LETTERS
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Vulnerability of coastal aquifers to groundwater use and climate change

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Climate change and human population growth are expected to have substantial impacts on global water resources throughout the twenty-first century[1,2]. Coastal aquifers are a nexus[3] of the world's oceanic and hydrologic ecosystems and provide a water source for the more than one billion people living in coastal regions[4,5]. Saltwater intrusion caused by excessive groundwater extraction is already impacting diverse regions of the globe[5–7]. Synthesis studies[8,9] and detailed simulations[10–13] have predicted that rising sea levels could negatively impact coastal aquifers through saltwater intrusion and/or inundation of coastal regions. However, the relative vulnerability of coastal aquifers to groundwater extraction and sea-level rise has not been systematically examined. Here we show that coastal aquifers are more vulnerable to groundwater extraction than to predicted sea-level rise under a wide range of hydrogeologic conditions and population densities. Only aquifers with very low hydraulic gradients are more vulnerable to sea-level rise and these regions will be impacted by saltwater inundation before saltwater intrusion. Human water use is a key driver in the hydrology of coastal aquifers, and efforts to adapt to sea-level rise at the expense of better water management are misguided.

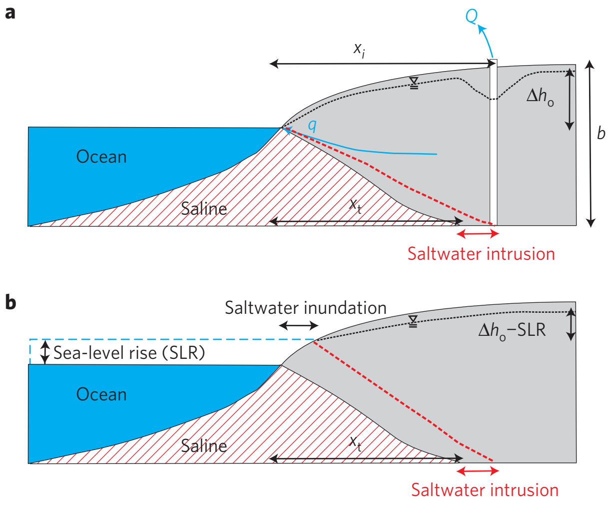

Figure 1 | Coastal aquifers are affected both by groundwater extraction and sea-level rise. a,b, Conceptual model used for simulating the impact of groundwater extraction (**a**) and sea-level rise (**b**) including both saltwater intrusion and saltwater inundation. The simulation variables include discharge per unit coastline (q), groundwater extraction rate (Q), aquifer thickness (b), the difference in hydraulic head between the inland boundary of the flow system and the coast before sea-level rise (Δh_o), and the distance from the coastline to the well (x_i) and the toe of the saltwater wedge (x_t). The grey area shows the distribution of the fresh aquifer water before extraction or sea-level rise.

A substantial portion of the renewable water in the world's hydrologic cycle is diverted for human use[14]. The impact of population growth on water resources is anticipated to increase over the next few decades and to be more significant than that of climate change[2]. Large-scale analyses of human impacts on hydrologic fluxes and stores have focused on surface-water discharge and evapotranspiration[2,14], and more recently on inland aquifers[15,16]. The present study examined the vulnerability of coastal aquifers, using a modified analytical model[17] capable of simulating changes in sea level and groundwater extraction, combined with a geographic information system (GIS) synthesis of coastal aquifers that included hydrogeologic parameters, population densities and known cases of saltwater intrusion. Saltwater intrusion and saltwater inundation were defined, respectively, as the landward movement of the toe of the saltwater–freshwater interface in the coastal aquifer and the landward movement of the coastline (Fig. 1). Vulnerability was defined, in accordance with the Intergovernmental Panel on Climate Change (IPCC)[8], as the degree to which a coastal aquifer is susceptible to, and unable to cope with, the adverse effects of sea-level rise or groundwater extraction. The GIS synthesis focused on coastal watersheds in the contiguous United States, owing to the diversity of hydrogeologic conditions[18] and population densities[4,19], as well as the availability of data sets[19–22] and previous research on saltwater intrusion[7]. As the focus was on general relationships, rather than site-specific conditions, the results are applicable to coastal regions around the globe.

The first step was to analyse the geographic distribution of hydraulic gradient, population density and known saltwater intrusion cases in 1,419 coastal watersheds, including those bordering large saline bays. Figure 2 shows the importance both of low hydraulic gradients and high population densities in assessing the vulnerability to saltwater intrusion (see Supplementary Information for descriptions of individual locations). The analysis used the 12-digit subwatershed hydrologic unit, commonly referred to as HUC12 watersheds[21], which is the smallest scale for systematically mapping watersheds (average coastal watershed length ~10 km). Hydraulic gradients were estimated by dividing the maximum simulated water-table elevation[20] by the distance to the coastline[22]. Population densities were derived from the gridded population of the world[19]. Population density is a reasonable proxy for overall water use, except where industry and agriculture

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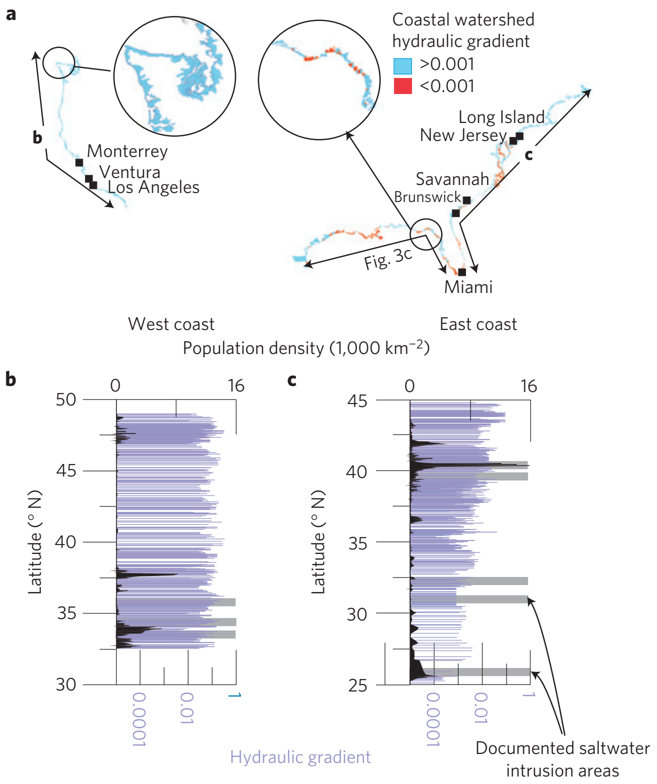

Figure 2 | Present saltwater intrusion areas have a high population density and/or low hydraulic gradients. a, For coastal watersheds in the contiguous United States, hydraulic gradients >0.001 are mapped in blue and those with hydraulic gradients <0.001 are mapped in red. Insets showing watershed boundaries in the Pacific northwest and the Florida panhandle are provided as more detailed examples. **b**,**c**, The distribution of hydraulic gradients and population densities along the west coast (**b**) and east coast (**c**) of the contiguous United States. Documented saltwater intrusion locations[7] are labelled with black squares in **a** and grey bars in **b** and **c**.

use unusual amounts of water per capita. Although this estimate of water use does not discriminate between surface water and ground water, that information is available for most large cities in the United States.

The relative impacts of sea-level rise and groundwater extraction were examined by modifying a steady-state analytical solution[17] (equation (1)) to estimate the change in position of a discrete freshwater–saltwater interface for a given extraction well at a known distance from the coast (Fig. 1). This approach allowed isolation of the impacts of key variables. More complex models have typically been used to examine saltwater intrusion[10,11,13,23], but in most cases they have failed to resolve the timing and extent of saltwater intrusion at specific sites[23]. The analytical model in the present study did not account for groundwater mixing and diffusion, which although may have important effects in specific cases, were not first-order variables among the hydrogeologic and anthropogenic drivers of saltwater intrusion. The analysis assumed steady-state sea levels based on the maximum rise of 0.59 m predicted for 2090–2099 by the IPCC[8]. This prediction is based on the fossil-fuel intensive A1FI scenario, which assumes rapid population and economic growth in the first half of the twenty-first century, but does not consider changes in the melting of ice sheets. The steady-state assumption was useful for the present analysis, although adjustment of aquifers to sea-level rise will probably be a long and gradual process[11,13]. The parameter values for the base-case scenario (Supplementary Table S1) and sensitivity analysis (Supplementary Figs S1–S4) were derived from the GIS synthesis or taken from the literature. The base case assumed a 30-m-thick carbonate aquifer, because carbonate rock has the median hydraulic conductivity of coastal aquifer materials[24]. Wells are assumed to extend through the entire thickness of the aquifer and groundwater flow in the underlying formations is neglected. Upward vertical migration of salt water (or upconing) is possible if wells extend only part way through the aquifer and are above the freshwater–saltwater interface[7,25]. Such cases can occur without substantial rearrangement of the water table regionally or lateral movement of the saltwater interface[25]. The analytical solution does not include upconing, which can be a relatively fast process compared with lateral intrusion. Not including this potentially faster upconing process is conservative in the comparison of relative impacts of sea-level rise and groundwater extraction. Per capita groundwater extraction rates were assumed to be the mean of US domestic usage ($550\,\mathrm{l\,d^{-1}}$), which is near the high end of worldwide water-consumption rates[26]. These rates exclude the potential for return flow (for example, septic systems). The average length of the flow system was assumed to be 10 km, based on the analysis of HUC12 watersheds. Other flow-system lengths were also considered (Supplementary Fig. S1) to allow comparison with results of previous studies[11,12].

The impact of groundwater extraction on coastal aquifers was more significant than the impact of sea-level rise or changes in groundwater recharge (Fig. 3a). Of the hydrologic, geologic and topographic variables included in the model, hydraulic gradient before sea-level rise was the single most important variable controlling saltwater intrusion (Fig. 3a). The distribution of hydraulic gradients on the watershed scale indicated that sea-level rise will have a negligible impact on water supplies for most communities, compared with the effects of groundwater extraction. For the well location used in the analysis (1 km from the coast), the impact of sea-level rise on saltwater intrusion was significant only at very low population density and where hydraulic gradients were <0.001. Most of the coastal watersheds in the United States have hydraulic gradients >0.001 (Fig. 3a). For all other hydraulic gradients and population densities, extraction was more important than sea-level rise. Sea-level rise did not have any significant impact on saltwater intrusion for larger groundwater extraction rates (Supplementary Fig. S2). Uncertainty over future recharge rates was simulated by changing recharge by ±30%. Döll[27] simulated how recharge will change globally from 1961–1990 to 2041–2070 using four different climate-change scenarios. Most of the global population (75–86%, depending on the scenario) live in areas where recharge is predicted to change by $\leq 30\%$. Figure 3a shows that predicted changes to recharge do not impact saltwater intrusion as much as groundwater extraction.

In the model results, the effects of sea-level rise were more pronounced in shorter flow systems (Supplementary Fig. S1), indicating that previous analyses using 2-km flow systems[11,12] may have overestimated the potential impact of climate change. Aquifer materials, which affect hydraulic conductivity (Fig. 4) and thickness (Supplementary Fig. S3), also influenced the extent of saltwater intrusion predicted by the model. Given constant hydraulic gradients, thicker aquifers or aquifers with high hydraulic conductivities, such as coarse-grained unconsolidated sediments, would be able to support relatively high demands for water. However, the distribution of hydraulic conductivity in aquifer materials can be highly complex. Although recent estimates of regional scale hydraulic conductivity[24] were used (Fig. 4), the uncertainty was significant.

Watersheds with low hydraulic gradients generally have low topographic gradients, making them susceptible to inundation as well as lateral saltwater intrusion. Inundation was calculated as the product of topographic gradient and steady-state sea levels based on the maximum rise of 0.59 m predicted for 2090–2099 by the

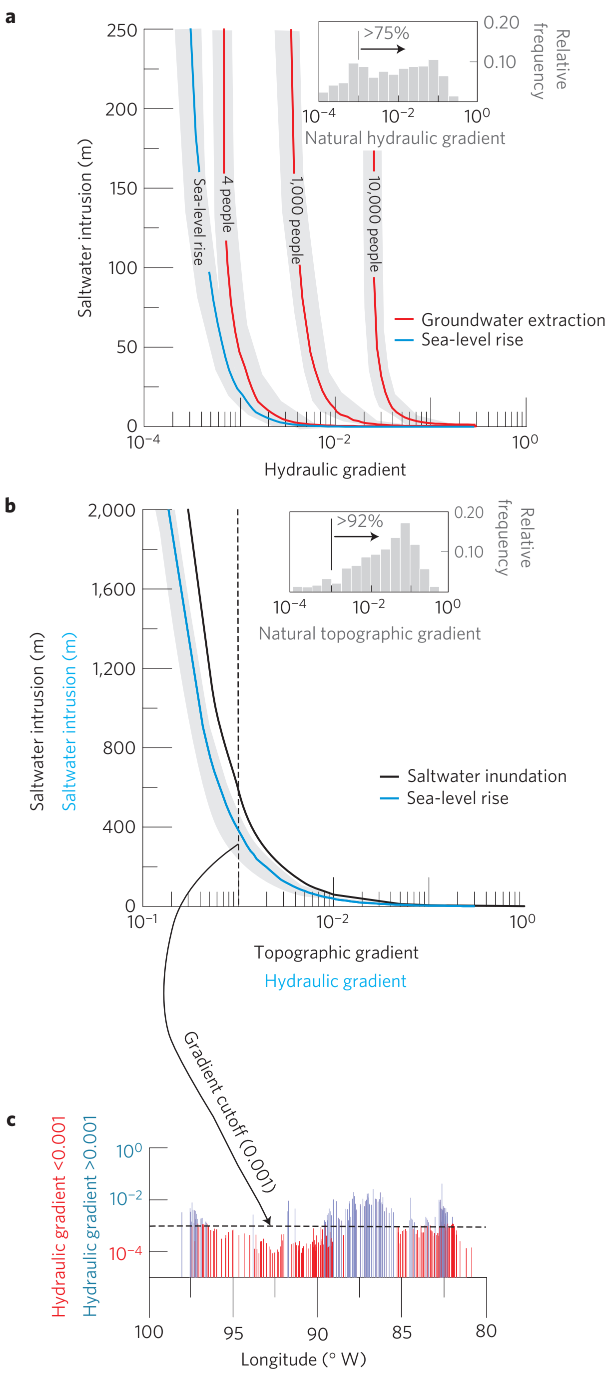

Figure 3 | The impact of groundwater extraction on coastal aquifers is more significant than the impact of sea-level rise. **a**, Saltwater intrusion for various hydraulic gradients with extraction from a well 1 km from the coast in a 10-km-long watershed (Supplementary Table S1). Grey area denotes changes in recharge of ±30%. Inset histogram summarizes coastal hydraulic gradients (Fig. 2a)[20]. **b**, Saltwater inundation and associated infiltration of sea water will be more important than saltwater intrusion from sea-level rise assuming equal topographic gradient and hydraulic gradients. **c**, Hydraulic gradients for watersheds adjacent to the US Gulf Coast with red indicating greater vulnerability.

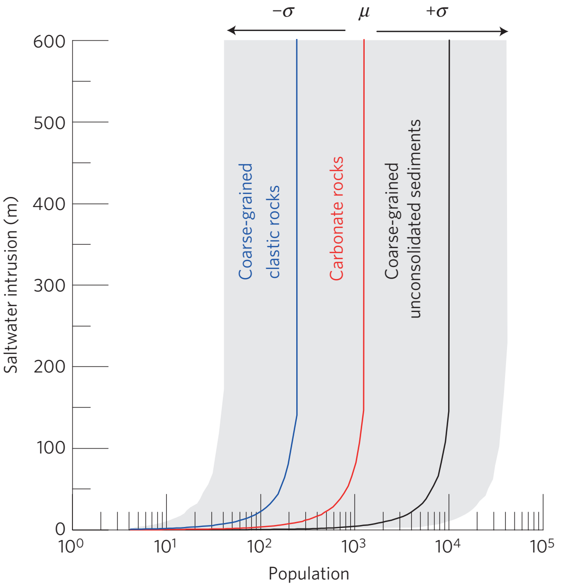

Figure 4 | The uncertainty owing to different aquifer types is significant as shown by simulation of these types over a range of coastal populations. Hydraulic conductivity is controlled by aquifer type. The grey shaded region illustrates the range of possible saltwater intrusion for carbonate rocks over the range of one standard deviation ($\pm 1\sigma$) in hydraulic conductivity[24]. The geometric mean value (μ) is also denoted in the figure. The saltwater intrusion predicted for coarse-grained unconsolidated sediments and clastic rocks falls within the $\pm 1\sigma$ range for carbonate rocks highlighting the significant uncertainty in hydraulic conductivity values.

IPCC (ref. 8; Fig. 3b). Inundation will be particularly acute for topographic gradients of <0.001, which occur in $<8\%$ of coastal watersheds in the contiguous United States. Inundation is a faster process than lateral saltwater intrusion, so this intrusion mechanism is probably not the main concern of communities in areas with low topographic gradients. Following inundation, the saltwater wedge will move inwards to equilibrate with the new position of the coastline, with much of the adjustment coming from vertical seepage of sea water in the flooded zone. Storm surges cause additional transient impacts on groundwater chemistry in areas with low topographic gradients[28] and may exacerbate the long-term impacts of sea-level rise on coastal aquifers.

The model and sensitivity analysis (Fig. 3 and Supplementary Figs S1–S4) developed here could be used by managers of coastal aquifers and watersheds to diagnose vulnerability to saltwater intrusion on a regional scale for various distances from the coast. Communities where saltwater intrusion is predicted to extend some critical distance inland might develop a water management policy aimed at avoiding or forestalling that outcome. For example, this could apply to coastal watersheds with a hydraulic gradient of <0.001 in which saltwater intrusion is predicted to extend $\sim$400 m inland (Figs 2a and 3). We have mapped watersheds with a hydraulic gradient of <0.001 in Fig. 2a as well as showing their distribution along the Gulf Coast in Fig. 3c to illustrate how our results could be used as a management tool, although the gradient cutoff is arbitrary and dependent on the system and management priorities.

Climate change is expected to have critical effects on a variety of human and biophysical systems[29], and will undoubtedly cause or exacerbate water resource issues[1,2]. However, results of the present study indicate that the direct impact of groundwater extraction on coastal aquifers has been[7] and will be much more widespread and significant than the impact of sea-level rise. Even areas with moderate population densities and water demand are expected to experience saltwater intrusion (Fig. 2), which is particularly disturbing, as most of the coastal population lives in towns and small cities[4]. The analysis presented here provides a large-scale management tool that can be used to identify vulnerable aquifers, as well as a framework for more detailed future analyses.

Understanding the interactions between and relative importance of human and biophysical effects is critical to managing, mitigating, or adapting to the impacts of global climate change[30]. Coastal aquifers with all but the smallest topographic gradients are more vulnerable to groundwater extraction than to sea-level rise. Therefore, efforts to adapt to sea-level rise at the expense of better water management are misguided.

Methods

We used an analytical solution[17] to estimate the position of the freshwater–saltwater interface for the case where there is a regional flux of groundwater to the sea along with a pumped well:

$$\frac{qx_t}{K}+\frac{Q}{4\pi K}\ln\left[\frac{(x_t-x_i)^2}{(x_t+x_i)^2}\right]=a \qquad (1)$$

where Q is the pumping or injection rate, K is hydraulic conductivity, q is the flow per unit of coastline, (x_t) is the inland position the toe of the saltwater wedge, (x_i) is the position of the well and $a=s(s-1)d^2/2$ where s is the specific gravity of saltwater and d is the depth below sea level to the impermeable base of an unconfined aquifer (Fig. 1). Aquifer bases are never impermeable in reality but this assumption is frequently made in hydrogeologic models when there the underlying aquifer is greater than two orders of magnitude less permeable. In this treatment, the well is assumed to be screened or open through the entire thickness of the aquifer. This formulation does not allow for an explicit treatment of an increase in sea level through a hydraulic head term at the coast but changes in the hydraulic gradient can be used to assess the effect of sea-level rise in the absence of inundation. Before sea-level rise, discharge per unit length of coastline is described by the following equation:

$$q=Kb\Delta h_o/\Delta x \qquad (2)$$

following a rise in sea level, the gradient becomes:

$$q'=Kb(\Delta h_o-\mathrm{SLR})/\Delta x \qquad (3)$$

where b is aquifer thickness, which is assumed to be approximately equal to d, the depth to the bottom of the aquifer below sea level, and Δh_o is the difference in hydraulic head between the inland boundary of the flow system and the coast before sea-level rise (SLR). This treatment assumes that the inland hydraulic head boundary will remain unchanged with climate change. This and other treatments where this boundary condition was permitted to increase have been explored[11], and the treatment used here was found to produce the most marked change in the position of the saltwater wedge. From equations (2) and (3) it is apparent that changes in sea level will have more pronounced effects on shorter flow systems (Supplementary Fig. S1). The analysis presented here is strictly valid only for unconfined aquifers and steady-state conditions, which conservatively overestimates the immediate threat of saltwater intrusion in many areas. In confined situations, centuries could be required to reach steady-state conditions owing to changes in sea level[11] and there is evidence that this could take millennia in some confined systems.

Analyses of the effect of changing groundwater recharge rates assumed simple systems where a change in recharge in the flow system would result in an equal change in the amount of discharge per unit coastline (Δq):

$$q'+\Delta q=Kb(\Delta h_o+\Delta h_r-\mathrm{SLR})/\Delta x \qquad (4)$$

where Δh_r is the change in hydraulic head associated owing to the change in recharge. Equation (4) describes a simplified situation that represents the flux-controlled end member of possible responses to a change in recharge. In cases where a fixed boundary exists inland, the change in discharge per unit coastline and hydraulic gradient will be less pronounced.

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Author contributions

Both authors contributed to planning of this paper. G.F. carried out the analytical modelling and T.G. conducted the GIS analyses. Both authors contributed to the writing of the paper and drafting of figures.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.F.