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# Groundwater pumping in head-controlled coastal systems: The role of lateral boundaries in quantifying the interface toe location and maximum pumping rate

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## SUMMARY

The current study explores quantitatively the impact of lateral impermeable boundaries on groundwater pumping in head-controlled coastal systems, based on the potential theory and the image-well superposition method. We compare the interface toe location and maximum pumping rate among three scenarios that assume (S1) an infinite domain width and a finite domain length, (S2) a finite domain width and length, and (SS) an infinite domain width and length. Focusing exclusively on boundary effects, the upstream freshwater discharge is assumed the same for all scenarios, regardless of the variation in domain size. It is found that the impact from both inland and lateral boundaries could play a significant role on the interface toe location and maximum pumping rate (defined as the maximum allowable pumping rate that will not lead to pumping saltwater), depending on sizes of domain length and width. Since the impacts of inland fixed-head boundary and lateral impermeable boundaries are contrary on the maximum interface toe location (defined as the farthest inland point of the interface toe under pumping condition) and maximum pumping rate, they can be offset under certain critical conditions such that the results of the two quantitative indictors (i.e. the maximum interface toe location and maximum pumping rate) in S2 are close to those in SS. In particular, a linear equation is derived to reflect the relationship between the domain width and length under such critical conditions and expressed as $L^* = 0.87W^* + 0.62$ ($W^* > 1$ or $L^* > 1.5$), in which $W^*$ and $L^*$ are the domain width and length normalized by the distance between the coastline and pumping well. When $L^* > 0.87W^* + 0.62$, the impact from lateral overcomes that from inland, producing a larger maximum interface toe location and a lower maximum pumping rate than those in SS. When $L^* < 0.87W^* + 0.62$, by contrast, the impact from inland exceeds that from lateral and hence, resulting in a smaller maximum interface toe location and a higher maximum pumping rate. It is expected that the results developed in the current study could support the design of numerical models and 3D laboratory experiments as well as the assessment of domain size impact on pumping in head-controlled coastal groundwater systems.

## 1. Introduction

Coastal aquifers serve as major sources for freshwater supply in many countries around the world, supporting the needs of agriculture, industry and communities. Consequently, they need to be well protected from being contaminated, from the perspective of water resources management. One of the main causal factors of contamination is aquifer salinization due to seawater intrusion, a worldwide issue triggered by individual or combined effects of climate change, groundwater pumping, and sea-level rise (Werner et al., 2013). Once a coastal aquifer is salinized, the cost required to restore to its original condition may be very high (Bear et al., 1999).

The impact of groundwater pumping on seawater intrusion has been investigated extensively in recent decades (e.g., Strack, 1976; Rejani et al., 2008; Park et al., 2009; Ferguson and Gleeson, 2012; Langevin and Zygnerski, 2013), since such a human activity may lead to the occurrence of aquifer salinization within a short timescale, in comparison to other causal factors such as sea-level rise. It is believed that a critical pumping rate exists, below which the pumping well can produce fresh groundwater sustainably (Strack, 1976). This critical pumping rate is therefore considered theoretically as the maximum allowable pumping rate, which can be derived analytically or numerically, depending on the complexity of the scenario (e.g., Strack, 1976; Pool and Carrera, 2010;

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Koussis et al., 2012; Kaleris and Ziogas, 2013; Lu et al., 2013a). Despite pumping limits in most of coastal aquifers, overexploitation is still occurring (e.g., Rejani et al., 2008; Lu et al., 2013c), giving rise to the attention of water resources managers. Based on the analytical expression of the interface toe location, a number of optimization methods have been employed either to optimize well locations under the specified total pumping rate or to explore the maximum total pumping rate under the specified well locations (e.g., Cheng et al., 2000; Mantoglou, 2003; Ataie-Ashtiani and Ketabchi, 2011). Moreover, several engineering strategies using double wells (Pool and Carrera, 2010; Lu et al., 2013a) or a cut-off wall (e.g., Kaleris and Ziogas, 2013) have been introduced to enhance groundwater extraction. These optimization methods and novel engineering strategies provide possible solutions for the increasing demand of coastal groundwater production.

The geologic and hydrologic settings of coastal groundwater systems play an important role in assessing the impact of well pumping on the maximum pumping rate and the interface toe location. Considering a simplified conceptual model as used in the study of Strack (1976), a higher hydraulic conductivity, sea level above the aquifer base (for unconfined aquifers or aquifer thickness for confined aquifers) or/and a lower upstream freshwater discharge rate result in a more inland location of interface toe under a given pumping rate, and thus a lower maximum pumping rate. In addition to theoretical studies, these factors have been evaluated at particular sites (e.g., Ferguson and Gleeson, 2012; Kerrou et al., 2013; Lu et al., 2013c), providing insights for local and regional water resources management.

In contrast to hydrogeologic factors mentioned above, the impact from boundary conditions has occasionally been considered in previous studies of coastal well pumping (Lu et al., 2012). Physically, a fixed-flux inland boundary (or flux-controlled coastal system) represents a system that has a constant upstream discharge, regardless of the upstream water table variation. Conversely, in a head-controlled system the upstream water table at a specified distance is fixed such that an increase in the pumping rate will result in an increase in the upstream discharge, because of a larger hydraulic gradient developed between the inland boundary and the pumping well. With no doubt, the former system is more vulnerable to groundwater pumping (Lu et al., 2012, 2013b). Despite flux-controlled coastal systems assumed in most of previous studies, head-controlled systems are often neglected in assessing coastal aquifer vulnerability to groundwater pumping (e.g., Ferguson and Gleeson, 2012), which may be formed due to a head-controlling feature in the landscape such as a river, lake, etc. Neglecting these features in conceptual models may lead to an overestimate of seawater intrusion and an underestimate of the maximum pumping rate. As pointed out by Lu et al. (2013b), in reality, inland boundary conditions are likely fall between the two extremes of constant flux (or fixed flux) and constant head (or fixed head), and therefore, it is necessary to consider both boundary conditions (flux-controlled and head-controlled) to evaluate the vulnerability of coastal aquifers to groundwater pumping and sea-level rise. Werner and Simmons (2009) also highlighted the importance of different boundary conditions in assessing the impact of sea-level rise on seawater intrusion. Recently, Lu et al. (2012) derived a closed-form analytical solution for the maximum pumping rate of a well in a head-controlled coastal system. Comparison between the solutions of the two different inland boundary conditions (i.e. fixed head and fixed flux) indicated that the effect of setting different boundary conditions on the maximum pumping rate becomes insignificant, when the length of the model domain is five times greater than the distance between the well and coastline (Lu et al., 2012).

In comparison to inland boundary conditions, quantitative impacts of lateral boundaries on the interface toe location and maximum pumping rate have much less been studied probably owing to that analytical solutions can be more easily derived by assuming an infinitely large domain width (Lu et al., 2012). As indicated by Mantoglou (2003), however, coastal aquifers in most cases are of finite size. In other words, the boundary effects come not only from inland, but also from lateral. Furthermore, a finite domain must be designed for three-dimensional numerical simulations of coastal well pumping. When modelling a theoretical case with an infinitely large domain width, one may encounter the problem of defining the size of domain width such that the lateral boundary effects can be removed. It is straightforward that a sufficiently large domain width will remove the lateral boundary effects. However, the larger the domain size, the longer the computation time, given the same gridding resolution. Since simulating a three-dimensional (3D) coastal well pumping case based on the variable-density numerical model is often a time-consuming task, it is necessary to evaluate quantitatively the domain width associated boundary effects, supporting the design of numerical models.

Recently, Lu and Luo (2013) evaluated analytically the quantitative impact of domain length and width on pumping in a flux-controlled coastal groundwater system, based on potential theory. They developed implicit analytical solutions for the interface toe location and maximum pumping rate for three different scenarios assuming that the model domain has respectively a finite width and an infinite length, a finite length and an infinite width, and a finite length and width. Comparison between these three scenarios and the scenario of an infinite width and length suggested that the model domain size has a significant impact on the modelling results, and particularly, the impact from lateral boundaries is larger than that from inland. Furthermore, they obtained a linear equation that reflects the relative impact between the domain length and width on the interface toe and maximum pumping rate, with which length-dominated or width-dominated boundary effects can be identified. Unfortunately, the quantitative impact of lateral boundaries on pumping in a head-controlled coastal system has not been known so far, while this information is useful for designing numerical and experimental models as well as evaluating the model size impact for real-world head-controlled cases.

The main purpose of this study is to assess quantitatively the role of lateral boundaries in modelling a pumping well in a head-controlled coastal groundwater system, focusing specifically on the interface toe location and maximum pumping rate. Based on the potential theory together with the image-well superposition method, we intend to compare analytical solutions among three different scenarios assuming that the model domain has respectively an infinite width and a finite length, a finite width and length, and an infinite length and width. In comparison to the last scenario, it is clear that the presence of a fixed-head inland boundary at a finite distance from the pumping well would lead to less seawater intrusion and a larger maximum pumping rate, while impermeable lateral boundaries would result in more seawater intrusion and a less maximum pumping rate (Lu et al., 2012; Lu and Luo, 2013). Therefore, it is of particular interest to know under what conditions the impacts from inland and lateral are offset. We expect that the results yielded from the current study can offer a thorough understanding of the boundary size impact on pumping in head-controlled coastal groundwater systems.

## 2. Theory

### 2.1. Conceptual model

We consider both unconfined and confined coastal aquifers with negligible surface recharge and with a fixed head at the inland boundary, as shown in Fig. 1. It is assumed for simplicity that the