HYDROLOGICAL INTERACTIONS BETWEEN UNREGULATED RIVER AND ITS FLOODPLAIN: FIELD STUDY OF THE LUŽNICE RIVER FLOODPLAIN

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ABSTRACT

This paper presents preliminary results of an assessment of the groundwater – surface water (GW-SW) interaction processes of the Lužnice River floodplain during a selected time period, comprising high and low stream flow. It analyses various events that reflect the spatial and temporal variations in water flows to and from the floodplain. Hydrological exchange processes in the floodplain of a groundwater – surface water system are studied on the basis of an experimental site. The chosen study area comprises a c. 10 km long section of the Lužnice River floodplain, located in the south part of the Czech Republic. Water stages in Lužnice River were continuously measured with limnimeters installed upstream, downstream and in the middle of the floodplain length. Five boreholes were drilled along a transect perpendicular to the river to monitor the water table fluctuation in the floodplain. Water level variations of a wetland pool, located at the floodplain left margin in the transect were also continuously recorded. The results indicate that observed groundwater levels are closely associated with the river flows and the assessed reach was gaining most of the time. Downstream flood wave attenuation was not observed during the period of the highest flows due to the large lateral subsurface inflow contribution.

Key words: Floodplain hydrology, Groundwater-river interactions, floodplain wetlands, Lužnice River

1. Introduction

Floodplain is a flat valley floor inundated during exceptionally high flows, when the capacity of the main river channel is exceeded. Therefore, during the flood stages the floodplain provides both a natural conduit and temporary storage capacity for water. By the end of the last century, most research was carried out in headwater catchments without focusing on extended floodplains (Bates et al. 2000). Insufficient attention has been paid to the hydrological processes that occur on the floodplains of lowland rivers. Only few studies provided more details on water level fluctuations within floodplains. This lack of information is all the more surprising given the current research interest in the use of floodplains as buffer zones between farmland and the riverine environment (Burt et al. 2002a,b). However, the majority of these studies focus on the river water and its exchange with the hyporheic zone. Groundwater seepage into the stream from the adjacent aquifer, as well as impacts of streams on aquifers by infiltration of surface water into aquifers is often neglected in analysis (Lewandowski et al. 2009). Considering the lack of studies focusing on this theme, our study aims at identifying hydrological exchange patterns and processes on a site at the unregulated middle reach of Lužnice River and its adjacent floodplain.

Floodplain and its natural storage capability reduces the eventual flood peak and mitigates the damaging effects of downstream flooding (e.g. Bayley 1991; Plate 2002; Bridge 2003). Pithart et al. (2003) discuss the positive impact of floodplain features on the flood wave attenuation and other ecological functions of Lužnice River floodplain. During floods, stream flow exceeds the capacity of the channel. As floodwaters spill out of the channel and spread across the valley bottom, the water encounters much more frictional resistance from trees and other objects situated on floodplain. The velocity of the water decreases dramatically, and the sediment is transported to, and deposited onto the floodplain (e.g. Winter 1999; Woessner 2000). The hydrology of stream riparian zones is strongly influenced by the landscape hydrogeologic setting. This encompasses the location of the riparian zone in the catchment in relation to surface and groundwater flows, as well as the geological characteristics such as topography, stratigraphy and hydraulic properties of sediments that control hydrology (Vidon and Hill 2004).

Given their topographic location and sedimentary structure, most floodplains are characterised by high water tables. Even above the water table, the soil is likely to remain close to saturation given the upward extension of the capillary fringe. Very low gradients across the floodplain, often in conjunction with fine-grained alluvium, help to sustain waterlogged conditions (wetlands). This is especially true in the case of wide floodplains. In summer or autumn, the water table may fall significantly as inflows from nearby slopes diminish and evaporation lowers the water table even further. Under such conditions, the normal hydraulic gradient may even reverse,

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with discharge from the river to the floodplain (especially during flood events). In the lower parts of floodplain, the river is more likely to burst its banks. The floodplain can remain inundated for long periods and possibly form seasonal wetlands (Burt et al. 2002a).

Wetlands in floodplains are characterised by considerable differences in terms of their water budget and pattern of water table fluctuations, which reflect the spatial and temporal variations in water flows to and from the wetland, as well as the extent of water redistribution through the wetland (Mitsch and Gosselink 2000). For many wetlands, groundwater represents an important component of the water budget, albeit one that is difficult to quantify more accurately, especially given the spatial and temporal variability of groundwater inputs that a wetland may receive (Grapes et al. 2006).

The paper aims to identify the relationship between Lužnice River flows and groundwater levels and to investigate the hydrological controls on floodplain water table. Interpretation of the collected field data in this paper is the first step towards building a reliable numerical model to simulate GW-SW interactions at the study area. There is a clear need to define water budget components more accurately and to identify controls on water redistribution in order to improve our understanding of floodplain wetland hydrology (Grapes et al. 2006). This paper examines the local hydrological data of a selected time period from May to September 2009, of a limited recorded dataset, in order to determine spatial and temporal hydrological control on Lužnice River and its floodplain. This paper deals with qualitative analyses of data and outlines some preliminary results. Quantitative analysis and an assessment of a large dataset will be a matter of the next study, because a description of longer-term patterns is essential for understanding natural hydrodynamics of unregulated rivers. This is particularly relevant for attempts to restore previously altered river systems.

2. Study area

The study area chosen comprises c. 10 km long section of the Lužnice River middle reach lying within a broad floodplain, located in the south of the Czech Republic near the Austrian border (Fig. 1). The chosen part of floodplain is stretched along the unregulated river between towns Nová Ves nad Lužnicí and Suchdol nad Lužnicí (Fig. 2). The floodplain, flanked by a series of alluvial terraces, is distinctly defined by the first terrace. Width of the floodplain ranges between 150 and 1100 m and its area is c. 4.3 km². It is covered mainly in grass and the stream is often lined with willows.

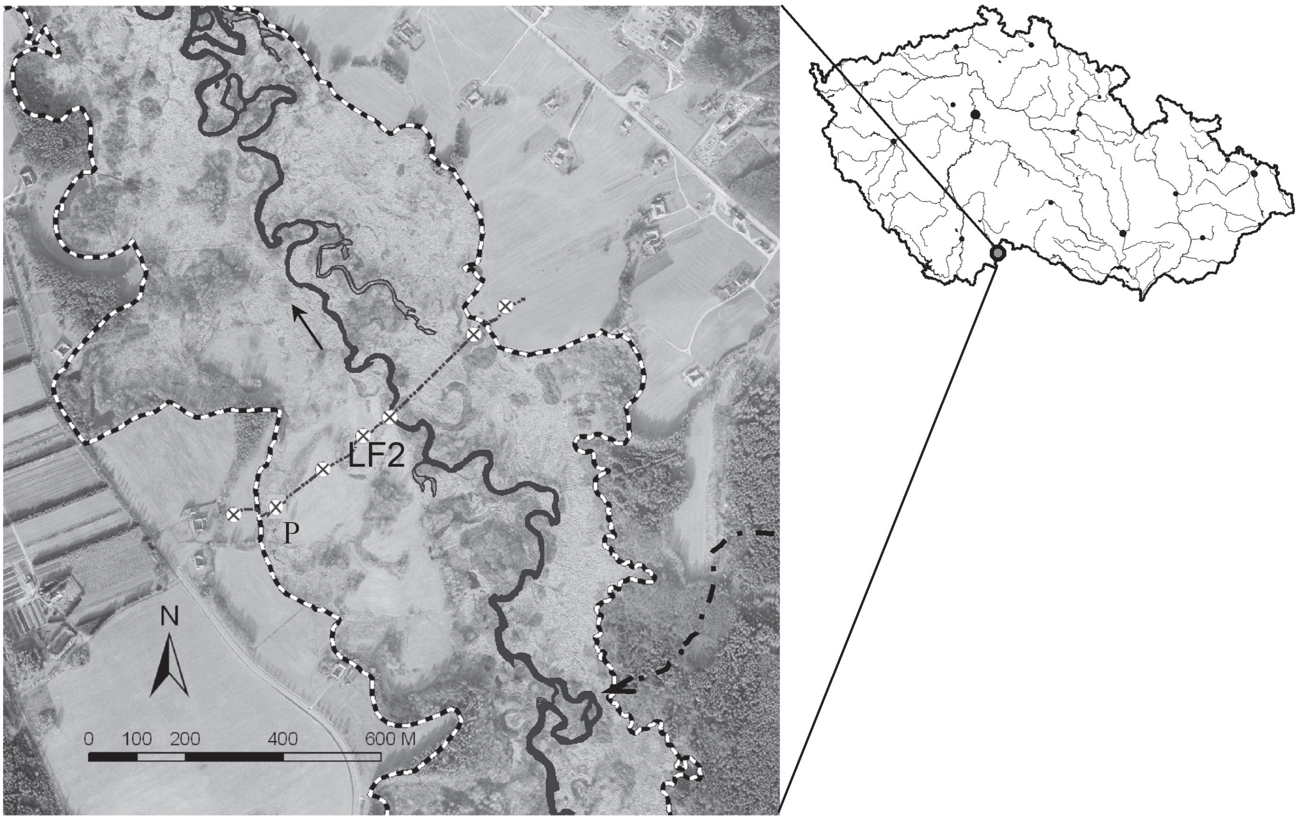

Fig. 1 Location map of the study reach on the Lužnice River in the Czech Republic and the aerial photography, showing the floodplain section with a location of the water table gauging points (mainly boreholes, incl. the borehole coded LF2) along the transect. Letter (P) refers to limnimeter in the wetland pool. Dashed line indicates the floodplain margins. Dash and dotted line with arrow indicates Halamecký stream

The soil types in studied area range from cambisols through fluvisols and glaysols to peats (Prach et al. 1996). The Cretaceous is in the study area overlain by sediments of Pleistocene age, which form 7 levels system of terraces. The lowest terrace (Würm age) consists of gravels and sands layer, which is more then ten meters thick (Chábera and Vojtěch 1972). The floodplain deposits comprise between c. 1–2 m of Holocene alluvial sand and sandy loam overlain with occasional clay lenses. The floodplain has mostly unconfined aquifer, with a high hydraulic conductivity (approx. 10^{-3} m s^{-1}), and is hydraulically connected with the river. Above the water table, the soil is likely to remain close to saturation given the upward extension (0.5–2.5 m) of the capillary fringe (Kraus 1988).

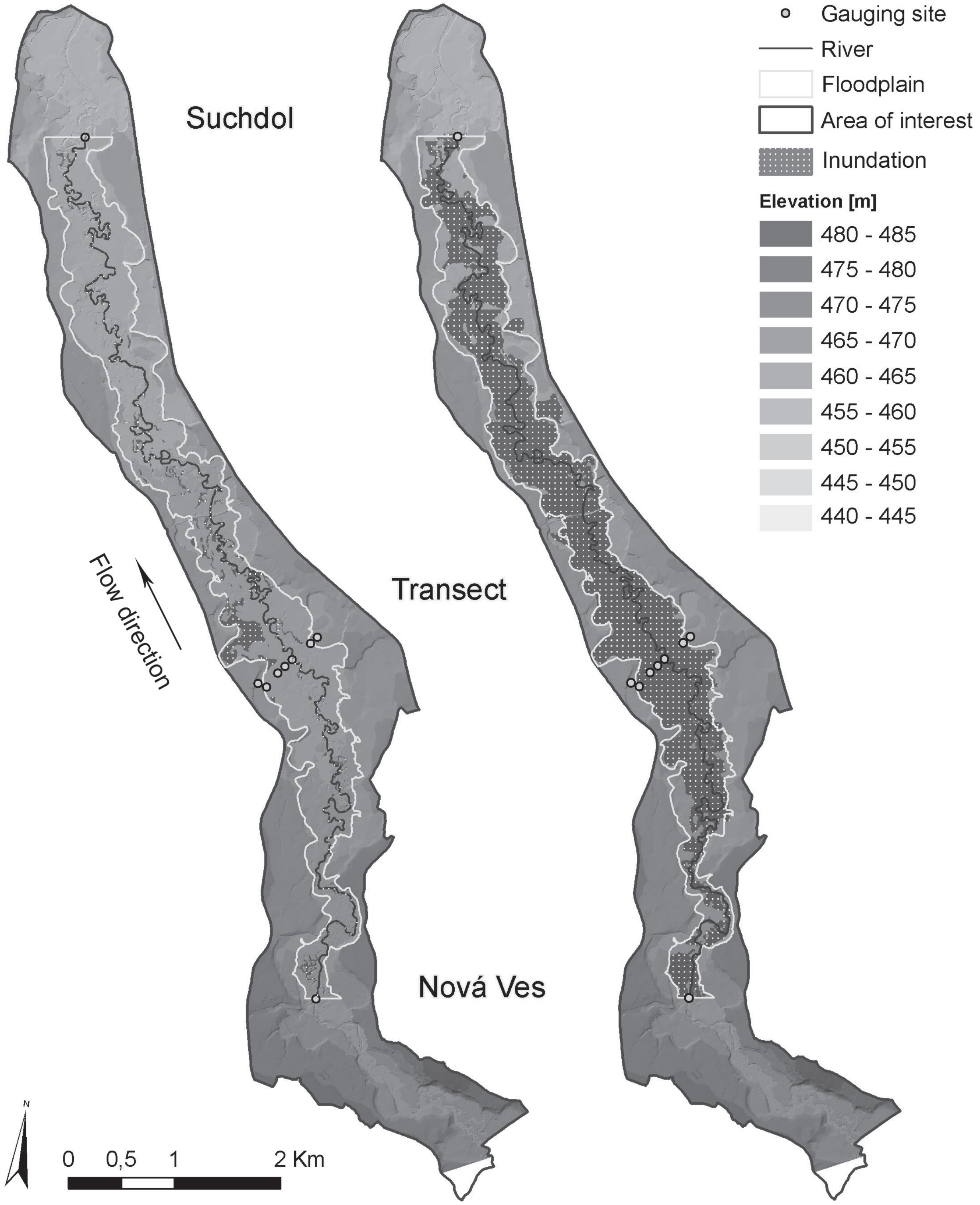

Fig. 2 Two maps showing water area on 13 September during the mean river flow (on the left) and on 8 July during the highest flow within the analysed period (on the right)

The Lužnice River in the study area is a classic meandering river, which has been relatively unaffected by channel alteration or groundwater abstraction in the past. This is reflected in a sinuosity index of the stream channel of approximately 2.5. The gradient of stream channel is approximately 0.08%. Channel width at the monitoring site in the middle of the study area is c. 6–7 m and the mean depth is c. 2 m. The mean annual discharge is approximately 5 $m^3 s^{-1}$. There are many abandoned meanders and oxbow lakes in the surrounding floodplain. The floodplain area was defined as a natural reserve in 1994.

3. Methods and Materials

Characterization of the exchange of groundwater with river water in floodplain has been accomplished by measuring water levels in boreholes and stream, as well as by comparing groundwater and stream temperature, as described by Woessner (2000), Sophocleous (2002) and Kalbus et al. (2006).

Fieldwork was carried out in 2008 and consisted of geodetic surveying and installing of various monitoring equipment combined with data loggers to monitor the stream and surrounding groundwater interaction. Five boreholes were drilled along a c. 700 m wide W-E transect perpendicular to the channel approximately in the middle of the floodplain length. Their locations in the floodplain and terraces are shown in Fig. 1 and 2. Boreholes at both ends of the transect in terraces were c. 3 m deep and in the floodplain was their depth about 2.5 m. All boreholes were installed using a power rig and constructed from 50 mm internal diameter PVC fully screened casing. For the purpose of long-term monitoring, the pressure transducers with built-in data loggers were installed in each borehole and were programmed to record water level on half an hour basis. Surface water was monitored on the Lužnice River, on its small tributary Halámecký stream (only sole river's tributary in the study area, Fig. 1) and on a small wetlands pool (marked with the letter P in Fig. 1) located in the transect, on the left floodplain margin. Water level fluctuations in the Lužnice River were monitored with three limnimeters with installed data loggers. They were placed upstream (Nová Ves) and downstream (Suchdol) of the study area and on the site, where the groundwater monitoring transect intersects the river (Fig. 2). Stream water level fluctuations were recorded on ten minutes basis. To obtain discharge, rating curves were developed with stream velocity measurements. An on-site meteorological station was installed to monitor precipitation. All the monitoring instruments placed in the study area contained temperature sensors. They were used for temperature time series analysis, which revealed more information on the surface water and groundwater interaction, and seepage rate through the riverbed sediments (Constantz and Stonestrom 2003).

The calculation of water volume accumulated during a flooding on floodplain above the terrain was performed in ArcGIS GIS software. More specifically, models designed within the Model Builder environment were used extensively. The precision of an existing digital terrain model (DTM) of the study area was improved with additional data obtained by a survey using a total station.

4. Results

Considering limited measurement time at gauging sites, the preliminary results show an assessment of various parameters influencing the groundwater – surface water (GW-SW) interaction processes during a selected time period from May to September 2009. They embraces high and low flows of the Lužnice River.

In the beginning, the discharge rates at the upstream (Nová Ves) and the downstream site (Suchdol) were roughly equivalent, under the annual average, which is approx. 5 $m^3 s^{-1}$ (Fig. 3). A temporary river flow increase (2nd June) resulted in a moderate groundwater level elevation in an immediate riverine area (Fig. 4). Losing stream water infiltrated into an adjacent floodplain aquifer through the streambed or stream banks, causing a net loss of water to the stream. This was the only event of negative hydraulic gradient between floodplain water table and stream water level in the monitored transect during the observed period. Another negative hydraulic gradient was not even observed during a significant difference between upstream and downstream, c. 1 $m^3 s^{-1}$ (i.e. 58 per cent of discharge less at downstream), occurred during the lowest flow on 19 June.

In the second half of the analysed time period the Lužnice River was obviously a gaining stream in which groundwater discharges contributed significantly to the streamflow volume. Hydraulic gradient between the groundwater level in the terraces and the floodplain was positive all over the observation period, as well as the hydraulic gradient between a floodplain groundwater and a river water level in the transect (the highest was on 13th September, Fig. 4) with the exception of negative gradient on 1 and 2 June (see above). The baseflow of that time was probably a result of previous floods and heavy rainfall events.

River flow significantly increased on 24th June. The stream remained at flood stage for about a month. In the beginning of flooding three flood waves successively passed through the studied area and their peak discharges were gradually increasing. Outflow of the first flood wave, leaving the study area at Suchdol, was 10 per cent higher then its inflow at Nová Ves gauging site. There was 14 per cent growth of the second wave and the outflow of the third wave was 19 per cent higher (i.e. 6 $m^3 s^{-1}$) then its inflow. Thus, no downstream attenuation of the flood peak was observed; on the contrary, all the three flood peaks increased. The least increase of the

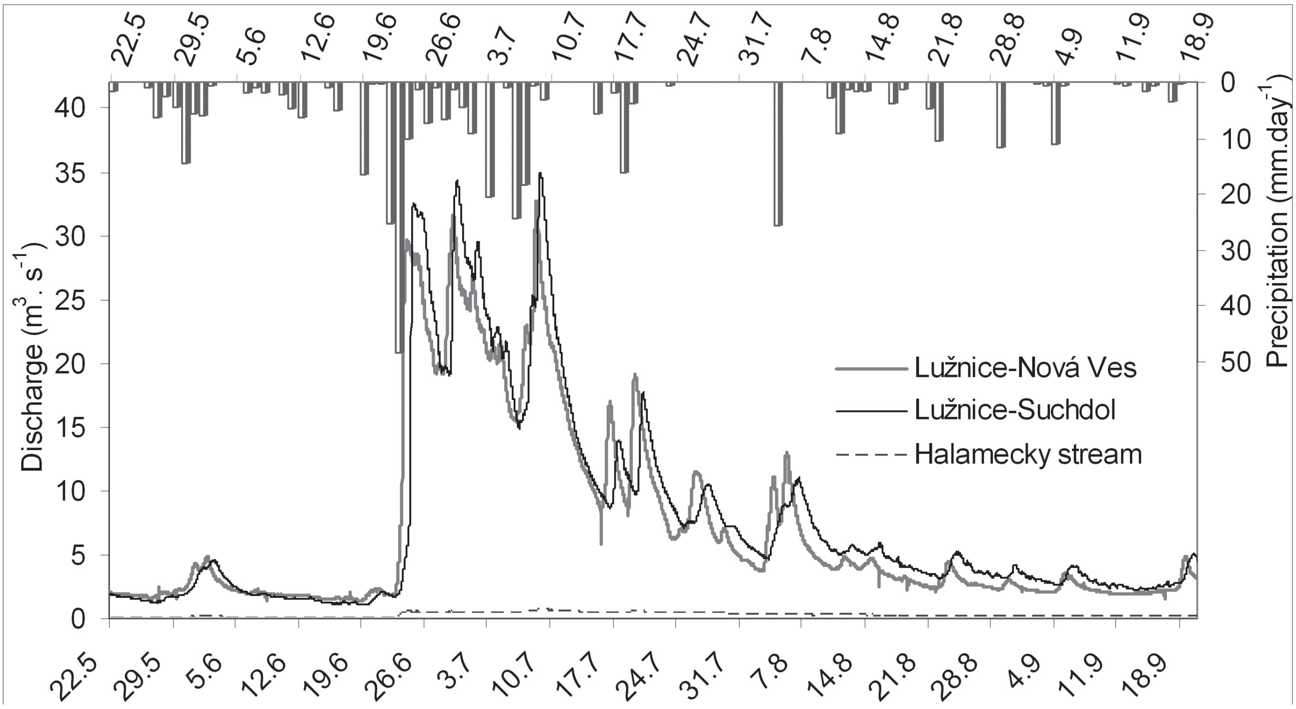

Fig. 3 Time series of a flow at the Lužnice River stations Nová Ves (upstream) and Suchdol (downstream), its tributary Halámecký stream and of daily precipitation measured in the study area (May to September 2009). The mean annual discharge of the Lužnice River is c. 5 m^3 s^{-1}

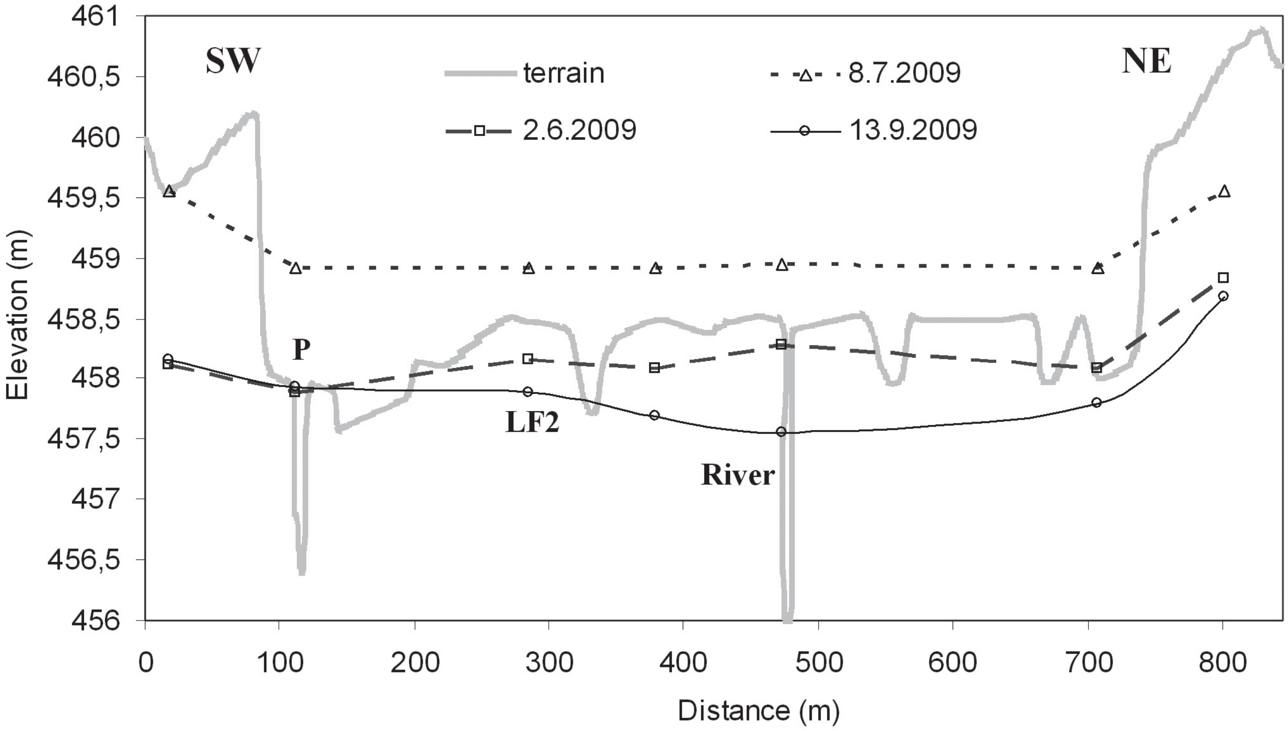

Fig. 4 Schematic cross-section across the Lužnice valley showing the locations of boreholes and limnimeters and water table profiles along transect during the events mentioned in text. Letter (P) refers to limnimeter in the wetland pool. The vertical exaggeration is 100×

first peak was probably a result of an infiltration and bank seepage of flood waters into the soils of the floodplain. The two other waves show an increasing size of the downstream flood peak relative to the upstream hydrograph and water mass balances that require an increasing flux of water from the floodplain and neighbouring slopes and terraces to the river to account for the discrepancy between inflow and outflow.

The dramatic increase in this flux to the river occurred as a consequence of heavy and sustained rainfall that increased a groundwater level in terraces (the left in particular, Fig. 4) and the hydraulic gradient towards the inundated floodplain. A discharge travel time of the first wave (after the large total precipitation on 23rd June – c. 50 mm per day) took much longer, c. 18 hours, than the other two waves, which were c. 10 hours, due to frictional resistance and storage capacity of the floodplain, which was lesser by successively passing other two waves.

The research recorded a significant propagation of a wave passing through the reach in the beginning of August. Two discharge peaks of the flood wave at upstream gauging station (Nová Ves) were transformed into an individual attenuated peak at downstream station (Suchdol), despite a one-day precipitation event in the area of interest. Above bankfull water storage on the floodplain and associated delays due to frictional resistance suppressed flood growth.

In September, during the low river flow, was about 10 per cent of floodplain area covered with water. The water occupied a volume of c. 300 thousand cubic metres above terrain. About 80 per cent of floodplain area was flooded during the highest streamflow in September by c. 1.8 million cubic metres of accumulated water (Fig. 2).

Wetlands are located on the left floodplain margin hollows stretching along the left terrace. Limited water level fluctuation of the pool located within the wetland area ("P" in Fig. 4) was observed during the studied period (apart from floodplain inundation event when the pool was flooded with surface water). It was related to a damming effect produced by low conductivity peats maintaining surface saturation for considerable periods of the year. As a result, water table variations were lower here than at any other gauged sites that had a larger upslope depth of permeable sediments, which did not restrict subsurface flow. The layer consisting of low conductivity sediments is a result of a siltation process induced by lateral water flow, which is parallel to the main stream. This flow is divided one kilometre upstream from the main channel during the flood stages and is running on the floodplain margin along the terraces base. Springs often emerged within the wetlands area. Their occurrence was caused by an upwelling of groundwater through hydrostatic pressure of confined groundwater beneath the wetlands, fed by terraces aquifers, especially during the large hydraulic gradients periods.

A significant role of floodplain in mitigation of water temperature variation is clearly illustrated by Fig. 5. Water temperature variations at upstream (Nová Ves) gauging station (9 °C amplitude during four days at the end of May) were mitigated during the reach passage at downstream station (only 2 °C amplitude). Mitigation is associated with the interaction of stream water with groundwater. Groundwater temperatures are relatively stable throughout the year. They rise and decline relatively gradually in relation to stream temperatures, which vary strongly on a daily and seasonal basis (Halamecký stream in particular).

5. Discussion and conclusion

The paper presents preliminary results of an assessment of various parameters influencing the hydrological exchange processes of a groundwater and surface water

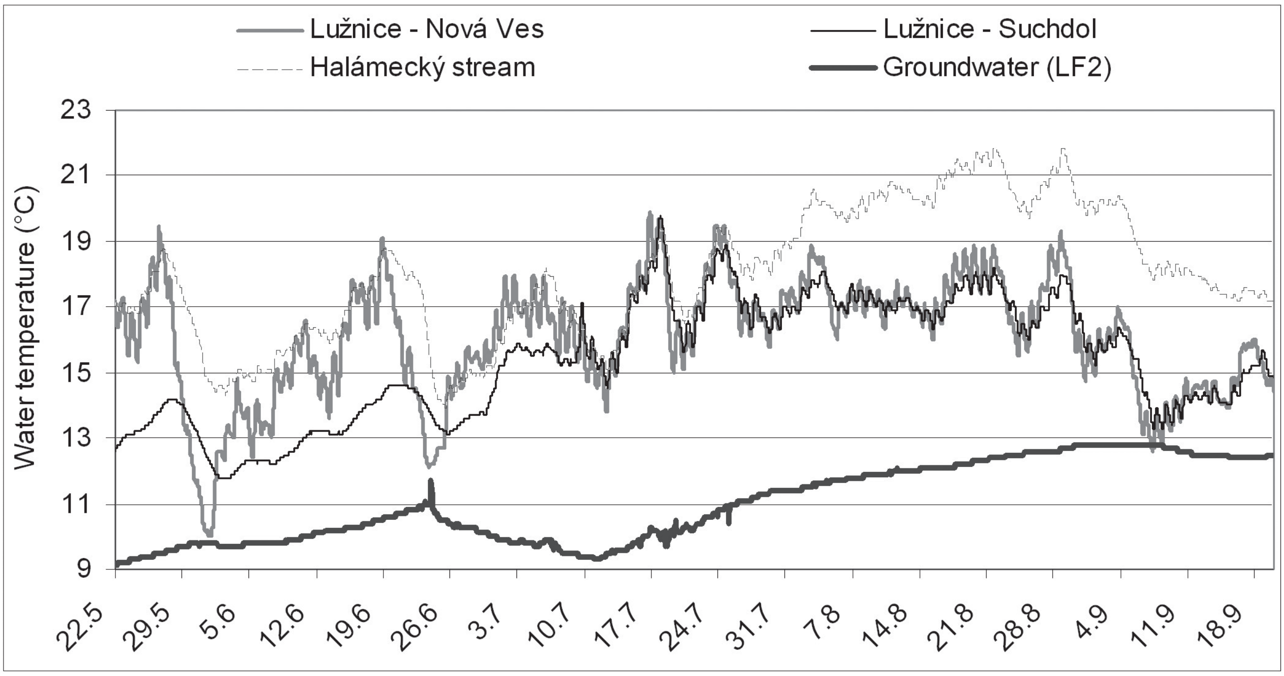

Fig. 5 Time series of a temperature fluctuation at Lužnice River stations Nová Ves and Suchdol, its tributary Halámecký stream and groundwater at gauging point coded LF2 (for its location see Fig. 1). Recorded May to September 2009

system of c. 15 km long unregulated reach of the Lužnice River lying within a broad floodplain. The analysis is based on hydrological data measured during a selected five months period comprising high and low river flow. Variations in hydraulic gradient between local borehole levels in floodplain or flanking alluvial terraces and channel water levels were described for a transect perpendicular to the main stream of the Lužnice River.

The overall pattern of changes during the above-mentioned period illustrated a reach with a complex hydrological interaction between the Lužnice River, its floodplain and the surrounding slopes. As noted by Bayley (1991), Plate (2002), Bridge (2003), all these processes could affect the propagation of individual flood waves through the reach reported. However, contrary to the reports of the afore-mentioned authors, flood wave propagation was not observed on the examined reach during a flood event within the analysed period. A reason for that was an exceptionally heavy and sustained rainfall in the region preceding the high inflow at Nová Ves gauging station. Precipitations resulted in high recharge of terrace aquifers and subsequent rise in their water table and increase of hydraulic gradient towards the floodplain. As a consequence, the capacity of bank or floodplain water storage was significantly reduced. Contrary to Pithart (2003) assumptions, the flood wave was not attenuated passing the reach, but its discharge peak even increased. As the floodplain water storage capacity was decreasing, the discharge peaks of all the three successively passing flood waves were gradually rising at Suchdol downstream gauging station in relation to upstream station Nová Ves. Additionally, the discharge travel time of these waves was declining with time.

A significant propagation of flood wave passing through the reach was observed at the beginning of August. Two discharge peaks of the wave at upstream gauging station were transformed into an individual attenuated peak at downstream station. Above bankfull increasing storage on the floodplain and associated delays due to frictional resistance suppress flood growth.

Although the reach was slightly losing in the beginning and gaining during the second half of the analysed period (according to an upstream and downstream diferences in discharge), positive (i.e. gaining conditions) or zero hydraulic gradient dominated between the groundwater level in floodplain and river water level in the transect all over the analysed period, apart from the temporal discharge increase at the beginning of June. Thus, the hydraulic gradient between floodplain and the river within all the studied area could not be identical to monitored transect.

When analysing the GW-SW interaction with hydrographic data, the temperature monitoring provided useful insights into the spatial and temporal variability of stream-aquifer connectivity. Water temperatures of Lužnice upstream and its tributary Halámecký stream varied strongly in dependence to a daily and seasonal base. In contrast, the Lužnice River downstream temperatures were relatively stable throughout the first part of analysed period (i.e. before flood event). The same can be said for groundwater temperatures. Damped diurnal variations in Lužnice downstream (Suchdol) water temperatures could reflect, according to Winter et al. (1998), Burt et al. (2002a) or Baskaran at al. (2009), an intensive hydraulic communication between the stream and adjacent aquifer.

Wetlands typically occur in floodplain areas where groundwater discharges to the land surface, or in areas where ground conditions impede the drainage of water. On the floodplain margin, along the left terrace, upward flow due to the damming effect produced by low conductivity peats maintained surface saturation with pools for all the year. As a result, water table variations were lower here than at the other sites in floodplain, which have a larger depth of permeable sediments, but where riparian subsurface flow is not restricted by low conductivity sediments at the perimeter of floodplain by a low permeability organic deposit.

During the analysed period the results indicate that observed groundwater levels are closely associated with the river flows. For a more accurate description of the GW-SW interaction in the study area, a long-term pattern is essential for establishing a better understanding of natural hydrodynamics of unregulated rivers, particularly as attempts are made to restore previously altered systems (see e.g. Benke at al. 2000).

The monitoring in the studied area still continues. The next step in our future analysis is to assess longer time series more accurately through the quantitative analysis. This work is a step towards attaining our ultimate goal of developing a better and more extensive understanding of the interaction between streams and floodplain aquifers and improving our capability to simulate stream-aquifer systems in floodplains. This can enhance our understanding of local flow and transport mechanism in floodplain that represents an important element for appropriate water management.

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RÉSUMÉ

Hodnocení hydrologické interakce mezi řekou a okolní nivou na příkladu středního toku Lužnice

Článek prezentuje předběžné výsledky hodnocení hydrologické funkce údolní nivy a věnuje se analýze faktorů, ovlivňujících interakci povrchové a podzemní vody. Studovaným územím je přibližně 10 km dlouhý úsek přirozené nivy Lužnice na jejím středním toku.

K hodnocení vlivu přirozené údolní nivy na hydrologický režim hlavního toku byly v zájmovém území během roku 2008 instalovány automatické hladinoměry s dataloggery. Ty zaznamenávaly vodní stav na třech místech v řece, dále na jejím jediném povrchovém přítoku ve studovaném území, v nivní tůni a hladinoměry byly též osazeny i vrty v okolní nivě a přiléhající terase, kde monitorovaly výšku hladiny podzemní vody v transektu přibližně kolmém na hlavní tok. Úhrn srážek spadlých na studovaném území byl měřen instalovaným srážkoměrem. Vodní stav na Lužnici byl v zájmovém území monitorován na horním (vstupním) profilu, dolním (závěrovém) profilu a přibližně uprostřed území – v místě příčného transektu. Pro hodnocení vlivů okolní nivy byly srovnávány průtoky řeky na horním a dolním měrném profilu během vybraného období od května do září 2009.

V průběhu tohoto období došlo k dlouhodobému zaplavení údolní nivy. Během vysokých vodních stavů na Lužnici prošly územím tři povodňové vlny, u nichž byly analyzovány změny jejich kulminačních průtoků po průchodu sledovaným územím a jejich postupová doba. Vzhledem k vysokým denním úhrnům srážek ve sledované oblasti a jejím okolí během nástupu povodňové vlny došlo k výraznému zvýšení hladiny podzemní vody v terasách lemujících nivu a velký hydraulický spád k nivě a ke korytu řeky měl za následek silný podpovrchový přítok do nivy a eliminaci zdejších retenčních kapacit. To se na dolním profilu projevilo zvýšením kulminačních průtoků u všech tří povodňových vln a zkrácením jejich postupových dob. Ke zřetelné transformaci průtokové vlny tak ve sledovaném období došlo pouze počátkem srpna, kdy se během vybřežení toku plně projevila retenční kapacita a hydraulická drsnost údolní nivy. Specifický je hydrologický režim nivních mokřadů a tůní v nivě, které nad poměrně dobře propustným kolektorem vytváří díky kolmataci dna, a tedy velmi nízkým koeficientům filtrace, stropní izolátor freatické vody. Teplotní režim toku a podzemní vody v nivě indikuje změny v jejich vzájemném hydraulickém spojení. Pro přesnější hodnocení vzájemné hydraulické interakce toku a okolní nivy je nezbytný dlouhodobý monitoring a analýza delších časových řad. Nicméně je zřejmé, že retenční potenciál nivy a její vliv na transformaci povodňové vlny je při vyšších průtocích zřetelně omezený.

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