October, 7 2017

**Re: Response to the review of Anonymous Referee #3 of the manuscript "Groundwater withdrawal in randomly heterogeneous coastal aquifers" by Martina Siena and Monica Riva.**

We appreciate the efforts Anonymous Referee #3 has invested in our manuscript and we are grateful for his/her insightful comments.

> *The authors study seawater intrusion in a three-dimensional heterogeneous aquifer using a stochastic approach. The aquifer characteristics are inspired by the Argentona aquifer in the Maresme region of Catalonia, Spain. The authors investigate the joint effect of heterogeneity and groundwater withdrawal on the width of the mixing zone and toe position (defined in terms of salt concentration isoline) of the saltwater wedge in a fully coupled variable density flow and transport scenario. First the authors consider the impact of heterogeneity on mixing zone and toe confirming the finding of previous studies. Then the effect of three different pumping scenarios is studied. Scenarios S1 and S2 pump at a location landward outside the transition zone between sea and freshwater, S3 is located within the transition zone. In S1, the well is screened in the upper part of the aquifer, for S2 and S3 and additional screen is added in the lower part of the aquifer. It is found that S1 and S2 cause the toe to move inland and spread at the aquifer bottom while the width of the mixing zone is not affected much. For S3 in contrary, the toe location moves seaward rapidly and then stabilises. The width of the mixing zone initially increases and then decrease toward a stable value of the order of the value without pumping. It is concluded that S3 is the most efficient scenario in reducing toe penetration. Heterogeneity leads to a reduced toe penetration for S1 and S1 compared to the equivalent homogeneous scenario, while it is similar for S3. The ensemble averaged concentration field leads consistently to an overestimation of the mixing zone as observed without pumping. The numerical Monte-Carlo analysis is sound.*

We thank the Reviewer for his/her appreciation of our work.

> *However, while the authors provide a thorough literature review in the Introduction, it does not become clear, which are the open questions that are addressed in the manuscript compared to the state of the art. This is of particular interest because many aspects of heterogeneity and pumping in variable density scenarios have been discussed in the literature. This is the case, for example for the effect of three-dimensional heterogeneity in Section 3.1. Thus, the authors should make an additional effort of identifying the knowledge gaps in the light of the state of the art, formulate their research objectives and clearly indicate which of their findings go beyond the state of the art.*

We thank the Reviewer for his/her very interesting and challenging comments. In the literature there is a quite vast number of contributions dealing with SWI in homogeneous and heterogeneous systems. Most of these contributions (a) deal with deterministic approaches, where the attributes of the system (e.g., permeability) are known (or determined via an inverse modeling procedure), so that (b) the impact of uncertainty of system attributes on target environmental (or engineering) performance metrics is not truly considered. This is in stark contrast with the widely documented and recognized issue that a complete knowledge of aquifer properties is not possible. In this context, the inherent uncertainty associated with aquifer systems must be considered, this objective being achieved framing our analyses within a stochastic approach. The latter enables us not only to provide predictions of an output quantity of interest, but also to quantify the uncertainty associated with such predictions, to be used (for example) in environmental risk assessment and probabilistic management and protection protocols for water resources. Our work is precisely set in this framework. Only a few contributions studying SWI within a stochastic framework have been published to date (less than 20 ISI-ranked papers). Amongst these, the studies most relevant to our work have been listed in the Introduction of the manuscript. It has to be noted that the vast majority of these works consider idealized synthetic showcases and/or simplified systems (typically in a two-dimensional context) and/or simple flow conditions (usually steady state mean uniform flow). In this context, considering the very limited number of stochastic studies, we are convinced that our work is markedly relevant to show the way stochastic approaches can find their place in the assessment of real settings. Key elements of novelty in our work include the introduction and the detailed analysis of an original set of metrics, aimed at characterizing quantitatively the effects of heterogeneity on the extent of seawater wedge penetration and of the seawater/freshwater mixing zone. These metrics yield a quantitative depiction of SWI in a global sense across a three-dimensional system (not only at the bottom of the aquifer and/or along the vertical direction, as is usually done in the literature). Additionally, the effects of pumping on SWI are investigated by comparing three diverse withdrawal scenarios. These are designed by varying the distance of the wellbore from the coastline and from the freshwater-saltwater mixing zone. While the effectiveness of simultaneous pumping of freshwater and seawater to reduce SWI has been already investigated in the literature (e.g., Aliewi et al., 2001, Pool and Carrera, 2009, and Saravanan et al., 2014; as we clearly state in Section 1 of our manuscript), it has to be noted that in this work we evaluate for the first time the effectiveness of the so-called “negative barriers” in limiting intrusion within a randomly heterogeneous aquifer. We will further stress the aspects of novelty of our contribution in the revised manuscript.