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Modelling and mitigation of storm-induced saltwater intrusion: Improvement of the resilience of coastal aquifers against marine floods by subsurface drainage

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A B S T R A C T

Storm-induced saltwater intrusion (SISWI) often starts with (i) overtopping/breaching of a coastal barrier followed by (ii) hinterland inundation and (iii) subsequent vertical seawater intrusion behind the barrier. Though these three processes are naturally successive, they are often analysed separately. However, the necessity of considering these processes as fully coupled has been increasingly recognised. This study, therefore, addresses the modelling of these processes in an integrated approach. The previous related studies are examined and four coupling scenarios are proposed. Thus, a new modelling scenario, utilising the model XBeach for simulating overtopping/breaching and subsequent flooding and SEAWAT for simulating the SISWI, is chosen for application to a case study in northern Germany. Moreover, the study addresses the mitigation of SISWI using a subsurface drainage network. The simulation results illustrate the high efficiency of such drainage in shortening the remediation time as well as in limiting salt intrusion to the deeper freshwater aquifers.

1. Introduction

In regions of limited surface water availability, groundwater resources are extremely important since they are often intensively used for drinking, domestic, irrigation or industrial purposes (Abdullah, 2017; Barlow and Reichard, 2010). Irrigational demands from aquifers, in general, account for ca. 70% of the world's freshwater usage (Narayan et al., 2007; Siebert et al., 2010; Walther et al., 2014). As more than 60% of the world's population lives within 100 km of coastlines, a large part of these demands are withdrawn from coastal aquifers (Yang et al., 2013; Tomaszkiewicz et al., 2014). The latter might explain why coastal aquifers have a special weightiness as freshwater sources, especially with the really limited surface water availability in coastal zones (Oude Essink, 2001). Moreover, demographic studies (e.g. Neumann et al., 2015) as well as the United Nations Environment Programme (UNEP) predict that the percentage of the nearshore population will increase from 60% to 75% by 2020, which might lead to an overexploitation of the freshwater aquifers (Kalaoun et al., 2016). Besides the latter effect of dense population on coastal aquifers, extreme storm surges and tropical storms are among the main indirect threats to coastal aquifers since any subsequent coastal flood might be a real source of coastal aquifers contamination (Holding and Allen, 2015; Williams, 2010; Yang et al., 2015a, 2015b, 2013). In fact, coastal areas and coastal aquifers are highly vulnerable environments and may experience severe impacts from coastal storms (Yu et al., 2016b; Elsayed and Oumeraci, 2017c). With global warming and sea level rise (SLR), many coastal systems may experience accelerated coastal erosion, coastal barrier breaching, coastal flooding and subsequent seawater intrusion into fresh groundwater (Elsayed and Oumeraci, 2016a, 2016b; Giambastiani et al., 2017; Ranasinghe, 2016; Taylor et al., 2012). Changing climate might lead to changes in the frequency, intensity, spatial extent, duration and timing of weather events, possibly resulting in unprecedented extreme events (de Winter and Ruessink, 2017; Parry et al., 2007; Stocker et al., 2014; Vousdoukas et al., 2017). Therefore, coastal barriers such as dunes, dykes and other engineered structures are often required. However, marine floods resulting from the overtopping/breaching of coastal barriers during extreme storm surges, besides being a threat to people, assets and further resources onshore, may result

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in SWI into coastal aquifers induced by the vertical infiltration of saltwater behind the overtopped/breached coastal barriers (Chaumillon et al., 2017; Steyer et al., 2007; Villholth and Neupane, 2011; Williams, 2010; Yang et al., 2015a, 2015b, 2013; Yu et al., 2016b). Vertical SWI contaminates the originally fresh groundwater by increasing its salinity (Elsayed and Oumeraci, 2016b; Mahmoodzadeh and Karamouz, 2017; Post and Houben, 2017). This may thus significantly reduce the water quality and the environmental values of groundwater and may possibly hinder any possible sustainable development in coastal zones exposed to coastal flooding.

Mainly, the four reasons R1 - R4 illustrated in Fig. 1 may lead to SWI in coastal aquifers. The first three reasons (R1 – R3) are mainly related to the hydraulic interconnection between seawater and groundwater. In fact, the mean sea level (MSL) and the groundwater table (GWT) in aquifers are interconnected like in a U-tube manometer as shown in Fig. 2 a. The location of the salt-freshwater interface (sea water in red colour inside the U-tube and freshwater in sky blue colour) depends indeed on the head difference Δh between MSL and GWT. The value of Δh increases spatially landward and thus results in lowering the interface in the same direction ($h = 40.\Delta h$ according to Herzberg, 1901).

In the case of a long-term SLR (i.e. R1) induced by global warming, for instance, the hydraulic head Δh decreases. As a result, the interface moves landward (as shown in Fig. 2 b throughout the black dashed line) to satisfy again the hydrostatic equilibrium. Such lateral shift of the interface represents a lateral seawater intrusion (see e.g. Ketabchi et al., 2016; Mahmoodzadeh and Karamouz, 2017). The same type of intrusion may take place (as shown in Fig. 2 b by the blue dashed line) if the GWT decreases (i.e. R2) due either to reduced rainfall rates or to human activities such as excessive pumping (e.g. Mishra and Dwibedy, 2015). Reason R3 related to local lateral intrusion (upconing) represents a special case of R2 that can take place in the case of a local lowering of the GWT under excessive pumping effect, leading to a local shift of the interface that often takes the form of an inverted cone (e.g. Werner et al., 2009).

The fourth reason (R4) related to coastal flooding represents the most complex type of intrusion. The complexity arises indeed from the high diversity of the involved processes and interactions. In fact, different flood paths might be possible: (i) direct inundation in the case without coastal defences as it is often the case in atoll islands under overwash events (e.g. Chui and Terry, 2015; Oberle et al., 2017; Gingerich et al., 2017), (ii) flooding through a coastal barrier breach, and (iii) inundation induced by overtopping/overflow over a coastal barrier. Moreover, different flow domains are involved starting from the sea where waves propagate toward the coastal barriers, which might result in overtopping and/or breaching, thus leading to coastal floods behind the barriers and subsequently to SWI due to the infiltrating seawater in the hinterland (Elsayed, 2017). On the other hand, diverse processes are involved (e.g. coastal hydrodynamics, sediment transport, soil avalanching on barriers' slopes and/or from breaching wedges, surface runoff of seawater over the hinterland and subsurface flow of the infiltrating seawater to the groundwater aquifers). In addition, several interactions among the latter processes exist. For instance, the breaching of a coastal barrier represents the outcome of complex interactions between nearshore hydrodynamics, coastal sediment transport and morphodynamics as well as soil avalanching from the barrier front and/or breaching wedges (Elsayed and Oumeraci, 2016a). Moreover, propagation of saltwater over the hinterland and subsequent infiltration to aquifers represent a surface-subsurface interacting transport of a conservative solute (Holding and Allen, 2015; Mahmoodzadeh and Karamouz, 2017; Violette et al., 2009; Werner et al., 2013; Wilson et al., 2011; Yang et al., 2015a, 2015b, 2013; Yu et al., 2016b).

The overtopping/breaching of a coastal barrier, the induced inundation and the subsequent SWI are naturally successive processes. Therefore, fluxes of water are continuous between the breach-induced inlet, the surface flow propagation and the subsurface intrusion, so that the flow through breaches represents the source for both surface runoff behind the breached barrier and the

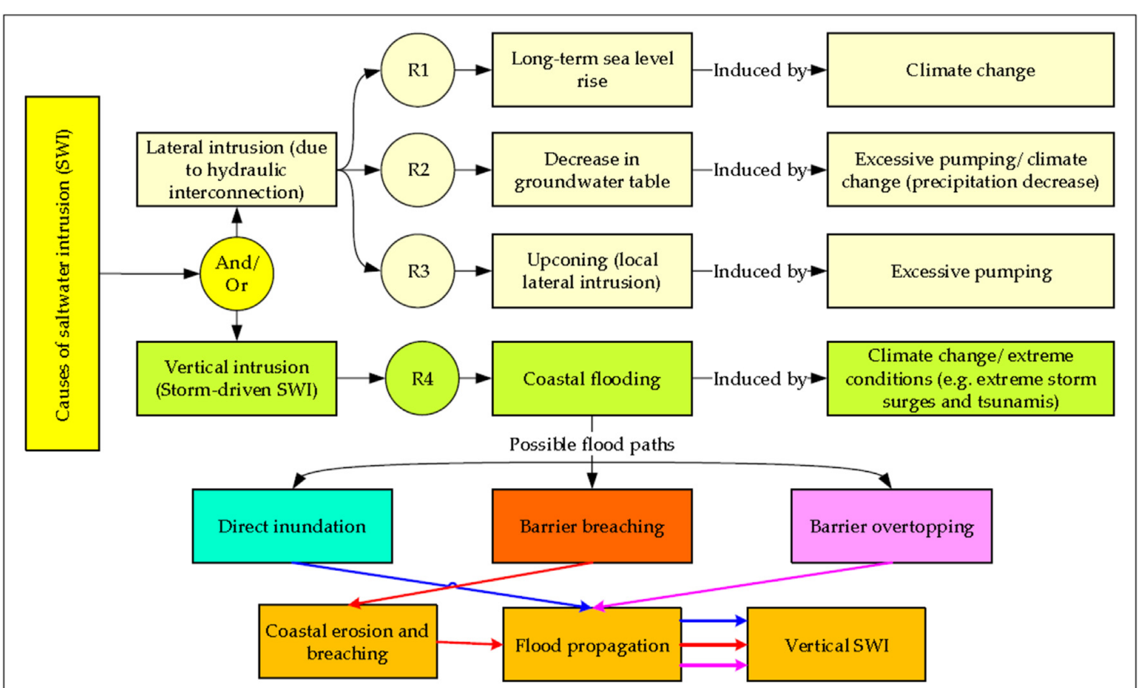

Fig. 1. Common reasons and involved processes in saltwater intrusion (SWI) into fresh coastal aquifers.