrc karstic mountains, with the highest peak 1107 m a.s.l. It is a 160 km^2 plain area, with an elevation between 288 and 300 m a.s.l. The area is a mosaic of meadows, fields, ditches and alder trees. It frequently flooded, but in recent periods urbanisation is slowly advancing toward the central part of Ljubljana Moor. The main river is the Ljubljanica. It has many karstic springs in the western side of Ljubljana Moor (Vrhnika town) and flows in a west–east direction (Fig. 1). It is 30 km-long and has a catchment area of 1700 km^2. It drains the majority of the southwestern part of the Slovenia karstic area (Postojna and Cerknica lake underground rivers systems). Ljubljanica River is a tributary of the Sava River and therefore belongs to the Danube River catchment. The Iska River, one of the main tributaries of the Ljubljanica, flows from the south to the north and drains the southern part of the mountains. The river is 25 km long, of which 5 km lie in Ljubljana Moor area (Fig. 1). At the outflow to the River Ljubljanica, the Iška River catchment is 90 km^2 in area.

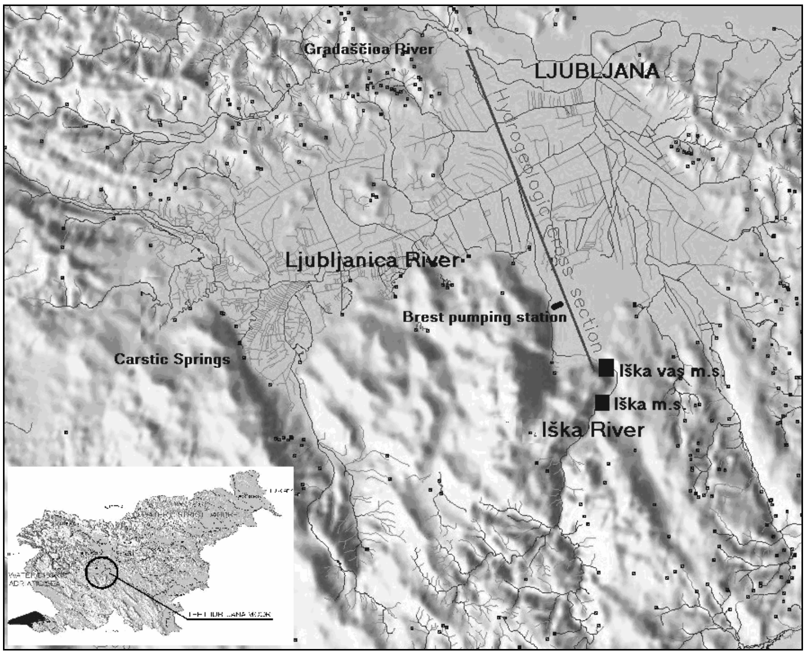

Fig. 1 The river network of Ljubljana Moor, position of hydrological monitoring stations and the Brest drinking water field (drinking water pumping station), and position of hydrogeological cross-section in Fig. 2.

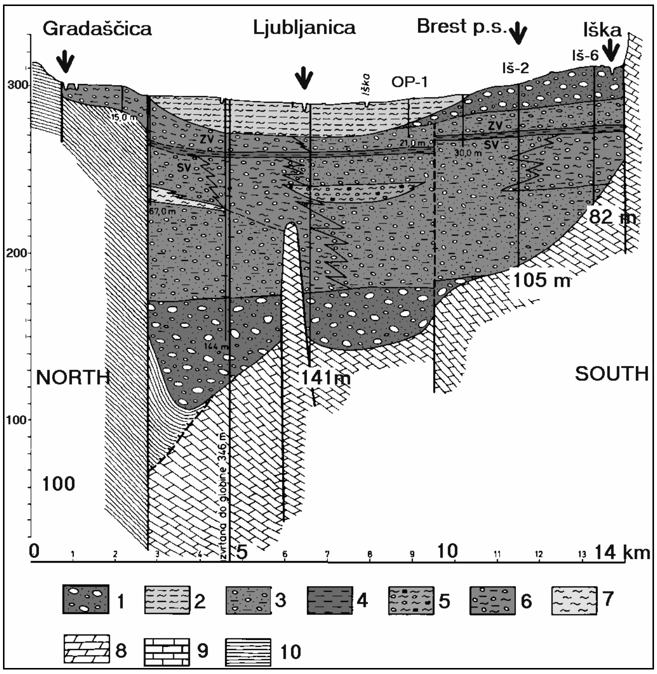

Fig. 2 Hydrogeological cross-section. Legend: 1: Gravel with sand and little silt; (at the surface: gravel fan); 2: Silty loam ("snail clay"); 3: Gravel with silt and sand; 4: Red silt and silty loam (border layer); 5: Loam and organic loam with pebbles; 6: Gravel with loam and silt (Pleistocene); 7: Loam; 8. Dolomite (Upper Triassic); 9: Limestone and dolomite (Low Jurassic); 10: Sandstone and shaly mudstone (Permo-Carbon). (Source: Mencej, 1989). Iš-6, Iš-2 and OP-1: groundwater monitoring.

In the national meteorological monitoring systems there are four precipitation stations that are located in the Iška River catchment, or very close to its watershed dividing line: Črna vas and Tomišelj are located close on Ljubljana Moor, whereas Sveti Vid and Rob are on the Krim-Mokrc mountainous area. Their altitudes are: Črna vas 289 m a.s.l., Tomišelj 299 m a.s.l., Sveti Vid 846 m a.s.l. and Rob 540 m a.s.l. The closest synoptic, climatologic and pluviographic station is in Ljubljana (Ljubljana Bežigrad, 299 m a.s.l.). The distance between the Iška River and Ljubljana-Bežigrad station is 8 km. Apart from the national monitoring system, there is a non-governmental meteorological monitoring and information system, ZEVS, with rainfall data for Slovenia (ZEVS, 2011). In this network, there is also one station representative of the Krim-Mokrc mountainous area, Rakitna (787 m a.s.l.). Very close are Rakek (592 m a.s.l.), Vrhnika (331 m a.s.l.; also in the national monitoring system) and Šentjošt (642 m a.s.l.). Average yearly precipitation on the Iška River catchment is 1700 mm/year, the lowest 850 mm/year and the highest 2300 mm/year (VGI, 1984).

At present there is one hydrological monitoring station, Iška vas. It was opened in 2001 and is situated 9.3 km upstream of Ljubljanica River in the village Iška vas. Water level is read from digital recordings of automatic gauging stations (AGS) with two independent water level gauges, an ultrasonic gauge and a float or pressure probe. In the period 1969–2001, daily recording of water level was carried out 1.8 km upstream of the present station, in the village Iška (the same name as the river). Average measured discharge at the monitoring station Iška for the period 1957–1980 was 2.2 m^3/s (VGI, 1984) and 1.9 m^3/s in the period 1971–2000. The highest monthly average discharges were January (3.11 m^3/s) and November (2.57 m^3/s). Summer months are the driest. Average monthly discharge in July is 0.98 m^3/s, August 0.28 m^3/s and September 1.33 m^3/s. The average yearly runoff coefficient is 52%.

The Ljubljanica Moor aquifer is one of the largest in Slovenia. Its geological base consists partly of non-permeable or very low permeable Permo-Carboniferous shale mudstone and sandstone, and partly of Triassic and Jurassic carbonate rocks, dolomite and limestone (Breznik, 1975; Mencej, 1976, 1989). The Quaternary deposits are in alterations of fluvial and lacustrine origin. Layers have different thicknesses of sandy gravel, clay, sand, silt, lacustrine chalk, peat and humus. The sediments can be up to 150 m thick. Figure 2 shows the hydrogeological profile of the Ljubljanica Moor in the east. Its plan view position is given in Fig. 1. In the north, the sediments originate from the River Gradaščica and the old Sava River. The fluvial sediments on the south originate from the River Iška. The edge of Ljubljanica Moor in the south consists of a very permeable gravel fan (unit no. 1 on the right side of Fig. 2). When it leaves the narrow valley at Iška village, the River Iška recharges the gravel fan. The low river flow decreases to a minimum and increases again at a geomorphological break between the Iška gravel fan and flat Ljubljana Moor surface. Here the river is recharged by shallow groundwater and springs.

In 1975, the groundwater pumping stations for drinking water supply, Brest, was installed at the edge of the Iška gravel fan (Fig. 1). In the first phase 10 wells, with a total capacity of 150 L/s, were drilled to pump groundwater from an unconfined Holocene gravel aquifer. In the second phase one 100-m deep well was drilled to pump groundwater from the confined upper and lower Pleistocene gravel aquifer. In the third phase the second deep well was drilled to pump groundwater only from the confined lower Pleistocene aquifer. The monitoring network is operated by the Public Water Utility JP Vodovod-Kanalizacija d.o.o., Ljubljana. For this study we obtained data on groundwater level in 2010 for five piezometers (Iš-1, P-0, P-11, P-12, P-13) and five wells (Vod-2, Iš-3, Iš-5, V-12, V-13) in the Brest drinking water field, two piezometers (P-19 and OP-1) on the Ljubljana Moor and five piezometers on the Iška gravel fan (Iš-6, Iš-7, P-8, P-20, P-21). At eight locations, groundwater levels are monitored manually every 14 days. On the others automatic sampling is done by different probes. The analysis of flood extent was done by field observations right after the event. We have collected available cartographic and aero-photographic material. Cartographic maps (vector and raster formats) are available on the scale 1:5000 from the National Geodetic Survey of the Republic of Slovenia. Digital elevation data for 25 × 25 m and 5 × 5 m grids were obtained (ASCI format, Gauss Krüger Slovenia, D-48 datum). On 20 September the Ljubljana Moor area was remotely sensed by infrared camera (GEOin, d.o.o. by order of the Agency for the Environment of the Republic of Slovenia).

RESULTS AND DISCUSSION

On 17 September 2010 three-day-long, evenly distributed, rain started to fall on an already wet area. It caused floods on almost all of the territory of Slovenia (Globevnik, 2010). The extreme forecast ECMWF rainfall index for all Slovenia for the period 17–22 September 2010 was from 0.8 to 1.0 (Globevnik, 2010). The rainfall lasted for three days (17–19 September 2010) over the west and central part of Slovenia, with the total precipitation between 200 and 300 mm (Hotedrščica 307 mm, Ljubljana 271 mm, Postojna 235 mm, Bovec 234 mm, Celje 220 mm, Kočevje 209 mm). There was between 250 and 280 mm of rain over the karstic part of the Ljubljanica River basin, with the highest amount on the west (490 mm). 80% of the Iška River catchment received 250 mm of rain, and there was an additional 230 mm (Globevnik & Vidmar, 2010), which gives 22.1×10^6 m^3 of water for the whole catchment, and 16.5×10^6 m^3 for the 66-km^2 catchment at the station of Iška vas.

Before the rise of the hydrograph on Friday 17 September 2010, the Iška River had discharge of 0.72 m^3/s. The water depth at the station was 26 cm. The water level started to rise at 00:30h on Saturday 18 September. The first flood wave had its peak at 07:30 h (49.3 m^3/s). The second peak occurred the next day at 04:30 h. The official record is that this peak had a discharge of 58 m^3/s. The Iška River over ran its right banks in Strahomer, 2 km upstream of the Brest drinking water field on 18 September. The flooded surface on 20 September is given in Fig. 3. The flood extended along a 3.5-km long and 1.45-km^2 section between the village Strahomer and the moor area. The volume of the hydrograph between 17 and 18 September was 7.36×10^6 m^3. The surface runoff coefficient was 45%, i.e. 20% less than the runoff coefficient for Ljubljanica runoff for the same flood event (Globevnik & Vidmar, 2010). Five days after the flood peak, on 23 September (at 15:30 h)

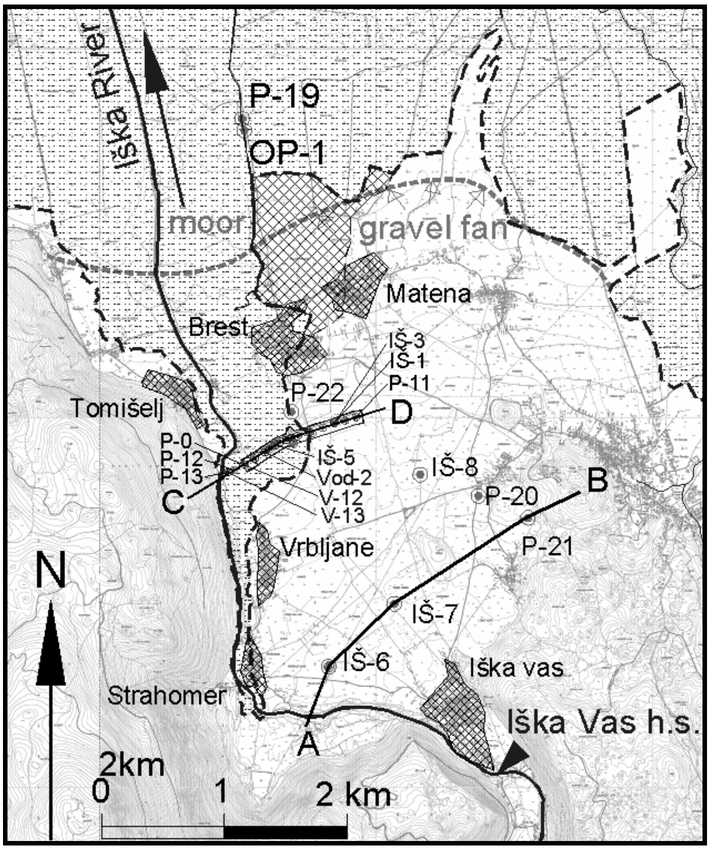

Fig. 3 The extent of flooded area on 19 and 20 September (horizontal dash-point-point hatch) reproduced from IR photography (Globevnik & Vidmar, 2010). Position of three cross-sections with piezometers (A–B, A–C, D–E) and villages in the area. Diagonal hatch: flood water also on 19 September, but not on 20 September.

the river water disappeared and the channel stayed completely dry. As seen from the recession curve, the water level first sharply dropped on 21 September. At 12:00 h the discharge at water level 172 cm was 1.5 m^3/s, but at 13:00 h the discharge dropped for 0.3 m^3/s. At 17:00 h the river discharge was only half of that at 12:00 h (0.77 m^3/s, 166 cm). Water height at that time was 26 cm. Next day (22 September) at 12:00 h the discharge was 0.33 m^3/s (19 cm of height).

As reported by local people, water has been disappearing from the channel in the 3-km-long section between Iška vas and Strahomer (Fig. 3). On Friday 24 September numerous 10- to 30-cm wide cracks appeared on the river bottom. Before the event, the Iška River had a colmated channel bottom. Due to intense precipitation over the whole catchment, hydrostatic pressure in the karstic fissured aquifer in the whole catchment and below the river bottom has risen and "opened" the cracks. At the same time, the river, due to high energy, eroded the colmated bottom of the riverbed, and therefore its permeability greatly increased. When rainfall in the area ceased, the hydrostatic pressure in the aquifer began to decrease and fell below the level of the river water. This was the reason the river was "sucked" into the ground. Water not only disappeared through opened cracks, but infiltrated through the channel bottom. Running water "came back" on 25 September at 10.00 h (Fig. 4) as a result of rain on 25 September (Table 1). The second high water peak was 12.7 m^3/s (on 25 September on 14:00 h). On 30 September the discharge reached a monthly average of 1.33 m^3/s. The flood wave and disappearance of the Iška River are detected in the groundwater level of the Brest drinking water field.

Figure 4 shows a cross-section profile of piezometers on the Brest facility horizontal (C–D on Fig. 3). The rise of groundwater level was first noticed at piezometer Is-7 on 17 September, at the start of the rainfall. On 18 September the rise is noticed in P-20. Groundwater has the highest level on 19 September at Is-7 and P-20, whereas at P-21 and Is-8 it has been reached on 20 September. Groundwater in the flooded part of the Brest drinking water facility has been the highest on 19 September (V-12, Is-5). The eastern side of the facility, that was not flooded had the highest level only on 24 September (P-11, Is-1).

The flood event caused groundwater rise of 6 m at the Brest facility on 19 September (Is-5). The groundwater level at V-13, the well that is the closest to the Iška River (Fig. 4), was the same as the water level in the channel, that is 299.9 m a.s.l.. The tops of wells at the Brest drinking water facility are higher by 1 m, but nevertheless, the flood water invaded into the wells through drainage pipes built at 298.7 m a.s.l. height. Electricity facilities were damaged as well as 10 out of 12 pumping wells, due to the irruption of surface water. The drop of groundwater level on 20 September is noticed on Is-7 and P-21, whereas P-8 and P-20 stay more or less stable for four

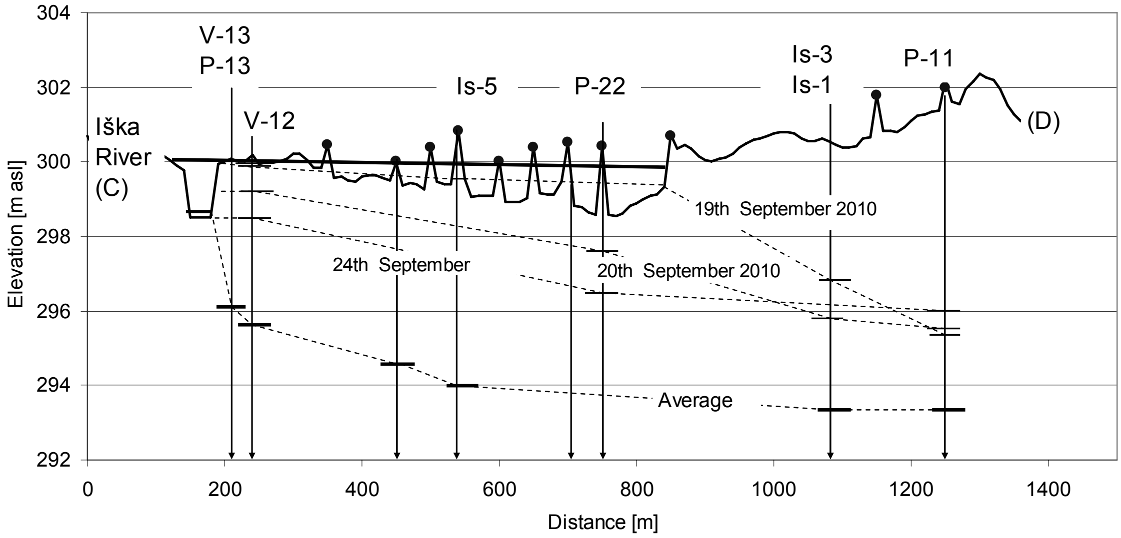

Fig. 4 Cross-section profile C–D of the terrain with the surface and groundwater level at the Brest drinking water field on 19, 20 and 24 September 2010.

Table 1 Average groundwater levels measured from January 2010 to August 2010, the date of the start of the rise of groundwater level in the September 2010 flood event, and of its highest peak.

	Average groundwater level (m a.s.l.)	Start of rise	Date of highest peak	Highest altitude (m a.s.l.)
Is-6pl (shallow)	307.6	(*)	19 September	310.5
Is-7	295.0	17 September	19 September	309.5
P-20	294.9	18 September	19 September	303
P-21	295.2	18 September	20 September	307
Is-8	296.1	19 September	20 September	300.5
V-13	296.1	(**)	–	299.3
V-12	295.7	(*)	19 September	299.93
Vod-2	294.5	(***)	–	–
Is-5	293.9	(*)	19 September	299.4
Is-1pl (shallow)	292.7	(*)	24 September	296.4
P-11	292.8	(*)	24 September	296.0
P-22	293.0	19 September	20 September	297.4

(*): Data available for 14 (or 15), 19, 20 and 24 September; (**): data available for 14, 20 and 24 September; (***): data available for 15 and 24 September 2010.

days. The same is true for groundwater under the non-flooded part of the Brest facility. Here we can even notice a rise of groundwater from 20 to 24 September. These facts show that: (a) the Iška River has been losing water mainly along the Iška vas, at the uppermost back of the gravel fan, and (b) the groundwater flow direction was south–north. Groundwater does not pose a flood risk to the Brest drinking water pumping facility. The flood risk is due to surface water intrusion into wells through drainage pipes.

CONCLUSIONS

On 17 September 2010 3-day-long, evenly distributed rain started to fall on an already wet area. It caused floods on almost three thirds of the territory of Slovenia. The flooding was caused by the River Ljubljanica and its streams and springs. It was the first time that the Brest drinking water extraction facility was also flooded since it began operating. Though the tops of the wells at the Brest drinking water facility were above the flood water, water invaded them through drainage pipes. Electricity facilities were damaged as well as 10 out of 12 pumping wells due to leakage of surface water. We showed that the Iška River infiltrated its gravel fan by approximately 2 m^3/s for five days of the event, mainly on the Iška vas section, at the uppermost back of the gravel fan. The groundwater flow direction was south–north, and it did not pose any flood risk to the Brest drinking water pumping facility.

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