

Measurement, modelling and analysis of hydrological and hydrogeological processes and trends in a marsh area

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Abstract The marshy area of Ljubljana Moor, extending from the southern part of Ljubljana city to Krim-Mokrc karstic mountains, is a large plain area with a mosaic of meadows, fields, ditches and copses of alders spread out over 160 km², originating some two million years ago through the sinking of an extensive area of the Ljubljana basin. The sedimentation basin of Ljubljana Moor is filled in the central part with lacustrine and marshy sediments and on the borders of the basin are the gravel fans. It is an area of different interests and the water, surface and groundwater, have a crucial role in specific land use. It is an important drinking water resource, it is an agricultural area, an area of Natura 2000 and Natural Park area with high biodiversity and an area for urban development. Established groundwater level measurements and surface water level and discharge measurements are important data for analysing trends of hydrological and hydrogeological characteristics of the area in input for modelling of surface and groundwater flow and their interactions at flood events and during drought.

Key words surface water; rivers; groundwater; flooding; drinking water source

INTRODUCTION TO LJUBLJANA MOOR

Ljubljana Moor lies in the central part of Slovenia. In the northeast it stretches towards Ljubljana, the capital of Slovenia located on the Ljubljanica River. The river is the main stream of a large plain area with elevation between 288 and 300 m that was covered by a lake approximately 4000 years ago. Due to natural succession it changed into a high bog and marsh, named Ljubljana Moor (Fig. 1). Lake and river sediments, partially separated by impervious layers of clay and mudslides, deposited from the hinterland mountains, are up to 160 m in depth. The system of vertically stratified aquifers is one of the biggest and important drinking water sources in the central part of Slovenia.

At the end of the 18th century settling of marsh edges and elevated parts of the marsh was begun. First land reclamation works started in the mid-19th century along the lines of the Dutch School and intensified in the 20th century. The land became mostly agricultural. Areas with permanent high levels of groundwater that was crucial for survival of a special type of moss “building” bog pits began to shrink. Today the area is crossed by 700 km of main ditches and over 20 000 km of field drainage ditches. Due to natural succession, drainage and settlements, the area is constantly subsiding.

The wetland character has been preserved due to frequent flooding. The Ljubljana Moor today represents an important nature–wetland conservation area. At the southern and western edge of the basin there are many karst springs and some surface flow. Groundwater is recharged and permanent surface flows (Ljubljanica River and its tributaries) are sustained. The lowest parts of the area are flooded several times a year. The floods occasionally reach settlements.

On the Iška fan, where the gravel sediments of Iška River and lake sediments intersect, the groundwater field of Brest is situated. The area is an important drinking water source for the city of Ljubljana and has never been intensively exploited. The drinking water pumping station was built in the beginning of the 1980s of the 20th century. In the first phase 11 wells with a common rate of 150 L/s were drilled and catch the groundwater from an unconfined Holocene gravel aquifer. In the second phase two deep wells, up to 100 m, were drilled and they catch the groundwater from semi-confined upper and lower Pleistocene gravel aquifer. In the third phase the deep well was drilled to only catch the groundwater from the semi-confined lower Pleistocene aquifer.

Ljubljana Moor has been subsiding and this is a natural phenomenon, intensified due to urbanization, drainage of agricultural land and lately by pumping of groundwater for heating

pumps. The impact of pumping the groundwater for water supply on subsidence has not been proved. Nevertheless, there is urgent need to study holistically the surface and groundwater regimes and recognize cause-effect mechanisms of watercourse maintenance, farming, land reclamation, urbanization and pumping of groundwater. These impact on water resources and change natural assets. Furthermore, it is expected that farmers needs are met, biodiversity sustained and flood risk mitigated to an acceptable level.



Fig. 1 Geographical setting of the Ljubljana Moor (Slovenia).

Water resources of the area are under significant pressure. Agricultural land managers expect amelioration canals to be regularly maintained. Land owners take advantage of high prices of land for urban development. Agricultural land and less commercially productive areas (marshes) are being changed to urban areas. New roads and transportation facilities are built, therefore the Ljubljana Moor landscape and its water regime are continually changing. Environmental problems include water pollution, rising demand for water, flood and drought risk and decline of water retention capacities, decreasing groundwater levels and terrain subsidence. As a consequence, wetland ecosystems are also at risk, as are the economic and social stability of the area. To give answers and proposals for sustainable water and soil management measures with a view to protect water resources and wetland ecosystems, we develop an integrated water resources modelling and decision support system. As a first step, we compiled all available information of surface and groundwater including spatial and temporal water flow dynamics of the Ljubljana Moor and conceptualised an integrated hydrological and hydrogeological modelling approach. In the second step we set and tested models that are used for the analysis of surface and groundwater spatial and temporal water flow characteristics on marsh areas of Ljubljana Moor. In this paper we describe the first step, present the modelling approach and give the first results of model testing.

MATERIAL AND METHODS

Hydrological measurements of surface flow on the Ljubljana Moor

Regular hydrological monitoring of water levels and water temperature is performed by the national hydrological service at Slovenian Environmental Agency (ARSO). They also perform discharge measurements. On the Ljubljanica River there are three active hydrological stations (Fig. 2): Moste in Ljubljana (since 1952), Komin (since 1954) and Vrhnika (since 1961). Regular hydrological monitoring is also carried out on its tributaries, Borovniščica (Borovnica, since 1954), Ljubija (Vrhnika since 1952) and Iška in Iška vas (since 2001). In the past there was

monitoring at other locations on Iška, Iški Vintgar (since 1948) and Iška (1967–2001). The length of the station Iška vas data is 12 years (2001–2012). For modelling purposes it can be expanded with the data from upstream location Iška. On the Ljubljanica River there were three additional stations in the past, Lipe (1954–1971), Špica (1954–1988) and Vevče (1954–1982).

In 2010 five hydrological stations were installed along the Iška River to enable management of Brest drinking water field (see Fig. 2). Water level and water temperature are recorded every 10 minutes with a pressure logger. Discharge measurements are performed every three weeks.

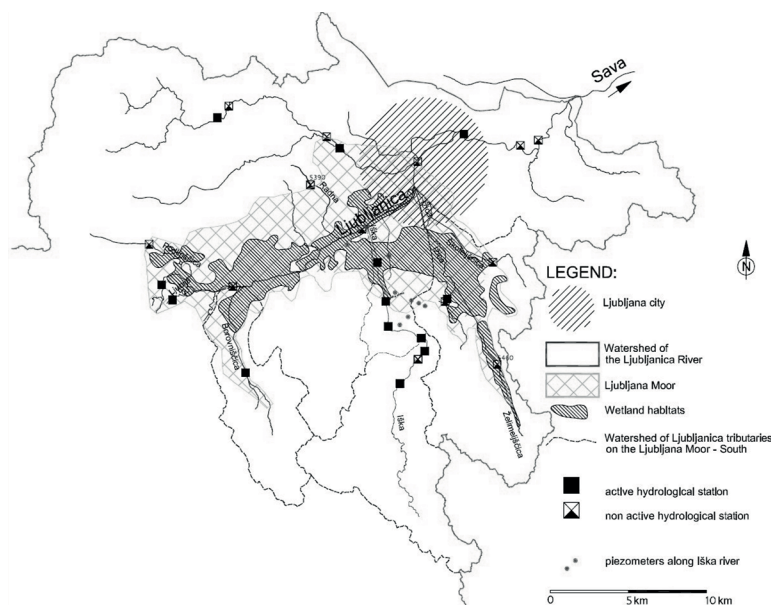


Fig. 2 The Ljubljana Moor area with monitoring locations on surface water and groundwater along the Iška River (on the right).

Hydrogeological measurement

Locations of piezometers along the Iška River are shown in Fig. 2, and their nomenclature in Fig. 3. The monitoring network of groundwater levels is operated by the Public Water Utility JP VODOVOD–KANALIZACIJA d.o.o., Ljubljana. Monitoring is performed at 22 piezometers on the Iška gravel fan area and Ljubljana Moor and 12 wells at the Brest drinking water pumping station. At 10 locations, groundwater level is monitored manually every 14 days, at the others automatic sampling is done by different probes. For the modelling we obtained daily data of water level at all locations for 2010 and 2011.

Ljubljana Moor is a basin with stone bedrock that consists in the southern part of Triassic dolomite and limestone and in the northern part of permocarbonic schists. The basin is filled with lacustrine, marshy and fluvial sediments. The upper layer, a zone up to 20 m deep, of the Ljubljana Moor consists of peat, peat mud and silty loam known as “snail clay”. Below this is a thick zone of gravel with silt and sand. The edge of Ljubljanica Moor in the south consists of a very permeable gravel fan (unit no. 1 in Fig. 3). When it leaves the narrow valley at the village Iška (hydrological stations with the code “5425”), the Iška River recharges the gravel fan. The gravel fan (see left side of Fig. 3) extends towards the flat surface of the Ljubljana Moor. The average surface altitude of the Ljubljana Moor is 290 m.a.s.l. The southern hills consist of dolomite from the Upper Triassic period. The highest altitude of the southern range of hills is 1100 m.

MODELLING

Analysis of water regime areas with wetland habitats typical for the Ljubljana Moor (wet meadows, Mollinimum, Phragmitium, Magnocaricium (CKFF, 2004) are done by modelling surface and groundwater flow and interactions in flood events and during periods without precipitation.

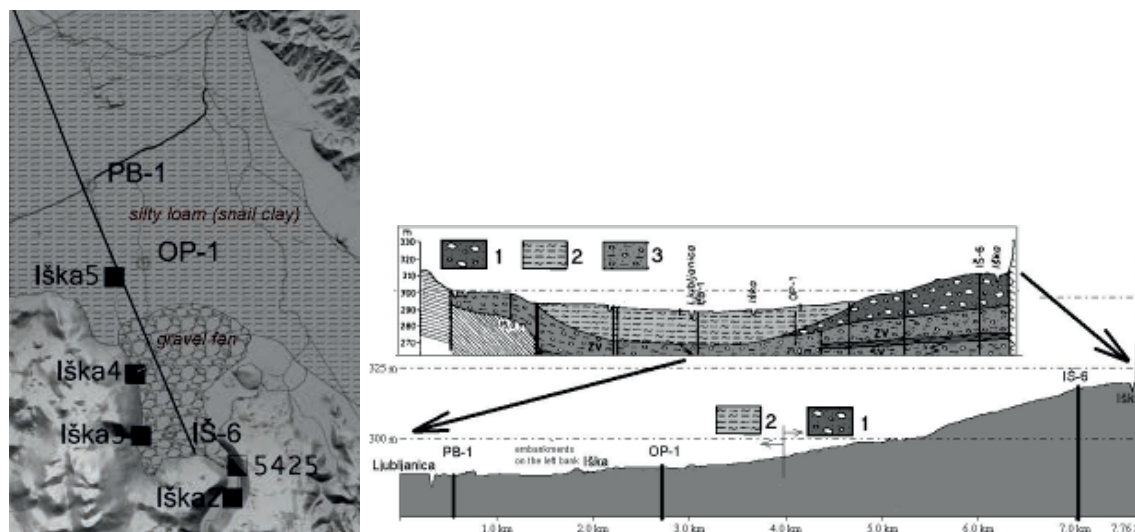


Fig. 3 Locations of surface water flow measurements and hydrogeological profile along the Iška River (piezometers are shown in Fig. 2). Hydrogeological units no. 1 represents gravel with sand and little silt with the gravel fan on surface, no. 2 represents silty loam (snail clay) and no. 3 is gravel with silt and sand.

The wetland area of the Ljubljana Moor and the analysed area along the Iška River are shown in Fig. 2. The general hydraulics of the Ljubljana Moor is driven by the Ljubljana River flow. The river is 30 km long and has a catchment area of 1700 km². It drains the majority of the south western part of the Slovenia karstic area (Postojna and Cerknica lake underground rivers systems). The Ljubljana River is a tributary of the Sava River (Fig. 1) and belongs to the Danube River catchment. It has many karstic springs in the western side of the Ljubljana Moor (Vrhnika town) and flows in a West–East direction (Fig. 2). The yearly average discharge of the Ljubljana River is 24.5 m³/s and in Vrhnika and Ljubljana is 55.4 m³/s (ARSO, 2012).

A dam located in the Ljubljana city controls the water level of the Ljubljana River. By a protocol, the water level at the dam should be set constant at 285.6 m a.s.l at discharges lower than 120 m³/s to hold the water level high along the whole river stretch in the Ljubljana Moor. When the water level starts rising at larger discharges, the gates at the dam open and water level of the Ljubljana River drops. By this protocol the channel flow capacity at high water levels is increased, otherwise the hydraulic head in the Ljubljana River along the Ljubljana Moor creates a higher soil water level in the Ljubljana Moor. In recent years, due to flood control, the gates are open at lower discharges or are set to a lower level than 285.6 m a.s.l. Consequently, the water level in the Ljubljana River drops more frequently and for a longer time. Furthermore, farmers demand that channels of tributaries and ditches are regularly cleaned to maintain groundwater low. To conclude, there are two main factors to control water regime of the wetland area. The first is a river network hydraulic head regime, the second is the exchange of water between the surface water and groundwater. There is permanent drainage and recharge of groundwater from tributaries. The Iška River, one of the main tributaries of Ljubljana River, 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 lies in the Ljubljana Moor area (Fig. 2). The catchment area at the Iška vas (location 5425) is 74.5 km². When it leaves the narrow valley at the village Iška vas, the Iška River recharges the gravel aquifer of Iška fan. The low river flow is at a minimum before and increases after the geo-morphological break between the Iška fan and the flat Ljubljana Moor surface (Fig. 3). Here the river is partly recharged by shallow groundwater and springs which exist along the whole gravel fan – moor edge, recharging the wetland area in a northerly direction.

A three level nested modelling approach was adopted. The first level was rainfall–runoff modelling of the Iška River. The second was surface water network modelling of the Ljubljana

River and Iška River. Flood hydrographs from high precipitation events in the catchment and runoff characteristics during periods without precipitation were used to define the dynamics. The third level was the surface–groundwater flow exchange modelling of the Ljubljana Moor aquifer in the Iška River recharge area. The rainfall–runoff was modelled using the HBV light model. The surface flow was modelled with MIKE 11 and MIKE FLOOD model (DHI) and the surface–groundwater modelling was done with the MIKE SHE module.

RESULTS

The daily precipitation values for the Iška River catchment are obtained by Thiessen method from stations Pokojišče, Želumlje, Črna vas, Sodražica and Cerknica for the period 2001–2011. All stations are situated around the watershed and are correlated. The lowest correlation of 0.87 is between Želumlje (307 m a.s.l.) and Pokojišče (737 m a.s.l.), 0.90 is between Želumlje and Črna vas (at altitude 289 m a.s.l.). Figure 4 shows the results of rainfall–runoff modelling by the HBV model. On the bottom, measured and simulated daily discharge values for 2010 are presented in milli-metres. Precipitation data are shown in the upper part. The efficiency of the calibrated rainfall–runoff model of the Iška using HBV software for the year 2010 is 0.80, an acceptable level for model performance. Nevertheless, the first calibration of the model coefficients with precipitation data from two stations (Pokojišče and Želumlje) and data on temperature for Ljubljana (299 m a.s.l.) for the period 2001–2010 gives a lower efficiency. When calibrating the model with temperature data from Nova vas that lies south of the Iška catchment at an altitude 722 m a.s.l., the model efficiency is 0.91.

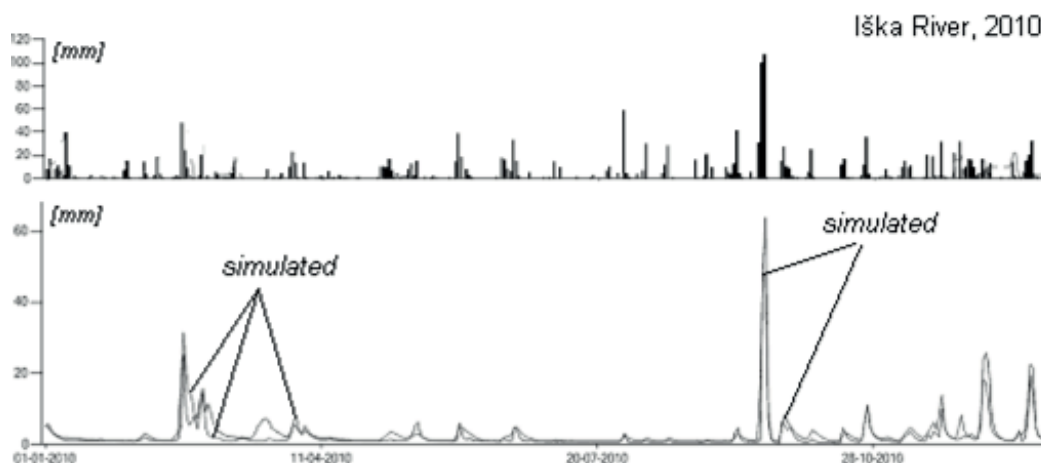


Fig. 4 Runoff of the Iška River as modelled from 2010 precipitation data.

The Iška River surface water flow modelling results are presented in Fig. 5. The overbank flow occurs at discharges greater than 60 m³/s at Profile 12, beginning of section 4 (Fig. 5). At sections 1, 2 and 3 the overland flow occurs at 90 m³/s. In Fig. 6 the hydrographs for the discharge in the Iška River and water level in the piezometer OP-1 for flood in September 2010 are given. One can see good correlation between groundwater level rise in the Ljubljana Moor wetland area (OP-1) and flood in the Iška River.

DISCUSSION

Modelling of the water regime of the marsh area of the Ljubljana Moor is done by distributed hydrological modelling, using MIKE 11 in the MIKE SHE software. The results of modelling the Iška River runoff with the conceptualization of the water flow dynamics were accurate. The simulated Iška River water level data and the measured data corresponded well. In the next step we will model the interaction between surface and groundwater stressed from the extreme weather events, such as extreme precipitation, flood and drought.

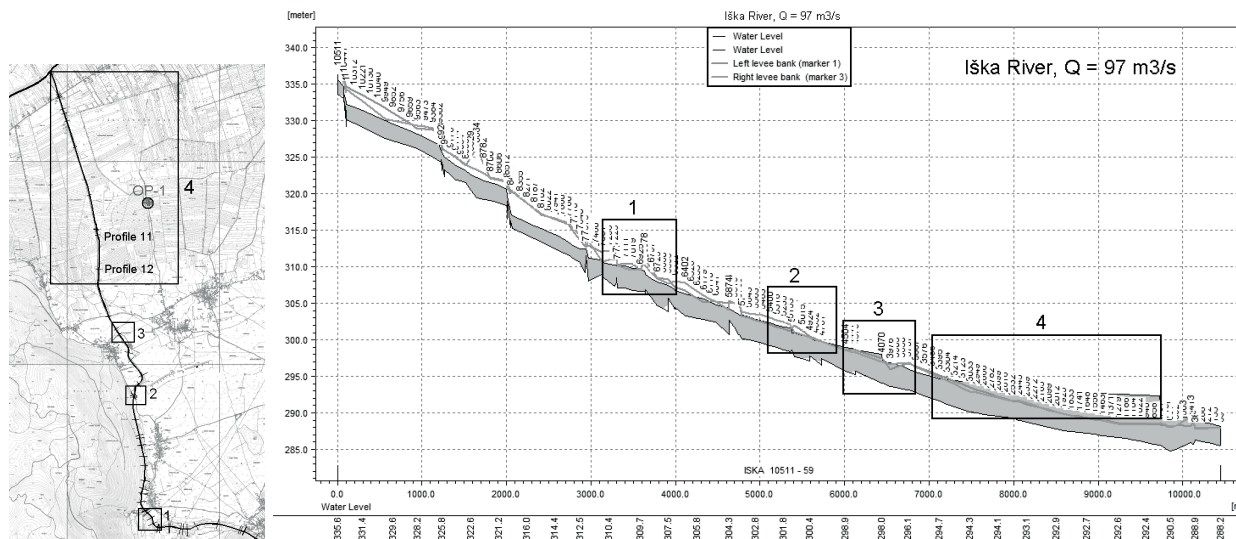


Fig. 5 The Iška River water level profile at 97 m³/s and sections of overbank flow.

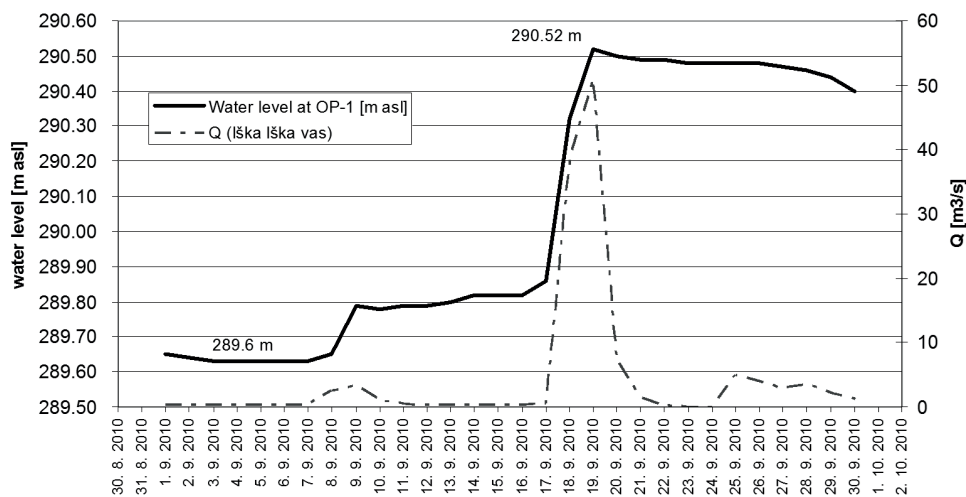


Fig. 6 Groundwater level change at September 2010 flood.

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