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The propagation of complex flood-induced head wavefronts through a heterogeneous alluvial aquifer and its applicability in groundwater flood risk management

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SUMMARY

The extraordinary rise of piezometric surface in aquifers may induce an unexpected interaction of groundwater with anthropogenic elements known as groundwater inundation phenomena. This could result in several damage processes, including building foundation destabilization, groundwater infiltration and pollutant remobilization, which are responsible for considerable economic losses worldwide. To improve our knowledge concerning flood-induced head wavefront propagation and groundwater inundation phenomena, the reconstructed kinematics of the head wavefronts obtained from a calibrated groundwater model simulating 12 ordinary flood events have been statistically analyzed. The correlation between kinematic variables of a flood-induced head wavefront, flood event characteristics and aquifer properties was the basis for the study of the aquifer response to river flood events along four different trajectories, i.e. the identification of river level rise rate, absolute–relative height of the maximum rise stage, hydraulic parameter variability, river–aquifer exchange rates, pre-event state of the aquifer and distance to the aquifer boundary as the key-influencing factors in groundwater inundation. Finally, model and scenario results were used to develop two synthetic models for groundwater inundation as novel decision-support tools for assessing both ordinary and extraordinary flood events in groundwater flood risk management and in urban development planning. These synthetic models gives the technical criteria to predict extraordinary rise of piezometric surface and therefore allows increasing the confidence of stakeholders in the risk assessment and improving the subsurface infrastructure design to mitigate damage processes derived from groundwater interaction.

1. Introduction

Although riverine surface flooding is the primary factor responsible for significant damage to urban areas throughout the world, another indirect consequence of flood events is groundwater inundation, which also produces considerable losses (Cobby et al., 2009; Hughes et al., 2011; Kreibich et al., 2009; Macdonald et al., 2008). Flooding is not always related to river level rise, since intense rainfall periods triggering an additional groundwater flow toward low-lying areas can result in groundwater rise above surface terrain causing also groundwater flooding (Macdonald et al., 2012). The concern of groundwater flooding in coastal-plain urbanized areas has also increased, since the groundwater table is expected to rise with sea level due to climate change (Rotzoll and Fletcher, 2013). A groundwater head change in an aquifer may affect the stability of building foundations through increasing pore pressure (Huber et al., 2003; Morrison and Taylor, 1994), infiltrating groundwater into subsurface infrastructures, including building basements, subways or other infrastructures, such as sewer systems (Karpf and Krebs, 2004; Wittenberg and Brombach, 2002), causing sewer overflows. Groundwater infiltration into subsurface structures may be a result of permeable basement floors, damaged structures, permeable walls or openings for service pipes. Considering the inertia of groundwater flow, the water may affect the structure for days, months, or more if no anthropic remediation measure is applied. In addition, capillarity phenomena may affect permeable subsurface structures above

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the water table (Kelman and Spence, 2004). Pollutant remobilization due to groundwater leaching may also occur, compromising safe drinking water (Engeler et al., 2011; Kelman and Spence, 2004; Osenbrück et al., 2007; Reinstorf et al., 2009). In August 2002, a flooding episode that occurred at the Elbe River in the State of Saxony (Germany) caused the groundwater level to rise to a record height. The damage caused by the flood were estimated in €6.2 billon, where 16% of the damage was caused by groundwater inundation (Huber et al., 2003). As an urban area example, in May 1999 (FOWG, 2004), a flood event at the Aare River caused €481 million damage in the Bern District (Switzerland), where groundwater inundation accounted for approximately 23% of the overall losses. The largest loss was produced in the installations of the highly equipped buildings, especially those of the opera, theater, castle and others. Losses mainly consisted in heating systems damage, contents deterioration, corrosion of foundations, contamination of contents with oil or fecal germs and destruction–destabi lization of buildings. To distinguish groundwater inundation losses from riverine losses, a survey campaign of households of catchments affected was taken as damage assessment (Kreibich and Thieken, 2008). The questionnaire contained questions addressing the characteristics flood losses, socioeconomic variables and specific criteria to identify cases affected only by groundwater inundation. These criteria consist, for example, of asking if water entered their buildings only from below and if the water level reached a maximum height above the ground surface.

To mitigate future groundwater flood losses, a comprehensive analysis of risks and of adequate risk management is required (Schanze et al., 2007). Managers adopting risk management practices for groundwater inundation should control five aspects: (1) risk identification of the events potentially harmful, (2) risk evaluation, in a qualitatively or quantitatively way, according to the probability or frequency of a given event and the magnitude of the damage which could produce due to high groundwater levels, (3) risk monitoring and control of groundwater levels, river stages, subsurface infrastructure characteristics (e.g. depth, distance to surface water, sealing, materials, toxicity hazard), precipitations, etc. as driving factors of harmful events, (4) Risk Management Planning establishing mitigation measures and design of a site-specific risk management plan, and (5) risk response planning where risk dealing procedures are specified and communicated.

The quantitative evaluation of risk should include numerical models reproducing the groundwater flooding processes to provide fundamental information for assessing damage and for developing new specific loss models (Kreibich and Thieken, 2008; Schinke et al., 2012). Surface and groundwater systems are often not separated systems and therefore have to be approached integrally, for example coupled surface and groundwater numerical models considering sewer system interactions have been used for assessing integrated flood risk management in Germany (Sommer et al., 2009). Nevertheless, groundwater models have demonstrated to be able to reproduce river–aquifer exchange fluxes when surface–groundwater exchange is produced mainly in the riverbed (Anderson, 2005; Doppler et al., 2007; Vázquez-Suñé et al., 2007). On the other hand, existing analytical solutions for transient stream–aquifer interaction have also been applied to reproduce flood wave response curves and to estimate hydraulic parameters (floodwave-response technique). The results obtained are different depending on the grade in which the ideal stream–aquifer relationship upon which the governing equation is based differs from reality. When the characteristics of the field problem fulfill the physical assumptions of the theoretic model, the analytic model can reproduce the observed response through all flood stages including rising limb, peak, and recession (Reynolds, 1987). In the literature, the successful application of floodwave-response technique in porous formations can be found in Ha et al. (2007), Mishra and Jain (1999), Pinder et al. (1969) and Reynolds (1987). The aquifers studied in these works showed a low variance (σ^2) in transmissivity (T) or storativity (S) fulfilling the physical assumptions of homogeneity. In particular, these works showed a $\sigma^2 < 0.36$ for the $\mathrm{Ln}\,T$ or $\mathrm{Ln}\,S$ distributions, even though the number of measurements were low ($n < 30$). In contrast, in instances where the aquifer is heterogeneous, boundaries are irregular, surface recharge occurs from precipitation or T/S changes with time, the observed floodwave-response deviates from the analytic models predictions. As an example, Vekerdy and Meijerink (1998) performed a statistical and analytical study of the flood-induced propagation of stage rises of the river Danube throughout the adjoining alluvial aquifer. This alluvial presents a higher variance of $\mathrm{Log}\,T$ ($\sigma^2 \cong 1$) compared to the previous works cited, and the formation could be classified as relatively heterogeneous (Dagan and Neuman, 2005; Rubin, 2003). This would explain, at least in part, the deviations observed from analytic models implemented, especially at more than 500 m from the Danube River where the deviation reached more than one meter. In addition, these authors also studied the head wave propagation induced by a flood event by describing the increase in lag times with the distance from the river along two sections perpendicular to the river over nine different flood events. Daily resolution hydrographs measured over 10 years from a relative dense piezometer network were used for lag correlation. The time lags obtained range from 1 to 10 days in the first 2 km up to 65 days at 8.8 km. This study also highlights the importance of river levels in the complex floodplain and the riverbed conductance of the silted-up branches of the flood plain during the rise of the flood.

The purpose of the present investigation was to evaluate the controlling factors which determine the groundwater regime during floods to quantify the effects on underground urban structures. This will provide the basis to improve flood risk management and corrective measure design. The investigations were performed in the Zaragoza metropolitan area (Spain), which is located on top of a heterogeneous alluvial aquifer subject to recharge induced by the Ebro River. In the recent years, an increasing number of complains referring to basement flooding (Martín, 2013; Valero, 2003) has caused local administrators (Zaragoza City Council) to create additional efforts in flood risk management (Álvarez-Rodríguez, 2002; TRAGSA, 2006). In this work, we used a calibrated groundwater numerical model to simulate 11 years of groundwater–river interaction to evaluate the groundwater inundation risks in the right margin of the Ebro River. This numerical approach was compared with an analytical approach by assessing the deviations obtained in flood wave response curves by assuming effective hydraulic properties for a representative flood event. Using the principle of superposition with two scenario head results obtained from the numerical model (with and without floods events) the flood signal was separated from the background hydraulic head distribution allowing us to reconstruct the kinematics of the head wavefronts induced by 18 specific flood events of interest along four transects. The flood events were chosen in order to be representative and to cover all the rating curve of Ebro River for the last 100 years in the city of Zaragoza. The interactions of these head wavefronts with subsurface structures have been evaluated and verified using available damage reports. Results obtained from numerical modeling were assessed statistically to identify the possible factors related to groundwater inundation and their relative importance. In this regard, we conducted a statistical analysis using Pearson correlation and regression methods to identify the factors affecting the velocity of the head wave and its implications