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Controls of groundwater floodwave propagation in a gravelly floodplain

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SUMMARY

Interactions between surface water and groundwater can occur over a wide range of spatial and temporal scales within a high hydraulic conductivity gravelly floodplain. In this research, dynamics of river–groundwater interactions in the floodplain of the Matane River (eastern Canada) are described on a flood event basis. Eleven piezometers equipped with pressure sensors were installed to monitor river stage and groundwater levels at a 15-min interval during the summer and fall of 2011. Results suggest that the alluvial aquifer of the Matane Valley is hydraulically connected and primarily controlled by river stage fluctuations, flood duration and magnitude. The largest flood event recorded affected local groundwater flow orientation by generating an inversion of the hydraulic gradient for 16 h. Piezometric data show the propagation of a well-defined groundwater floodwave for every flood recorded as well as for discharges below bankfull (<0.5 Qbf). A wave propagated through the entire floodplain (250 m) for each measured flood while its amplitude and velocity were highly dependent on hydroclimatic conditions. The groundwater floodwave, which is interpreted as a dynamic wave, propagated through the floodplain at 2–3 orders of magnitude faster than groundwater flux velocities. It was found that groundwater exfiltration can occur in areas distant from the channel even at stream discharges that are well below bankfull. This study supports the idea that a river flood has a much larger effect in time and space than what is occurring within the channel.

1. Introduction

A gravel-dominated floodplain and its fluvial system are hydrologically connected entities linked by interactions beyond recharge and discharge processes. Woessner (2000) emphasized the need to conceptualize and characterize surface–water–groundwater exchanges both at the channel and at the floodplain scale to fully understand the complex interactions between the two reservoirs. The stream–groundwater mixing zone is referred to as the hyporheic zone. It is generally understood that surface water–groundwater mixing exchanges at channel and floodplain scales are driven by hydrostatic and hydrodynamic processes, the importance of which varies according to channel forms and streambed gradients (Harvey and Bencala, 1993; Stonedahl et al., 2010; Wondzell and Gooseff, 2013). The boundaries of the hyporheic zone can be defined by the proportion of surface water infiltrated within the saturated zone (Triska et al., 1989) or by the residence time of the infiltrated surface water (Cardenas, 2008; Gooseff, 2010). However, pressure exchanges between surface water and groundwater can occur beyond the hyporheic zone, with no flow mixing (Wondzell and Gooseff, 2013). River stage fluctuations can lead to the generation of groundwater flooding via pressure exchanges.

Groundwater flooding, i.e., groundwater exfiltration at the land surface, is controlled by several factors in floodplain environments: floodplain morphology, pre-flooding depth of the unsaturated zone, hydraulic properties of floodplain sediments, and degree of connectivity between the stream and its alluvial aquifer (Mardhel et al., 2007). Two scenarios can lead to the rise of groundwater levels resulting in flooding: (1) the complete saturation of subsurface permeable strata due to a prolonged rainfall by the extension of the capillary fringe (Gillham, 1984) and (2) groundwater level rises due to river stage fluctuations. Concerning the second scenario, Burt et al. (2002) and Jung et al. (2004) noted that once the River Severn (UK) exceeded the elevation of the floodplain groundwater in summer conditions, the development of a groundwater ridge was responsible for switching off hillslope inputs at stream discharges below bankfull. Mertes (1997) also illustrated that inundation of a dry or saturated floodplain may occur as the river stage rises, even before the channel overtops its banks. In-channel and overbank floods perform geomorphic work that modifies groundwater–surface

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water interactions (Harvey et al., 2012). In contrast, groundwater floodwaves propagation performs no geomorphic work, but nevertheless can influence riparian ecology or flooding of humanbuilt systems on floodplains (Kreibich and Thieken, 2008).

Field studies at the river-reach scale have been carried out to document the hydrological interactions between river stage and groundwater fluctuations beyond the hyporheic zone in floodplain environments (e.g., Burt et al., 2002; Jung et al., 2004; Lewandowski et al., 2009; Vidon, 2012). It has been reported that river stage fluctuations were responsible for delayed water level fluctuations at distances greater than 300 m from the channel (e.g., Vekerdy and Meijerink, 1998; Lewandowski et al., 2009). The process of pressure wave propagation through the floodplains (Sophocleous, 1991; Vekerdy and Meijerink, 1998; Jung et al., 2004; Lewandowski et al., 2009; Vidon, 2012) and the direction of exchanges between groundwater and surface water at the river bed (Barlow and Coupe, 2009) have has also been documented. However, only a few field studies describe the interactions between surface water and groundwater on a flood event basis (e.g., Burt et al., 2002; Jung et al., 2004; Barlow and Coupe, 2009; Vidon, 2012). Moreover, field instrumentation usually covers only a limited portion of the floodplain with transects of piezometers (Burt et al., 2002; Jung et al., 2004; Lewandowski et al., 2009). The lack of empirical data on the propagation of groundwater flooding in two dimensions during several flood events limits our understanding of complex river–groundwater interactions. Using higher spatial and temporal resolutions is necessary to describe how flow orientations within alluvial floodplains are affected by flood events. Furthermore, the processes that generate groundwater exfiltration and the effects of floodplain morphology on river–groundwater interactions in alluvial floodplains need to be better understood to facilitate land use management in floodplains.

The aim of this paper is to document surface water–groundwater interactions in an alluvial floodplain at high spatial and temporal resolutions at the flood event scale. The study was carried out on the Matane River floodplain (province of Quebec, Canada). The Matane Valley is known to experience floods of different types every few years: overbank flow during snow melt, during rainstorms, or by ice jams. The valley is also known to experience flooding in areas that are distant from the channel when there is no overbank flow. An experimental site was instrumented and water levels were monitored for 174 days in the summer and fall of 2011. Time series analysis was used to interpret results and provide a detailed picture of the interactions between river and groundwater levels.

2. Materials and methods

2.1. Study site

The Matane River flows from the Chic-Choc mountain range to the south shore of the St. Lawrence estuary, draining a 1678 km^2 basin (Fig. 1). The flow regime of the Matane River is nivo-pluvial, with the highest stream discharges occurring in early May. The mean annual stream discharge is 39 $m^3 s^{-1}$ (1929–2009), and the bankfull discharge is estimated at 350 $m^3 s^{-1}$. Discharge values are available from the Matane gauging station (CEHQ, 2013; station 021601). The irregular meandering planform flows into a wide semi-alluvial valley cut into recent fluvial deposits (Lebuis, 1973). The entire floodplain of the gravel-bed Matane River is constructed by different types of meander growths that shift over time. The mean channel width and the mean valley with are 55 m and 475 m, respectively.

The study site, located 28 km upstream from the estuary (48°40′5.678″N, 67°21′12.34″W), is characterized by an elongated depression that corresponds to an abandoned oxbow and a few overflow channels (Fig. 1). The site was chosen for its history of flooding at river stages below bankfull. The floodplain is very low, i.e., at bankfull discharge, the deepest parts of the depression are lower than the river water level. During the study period, the mean groundwater level at the study site is 58.8 m above mean sea level, whereas the surface elevation of the floodplain is 60.4 m above sea level, i.e., the unsaturated zone is on average 1.4 m. The sediments overlying the bedrock and forming the alluvial aquifer consist of coarse sands and gravels overtopped by a overbank sand deposit layers of variable thickness from 0.30 m at highest topographic forms to 0.75 m within abandoned channels. The unconfined alluvial aquifer thickness of is 25 m according to a bedrock borehole next to the study site.

2.2. Sampling strategy

To investigate hydraulic heads in the floodplain, the local groundwater flows, and the stream discharge at which exfiltration occurs, an array of 11 piezometers was installed (Fig. 1). Arrays of piezometers have been used with success in previous studies to document the surface water-groundwater interactions (e.g., Haycock and Burt, 1993; Burt et al., 2002; Lewandowski et al., 2009; Vidon, 2012). Piezometers are made from 3.8 cm ID PVC pipes sealed at the base and equipped with a 30 cm screens at the bottom end. At every location, piezometers reached 3 m below the surface so that the bottom end would always be at or below the altitude of the river bed. However, because of the surface microtopography, the piezometers bottom reached various depths within the alluvial aquifer. Piezometer names correspond to the shortest perpendicular distance between the piezometer and the river bank. Slug tests were conducted at each piezometer, and rising-head values were interpreted with the Hvorslev method (Hvorslev, 1951). Results from the slug tests at each piezometer indicate that hydraulic conductivities are relatively homogeneous (from 8.48×10^{-4} to 2.1×10^{-5} m s^{-1}; Table 1) and representative of coarse sand to gravel deposits (Freeze and Cherry, 1979).

Data were collected from 21 June to 12 December 2011. This period correspond roughly to the end of the long spring flood to the beginning of winter low flow period where flow stage is influenced by the formation of an ice cover. From 21 June to 7 September 2011, eight piezometers were equipped with pressure transducers (Hobo U20-001) for automatic water level measurements at 15 min intervals. Three more pressure transducers were added at piezometers D139, D21, and D196 starting on 7 September. Two river stage gauges were installed on the riverbed, downstream and upstream of the study site (RSGdn and RSGup; Hobo U20-001) to monitor water levels in the Matane River every 15 min over the complete study period. Piezometer locations were measured using a Magellan ProMark III differential GPS. A LIDAR survey with a 24 cm resolution (3.3 cm accuracy) was used to obtain a high resolution map of topography. Precipitation was measured with a tipping bucket pluviometer located on site (Hobo RG3-M).

2.3. Data analysis

During the data collection period, water levels and river stages were never lower than the piezometer and RSGup data loggers. However, river stages at RSGdn occasionally dropped below the data logger, so time series at this location are discontinuous. The RSGdn time series was only used to analyze the 5–12 September event.

During flood events, the timing of maximum water level elevation differed between the piezometers and the river gauge. To determine the time lags between time series of river stages and