CORRESPONDENCE:

Threats to coastal aquifers

To the Editor — Based on a simple analytical method, Ferguson and Gleeson[1] concluded that coastal aquifers are more vulnerable to groundwater extraction than to sea-level rise (SLR). We argue that this conclusion is premature.

The researchers[1] used Strack's[2] solution to estimate the location of the freshwater/saltwater interface toe in an unconfined coastal aquifer subject both to pumping from a single well and a constant regional groundwater flux from inland. They also compared pumping impacts with those of SLR, except in this case, a constant hydraulic head was assumed at the inland boundary. The inconsistency in the boundary conditions has important implications for the comparison of SLR and pumping impacts. For example, in terms of steady-state toe location, constant flux gives maximum pumping impact and minimum SLR impact; whereas constant head gives maximum SLR impact and minimum pumping impact[3,4].

Werner *et al.*[3] and Lu *et al.*[4] provide the relevant equations and discussion for the different boundary conditions. Let us assume the case[1] of a pumping well located at the centre of an aquifer with a length perpendicular to the coastline of 2 km, a thickness of 30 m, a hydraulic conductivity of 1.6×10^{-5} m s^{-1}, hydraulic gradient of 0.001 and pumping rate of 4.4×10^4 l d^{-1}. This would lead to saltwater intrusion lengths of 162 m and 254 m, using constant head and flux inland boundary conditions, respectively. For the case of SLR, the same aquifer would experience saltwater intrusions of 161 m and 15 m following a SLR of 0.59 m, under constant head and flux inland boundary conditions, respectively.

In reality, inland boundary conditions are likely to fall between the two extremes of fixed flux and fixed head. This is partly owing to topographical controls on water table rise and the water table being impacted by land surface inundation under SLR. The fact that both boundary conditions assume an infinite supply of water at the inland boundary also plays a part. As a result, it is necessary to consider both types of boundary condition in assessing groundwater extraction and SLR. This analysis serves to demonstrate how important the choice of boundary condition is when making an assessment of the relative impacts of groundwater extraction and SLR. It also illustrates the difficulty in drawing generalized conclusions, especially for the cases with a short aquifer length. Furthermore, there are implicit and often unjustified assumptions that catchment boundaries coincide with groundwater basin boundaries[5].

Moreover, Ferguson and Gleeson[1] considered groundwater extraction from a single well, although well fields in coastal aquifers usually have multiple wells[5,6]. In the latter case, drawdown is reduced relative to the same total extraction from a single well, leading to a smaller inland penetration of saltwater intrusion.

Ferguson and Gleeson[1] considered only the location of the interface toe, which is but one of several measures of saltwater intrusion impact[3]. Saltwater volume is a key measureable given that spatial scales of influence and impact vary significantly between SLR and pumping. Considering a 10-km-wide coastline and the same cases as above, volumes of saltwater intrusion through pumping (flux controlled) and SLR (head controlled) are 4.2×10^6 m^3 and 1.9×10^7 m^3, respectively, despite the inland penetration of saltwater intrusion owing to pumping being larger than that caused by SLR. An assessment of saltwater volume will surely show that in many cases, where pumping is localized and not widely distributed, SLR-induced saltwater intrusion across vast lengths of coastline leads to more extensive freshwater storage losses than from pumping.

In summary, the selection of boundary conditions is a key aspect to the comparison between pumping and SLR impacts. Moreover, owing to the different mechanisms of saltwater intrusion induced by groundwater extraction and SLR, we suggest that the assessment of their relative impacts on the vulnerability of a coastal aquifer should consider changes in both toe location and saltwater volume, among other factors. In considering only the toe location, Ferguson and Gleeson's[1] results are biased towards pumping impacts; a comparison of saltwater volume changes would provide a more integrated analysis of saltwater intrusion impacts, given spatial differences in pumping and SLR effects. A more thorough assessment of the distributions of inland boundary conditions required and the various controls on saltwater intrusion need to be investigated further[5] before firm and well-found conclusions regarding the relative importance of SLR and pumping can be made. ❐

References

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Ferguson and Gleeson reply — We appreciate the correspondence of Lu *et al.*[1] on our analysis of coastal aquifer vulnerability[2]. They raise some interesting points of discussion that allow us an opportunity to further explain our analysis. Lu and colleagues' arguments[1] do not substantially change our conclusions[2] regarding the vulnerability of unconfined coastal aquifers (the focus of our study) to sea-level rise (SLR) but are of interest for smaller flow systems.

Lu *et al.* argue that our choice in boundary conditions affects the calculated values of saltwater intrusion. Two terrestrial boundary conditions are generally recognized for groundwater flow in unconfined coastal aquifers: head controlled and recharge or flux controlled[3]. We acknowledge that there is uncertainty about which boundary condition is most appropriate for a particular coastal aquifer. For our analysis, we chose a head-controlled boundary condition that leads to more significant changes in hydraulic gradient for a given rate of SLR[3] when compared with a flux-controlled boundary condition.