Aquifer contamination by coastal floods in the plain of Costa da Caparica, Almada, Portugal

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Abstract.

Climate change might lead to sea level rise, changes in the frequency, intensity and duration of wave storms, which will lead to an increase of coastal flooding events. One of the most important long-term effect of coastal floods is saltwater intrusion induced by the vertical infiltration of the salt water behind the overtopped and/or breached coastal barriers. A single overflow event may contaminate the freshwater aquifer for several years until it is remediated naturally under the effect of precipitation and subsequent seaward directed flow.

The main objective of this study is to understand the effects of a maritime storm and the induced hinterland inundation on the water quality of a coastal aquifer. The study targets the municipality of Almada (Portugal) which has an extensive coastline, with coastal aquifers with high susceptibility to contamination, namely the unconfined aquifer of the coastal plain of Costa da Caparica.

Groundwater flow modelling and mass transport in the aquifer were modelled using the MODFLOW and MT3DMS software. The aquifer contamination by an overflow was modelled considering wave overtopping and flooded area on the coast was estimated from previous works that coupled a wave transformation model (SWAN) with a high-resolution swash model (XBEACH). The extent of the subsurface contamination is a function of the flood extent.

Results showed that at an extreme storm event, waves can overtop the coastal dune causing a coastal flood that extends approximately 160 meters inland with a significant increase in chlorine concentration in the aquifer. Recover of the aquifer to previous concentrations was found to take several years.

Keywords: Coastal Flood, Coastal Aquifer, Salinization, Numerical Modeling, Mass Transport.

1 Introduction

Coastal aquifers are highly susceptible to several natural and anthropic related environmental changes such as sea level rise, reduction of recharge, pollution or coastal floods by wave overwash. These latter processes can induce significant saltwater intrusion in freshwater aquifers (Elsayed & Oumeraci, 2017). Contamination of groundwater by infiltration of seawater is a consequence that deserves attention.

In the coastal region of the municipality of Almada, there is an unconfined aquifer developed in sandy sediments that is exploited for irrigation purposes. This aquifer presents high susceptibility to contamination, especially in relation to the advance of the salt wedge, caused by sea level rise and overexploitation. Coastal flooding events can also have a significative impact, because they are fast and cover vast areas of infiltration. The salinization of the aquifer can undermine local economic activity linked to agriculture and the exploitation of groundwater in shallow wells.

The main objective of this study is to understand the effects of a extreme maritime storm and the associated hinterland inundation on the water quality of a coastal aquifer. The study targets the municipality of Almada (Portugal).

The municipality of Almada is located on the central coast of mainland Portugal, on the left margin of the Tagus River (NW region of the Setúbal Peninsula), Setúbal district. The plain of Costa da Caparica is located on the NW extreme of the municipality. It is limited by the Tagus River (and its estuary) at the north and at west by the Atlantic Ocean, and by a cliff at east (Figure 1).

The regional climate is marked by an oceanic regime with warm winters and hot summers, by proximity to the Atlantic Ocean (and whose weak annual thermal amplitude allows a regularization of temperature throughout the year). The annual average temperature is between 16 and 17.5 º C, and the average annual precipitation between 500 and 700 mm (in Caria *et al.*, 2013). During the winter period the plain of Costa da Caparica is recurrently affected by wave overtopping, with consequent flooding of inland areas.

The plain of Costa da Caparica is formed by deposits composed of dune sands, slope deposits and alluviums and / or landfills of Pliocene - Holocene (Pais *et al.*, 2006). Those deposits cover sedimentary formations of the Miocene also represented on the eastern cliff. The Miocene formations correspond to continental deposits alternated by other marine ones, characteristic of a broad alluvial plain in the form of an estuary, subject to transgressions.

The aquifer developed in Pliocene - Holocene deposits is unconfined, with thickness between 20 m – 25 m. The hydraulic conductivity of the formations varies from 3.4 m/day to 4.5 m/day, and Ferreira (2012) estimated an average value of 704 m^2/day for the transmissivity. The aquifer receives direct recharge from precipitation, around 250 mm per year, and lateral recharge from the Miocene formations at east (Ferreira, 2012) but the amount of the water transfer is not well known.

2 Materials and Methods

To achieve the objectives, the groundwater level and flow in the coastal aquifer were modelled using the MODFLOW software. The mass (chloride concentration) transport using the MT3D allowed to understand the aquifer contamination associated with floods during storm events. Both softwares are compiled by the Processing

Modflow (PMWIN) software (Version 5.3.1, by W. H. Chiang and W. Kinzelbach, 2001).

The aquifer was simulated in 3D and at steady-state regime, using a difference element mesh and one unconfined layer with 20 m of thickness. The mesh is composed by 440 columns and 430 lines with variable cells width (10, 5 and 2.5 meter) with higher resolution in the area affected by floods. The boundary conditions define the groundwater influx from the east, from the Miocene aquifers, and the constant head at sea side. The hydraulic conductivity of the layer was obtained by interpolation (inverse distance method) of values obtained through granulometric analysis of selected samples (equivalent diameter) and varies between 0.035 and 0.028 m/s (Figure 1). Considering the sandy composition of the plain aquifer a porosity value of 0.25 was assumed. The recharge by precipitation was obtained from Caria (2012, 2013) and ranges from 0 to 254 mm per year (Figure 1). The zero represents the impermeable zones (anthropic uses and actions), while the higher permeable zones are associated to agricultural land. The initial hydraulic heads, interpolated by kriging, are represented in Figure 1; the water level varies from 4.43 m at east to close to 0 m (mean sea level).

The mass transport model was simulated in transient regime for a particular section of the model (location in Figure 1), representing the area flooded during the storm on 8 - 10 of February of 2014. The highest volume of flood was estimated in 0.2 L/m/s, coupling a wave transformation model (SWAN) with a high-resolution swash model (XBEACH), (Pires, 2017). The extension of the flood was estimated in approximately 162 m inland, considering a wave overtopping of 600 seconds. The initial conditions for the chloride concentration were assumed as 60 mg/L for the regional groundwater, 5 mg/L for rain water and 20,000 mg/L for sea water. The simulation was carried out in two steps: the first consider the infiltration of the seawater on the top of the layer, representing a flood of 1 day; the second is equivalent to the period of natural remediation, and the chloride concentration was simulated for different periods (stress periods), 1, 2 and 5 years), to understand how long the aquifer will takes to recover.

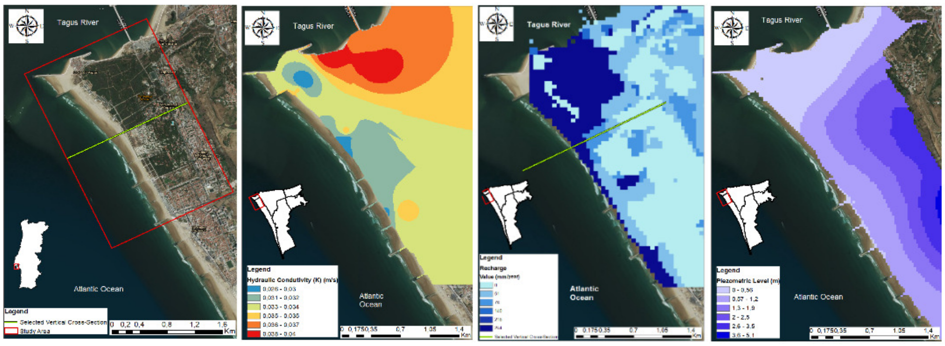

Figure 1 – Location and limits of the study area; spatial distribution of the hydraulic condutivity; variation of the direct recharge of the aquifer; piezometric map of the study area; (from left to right).

3 Results and Discussion

3.1 Groundwater flow modelling

The aquifer numerical modeling show that the groundwater flows from east to west into the sea, corroborating the results of Ferreira (2012) and Storm (2014). Figure 2 show a cross section of the simulated groundwater level in the aquifer, at steady-state conditions. It is possible to see that the infiltration of the seawater in the inundated area causes a rise in the groundwater level, that can be higher than the beach profile. In this simulation the piezometric level varies between 5 m at east and 0.16 m at the beach. The second simulation shows (Figure 3) that the heads recover when the storm ends and return to the normal values, i.e., 0 m close to the sea.

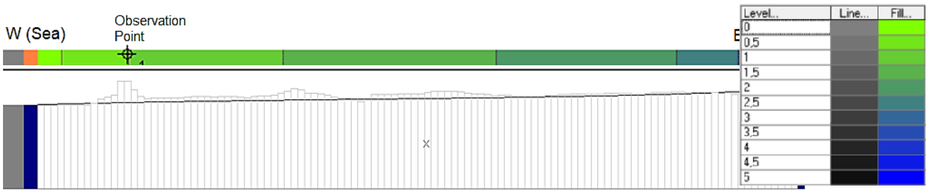

Figure 2 - Vertical section of the aquifer with the simulated piezometric level (dark line), when wave overtopping occurs on the study area (stress period 1).

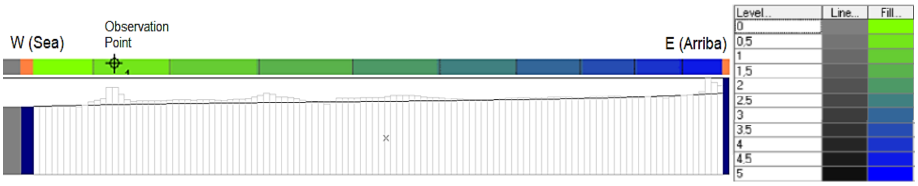

Figure 3 - Vertical section of the aquifer with the simulated piezometric level (dark line), after the storm (stress period 2).

3.2 Mass Transport Modelling

The mass transport modelling results, in transient regime and two steps, are represented in Figures 4 and 5. The first simulation corresponds to the flood period, with an inundation period of 1 day; the second concerns to the evaluation of the time the aquifer needs to recover from seawater contamination during the flood.

At an observation point in the aquifer (⌖), located at the limit of the flooded area, it is possible to see that the concentration simulated in the aquifer after 1 day of flood is 19,177 mg/L (stress period 1; Figure 4).

The evolution of the chloride concentration in the aquifer over time, at the observation point, can be seen in Figures 5 and 6 where is clear that the aquifer needs several years to recover the groundwater quality. At the time steps length of 1 to 5 years, the simulated chloride concentration at the observation point will be 318, 84 and 67 mg/L, respectively.

Figure 4 – Vertical section of the aquifer with the simulated chloride concentration in observation point after 1 day of flood; square represents the aquifer zone in Figure 5; dark line is the groundwater level.

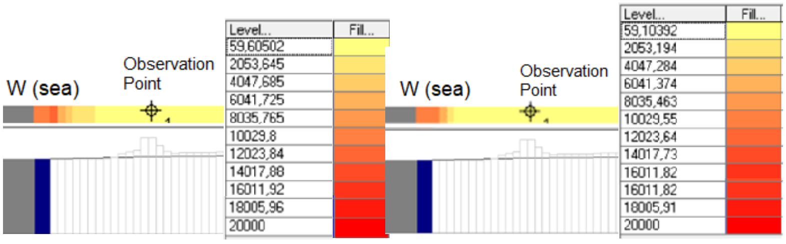

Figure 5 - Vertical section of the aquifer zone, delimited in Figure 4, with the simulated chloride concentration after 1 year, 2 years and 5 years of the storm; dark line is the groundwater level.

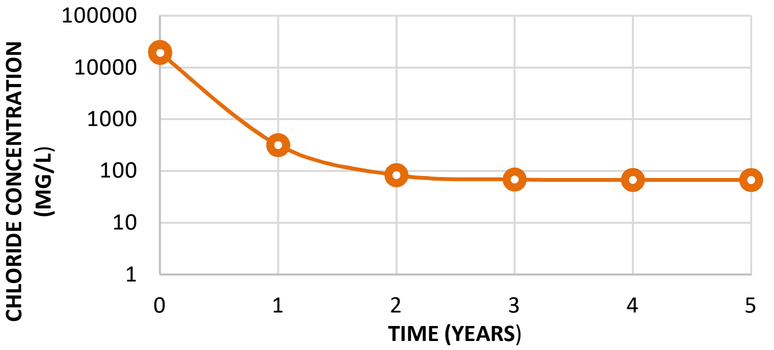

Figure 6 - Chloride concentration calculated on the vertical cross- section, after the wave overtopping occurs on the study area, versus time (years).

4 Concluding Remarks

The numerical simulation of the flow model and mass transport of the unconfined aquifer of the Costa da Caparica Plain shows that the coastal flood associated with extreme events can lead to the contamination of the aquifer over a long period of time.

During a storm, a wave with a flow rate of 0.2 L/m/s can cause a wave overtopping that reaches approximately 160 meters in land. The infiltrated seawater can contaminate the aquifer for a period that can reach several years.

Acknowledgements

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