Authors' Response to the first Referee's Interactive Comment on "*Intensively exploited Mediterranean aquifers: resilience to seawater intrusion and proximity to critical points*" by K. Mazi et al.

First, regarding the recommended publications, which we have consulted, we wish to point out that they concern aquifers on a *horizontal base,* while the characteristic feature of our model (correctly summarised by the Referee) is a *sloping aquifer base.* However, we now refer (Appendix L 764-767) to Kacimov et al. "Control of sea-water intrusion by salt-water pumping: Coast of Oman", Hydrogeology J., 2009, v.17, 541-548 DOI 10.1007/s10040-008-0425-8, noting the special conditions that can arise when pumping and evaporation coexist.

Abstract:

We have adopted all suggestions by the Referee, and in L 41 we have also replaced "advance of" by "intruding".

1. **Introduction**:

L 64-65 "sea intrusion changes" has been replaced by "changes of seawater intrusion", and generally, "sea intrusion" has been replaced throughout the manuscript by the better term "seawater intrusion", as recommended by the Referee.

2. **Materials and Methods**

L 139-142 "The depth of the aquifer at the Mediterranean coast can reach 1000 m, but near Cairo it is about 200 m (Sherif, 1999)." reads now

"The aquifer depth at the Mediterranean coast increases from west to east from ca. 600 m to ca. 1000 m, near Cairo it is about 200 m and at its apex drops to under 100 m (Sherif, 1999; Sherif and Singh, 1999)."

L 144-145 "Groundwater flows in a radial pattern from the apex of the Delta to the sea…" has been replaced by "Groundwater flows from the apex of the Delta in a roughly radial pattern (in plan view) to the sea…"

L 151 starts now as follows: "An accurate balance…" as proposed by the Referee.

The beginning of *2.1.2 The Israel Coastal Aquifer (ICA)* has been changed, by combining the first two paragraphs into one and by editing the text. Please consult the revised manuscript.

2.1.4 Aquifer Similarities and Differences

L 262 The term "dispersed" has been replaced by "distributed".

L 280-281 The phrase "No boundary inflows replenish the aquifer" has been replaced by "No inflows occur through the land boundary."

L 282 The statement "reaches today to 2.5 km" reads now "reaches today up to 2.5 km"

3. **Results**

L 313 We fully agree with the Referee that variable-density models require more and hard-to-find parameters; we have added "and particularly the aquifer's dispersive properties"

L 321 We have replaced the term "first-order" with "screening-level" assessments.

(old) **L 335** The term *hydrodynamic defect* has been eliminated; a more explicit description of the correction for the gap has been added in the paragraph **L 333-351**.

(old) **L 348** The reference to *high non-linearity* has been eliminated; the new text, **L 348-349**, reads: "…the aquifer's highly non-linear response to seawater intrusion…"

L 348-349: We do not disagree with the Referee with respect to the theory of catastrophes, but we use the term *tipping points* (common in environmental sciences) in our relevant paper Mazi et al. (ERL, 2013), so its continued use in this manuscript makes sense.

L 365-366 on the Referee's comment regarding the submarine discharge: The new text reads "and the important (Destouni et al., 2008) but hard to determine in the field (Prieto and Destouni, 2011) submarine discharge, q_{SD}."

(new) **L 414** "TDS" has been added; we thank the Referee for pointing out this omission.

(new) **L 472** We hope that the text is clearer, after removing "and illustrate in the following".

3.1 Model result interpretation of critical intrusion points

We agree with the analysis of the Referee regarding the approximation due to the Dupuit assumption and the resulting solutions that are based on the Dupuit-Forchheimer theory. However, our solution is based entirely on the D-F theory and is consistent with it, because we study planar flow in the vertical plane, without considering variation in the transverse direction (parallel to the coastline), for which reason we use a *gallery of wells*, not *point sinks*. In contrast, the well-known analysis of Struck (1989), mentioned by the Referee, deals with 2-D flow patterns in plan view caused by the presence of point sinks (separatrix, etc.). We also do not take transient flow into account, nor do we deal with the convective cell in the vertical plane –probably first articulated by Cooper (1964) and demonstrated by Henry (1964)– that brings salt to the transition zone (we mention this in Koussis et al., submitted).

4. Conclusions

L 644-647: In response to the Referee's comment that the last sentence of the first paragraph was unclear, we have restated it as follows: "The measure of moving pumping locations more inland beyond the limiting location of the prevailing groundwater divide in a coastal aquifer will offer no gain in more exploitable water volume or improved aquifer protection from seawater intrusion."

Appendix A

L 680 Again, we concur with the Referee that the sea does not always constitute a constant-head boundary. However, Chapter 7 in Strack (1989), to which the Referee refers, "*deals exclusively with 2-D flow in the vertical plane*", while we consider the flow as 1-D by virtue of the D-F assumption.

L 764-767: We have added the following text: "Finally, for the case of a shallow horizontal coastal aquifer, under exploitation and negative recharge (evaporation), we refer the reader to the analytical solution of Kacimov *et al*. (2009), who also showed that under extreme conditions, even a gap separating the saturated fresh and saline groundwater zones forms."

Authors' Response to the second Referee's Interactive Comment on "*Intensively exploited Mediterranean aquifers: resilience to seawater intrusion and proximity to critical points*" by K. Mazi et al.

Title:

The title has been changed slightly; see above.

4. Introduction:

L 94-95 We have added "…in terms of pumping location and rate of extraction" to more fully describe the parameters included in our investigations, as requested by the Referee.

Please note that the model that we use is completely analytical (not quasi-analytical), and it was introduced by Koussis et al. (2012) and further developed by Mazi et al. (2013).

We respond to the Referee's comments regarding the Figures farther below (see heading).

3.2 Analytical Approach

L 377-380 Response to the Referee's requested clarification regarding dimensionality: "We note that, due to considering a vertical plane (see Appendix), all flows are per unit width perpendicular to the aquifer plane (or parallel to the coastline), i.e., the flow units are m^3/m per unit time (day or year)."

REFERENCES

We wish to clarify that our publication Mazi et al. 2013. Tipping points for seawater intrusion in coastal aquifers under rising sea level, *Environ. Res. Lett.* **8** 014001, presents only generic applications. It does not deal with applications in real coastal aquifers, with actual hydrologic data. It introduces the concept of *tipping points* in SWI, applying it to climate-change stress conditions (sea level rise, decline of submarine discharge and decline of boundary head) for two types of regimes (flux- and head-control), also performing a parameter sensitivity study (hydraulic conductivity, slope, aquifer depth at the sea and sea salinity). In contrast, the current manuscript concerns real applications, quantifies aquifer resilience/vulnerability to actual current and to future seawater intrusion forcing, and identifies two different critical SWI limits under groundwater exploitation and/or climatic stress, adding to the tipping-points analysis in Mazi et al. (2013). We believe that the main points of the manuscript are presented clearly already in the Abstract, about which the Referee writes "The abstract is concise and (but) informative enough, and to the point. It covers (briefly): the study sites, concepts & methods of analyses, and also the main results (qualitatively)."

Regarding the presentation of the mathematical model *per se* (Appendix), please note that only the derivation of Eq. A6 is new, and now also the reference to the study of Kacimov et al. (2009) at the end. However, we believe that a terse but content-rich description is useful to the reader who may not be interested in the mathematical details yet wishes to understand the level of modelling complexity.

The paper by Koussis et al. (submitted) has no overlap with the present ms. It deals with a specific feature of the hydraulics/hydrodynamics of SWI, as is evident from its title.

Finally, in the revised ms, L 242-243, we refer to Milnes. 2011. Process-based groundwater salinisation risk assessment methodology: Application to the Akrotiri aquifer (Southern Cyprus), *J. Hydrol.*, **399,** 29–47, as additional source of information on the Akrotiri aquifer, Cyprus. The papers by Chang & Yeh (2010) and by Al-Bitar & Ababou (2005) deal with the heterogeneity of aquifers in a stochastic framework and do not pertain directly to our work here. Please note that the authors and co-workers have performed Monte Carlo simulations in the case of the Akrotiri aquifer (see among the References, Koussis (Ed.) (2001), Koussis, A.D. et al. (2010a, b), Prieto et al. (2006), and Prieto & Destouni (2005)), however, we do not refer to the stochastic aspect of these works in our ms.

FIGURES

Fig. 3 As requested, textures have been replaced by greyscales and legends have been enlarged, however, the final size of the figures will be determined by HESS.

Figs. 4 & 5 The Referee's interpretation is correct that the abscissa is the freshwater discharge to the sea; more precisely, it is its absolute and normalized value. The distance of the toe from the coastline, the ordinant, is also normalized.

Fig. 6 This figure shows the variation of the normalized toe location with the normalized remaining groundwater flow from the pumping location q_{norm}. Please note that q_{norm} is not the normalized "*remaining submarine flow to the sea*".

Regarding the "pumping well", we wish to point out that we have explicitly stated already in the main text (L 358-361, not only in the Appendix) that "the model solution can account for groundwater pumping in a collector trough (line sink, or well gallery)". Obviously, the distribution of pumping wells in an actual field will not conform to this idealization. This configuration, however, is necessary for obtaining analytical solutions in a ***sloping*** aquifer (it eliminates the transverse direction and thus the azimuthal variation of the gravitational flow component). We wish to reiterate that the applications of our model target screening-level assessments and aim at understanding the general functioning of a regional coastal aquifer under various stresses; this is also compatible with the assumption of the sharp interface as well as with the schematizing of the aquifer as having a constant base slope.