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A Perceptual Model of Drivers and Limiters of Coastal Groundwater Dynamics

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ABSTRACT

Coastal groundwater is a vital resource for coastal communities around the globe, and submarine groundwater discharge (SGD) delivers nutrients to coastal marine ecosystems. Climatic changes and anthropogenic actions alter coastal hydrology, causing seawater intrusion (SWI) globally. However, the selection of SWI and SGD study sites may be highly biased, limiting our process knowledge. Here, we analyse hydroenvironmental characteristics of coastal basins studied in 1298 publications on SGD and SWI to understand these potential biases. We find that studies are biased towards basins with gross domestic product per capita below (SWI) and above (SGD) the median of all global coastal basins. Urban coastal basins are strongly overrepresented compared to rural coastal basins, limiting our progress in understanding undisturbed natural processes. Despite the connection between anthropogenic activity and coastal groundwater issues, and the consequential overrepresentation of urban basins in coastal groundwater studies, perceptual (or conceptual) models of coastal groundwater rarely include anthropogenic influences aside from pumping (e.g., subsidence, land use change). Taking a holistic view on coastal groundwater flows, we have developed an editable perceptual model illustrating the current understanding, including both natural and anthropogenic drivers. As SGD and SWI in new areas of the globe are studied, we advocate for researchers to utilise and further edit this perceptual model to openly communicate our process understanding and study assumptions.

1 | Introduction

Groundwater is essential to meet freshwater demand of coastal communities (Johnson et al. 2022) and strongly impacts coastal ecosystems (Johannes 1980; Starke, Ekau, and Moosdorf 2020; Liu, Du, and Yu 2021). Given that 36% of the global population lives within 100 km of the coast (CIESIN 2012), coastal water resources are crucial to reach sustainable development goals 2 (Zero hunger) and 6 (Clean water and sanitation). As groundwater flow is driven by hydraulic gradients (Darcy 1856), changes in hydraulic gradients at the land-sea boundary cause changes in submarine groundwater discharge (SGD) and recharge

(SGR)—the exchange of water between aquifers and the ocean (Kohout 1964; Taniguchi et al. 2002; Michael, Mulligan, and Harvey 2005). The interacting terrestrial and oceanic drivers create complex coastal settings, making it difficult to predict seawater intrusion (SWI) (Werner et al. 2013) (Table 1).

Around the world, high freshwater demand and climate change have changed hydraulic gradients, decreasing fresh SGD and increasing SWI. Already, 32% of the global coastal metropolitan cities have been threatened by SWI (Cao, Han, and Song 2021). This situation is exacerbated by the fast-growing population in the low elevation coastal zone (i.e., below 10 m of elevation), predicted to grow from 0.6 to 1.3 billion people between 2000 and 2060 (Neumann et al. 2015). Anthropogenic activity reduces groundwater flow to the coast through urbanisation, and associated surface sealing causing decreased groundwater recharge (GWR) (Crossland et al. 2005; Loc et al. 2021). The biggest anthropogenic impact on coastal groundwater flow and the main cause of horizontal SWI is groundwater pumping (Ferguson and Gleeson 2012; Post et al. 2018).

Locations of SGD and SWI study sites have been mapped in literature reviews (Santos et al. 2021; Cao, Han, and Song 2021), but characteristics of the studied coastal basins (e.g., population density, aridity index) and thus possible biases remain unstudied. Expecting to find biases in study site selection, we analyse hydroenvironmental characteristics of coastal basins subject to SGD and/or SWI studies based on an extensive review of study site locations. The analysis reveals that coastal groundwater research accumulates in urban coastal catchments with a certain level of gross domestic product.

Despite the many studies in basins with high anthropogenic activity and despite the knowledge of various anthropogenic influences on coastal groundwater flows, perceptual models (also called conceptual models) of coastal groundwater flows rarely show anthropogenic drivers but groundwater pumping. While there are exceptions (e.g., Taylor et al. 2013; Richardson et al. 2024), even perceptual models in review articles generally focus on some of the many natural drivers (i.e., tidal pumping, GWR) (e.g., Taniguchi et al. 2002, 2019; Robinson et al. 2018). Here, we present a literature-based perceptual model of coastal groundwater, including various anthropogenic influences on coastal groundwater flows. This perceptual model represents our current system understanding and is also biased by the studied coastal basins and could look different if we had more knowledge about rural areas or geographical locations that have rarely been studied (e.g., the West Coast of South America or the Arctic). We use the perceptual model to describe drivers and limiters of the different coastal groundwater flows at the wide range of temporal and spatial scales studied in the literature.

2 | Materials and Methods

To analyse coastal groundwater study site locations, we searched Web of Science for terms related to coastal groundwater, SWI and SGD (Text S1), and retrieved 5896 publication records on 12 August 2022. To increase the likelihood of screening relevant records, we used an artificial intelligence software that proposes the next record based on decisions regarding the relevance of previous records: AS Review (https://asreview.nl/ and Text S2). Criteria for inclusion in the study site analysis were (1) the main topic is related to coastal groundwater flows, (2) the study is not a review or theoretical (i.e., not representing actual sites) numerical model, (3) the language is English and (4) it was published online before 2022. During screening, AS Review initially identified that SGD studies are relevant, and hence, roughly the first 700 studies marked relevant were from that field. After that, the hit rate worsened until it picked up that SWI studies are relevant for us, too, and it started showing them with high frequency. We screened 1502 of the 5986 records. Of those, 1332 were deemed relevant and only 170 were excluded (Figure S1). According to AS Review, the use of AS Review increased the share of relevant records from about 25% to almost 90% (Figure S2).

TABLE 1 | Abbreviations and respective terms used in this manuscript.

Abbreviation	Term
GWR	Groundwater recharge
SGD	Submarine groundwater discharge
SGR	Submarine groundwater recharge
SWI	Seawater intrusion

The 1332 records classified as relevant in the screening were joined with 26 publications identified through citations in high-impact reviews and manual Google Scholar searches. These 1358 records were then checked thoroughly for eligibility, and 60 publications were removed since they did not meet the criteria for inclusion. Hence, the final number of publications included in the study site analysis is 1298 (see PRISMA (Page et al. 2021) flow chart, Figure S1). The vast majority of these publications are peer-reviewed articles. We extracted the coastal groundwater flow type, main topic, shore type and study site/s (Table S1) from the publications. The results of the study site analysis adopt a publication bias due to its setup focussing on published journal articles (Dickersin and Min 1993) in English. Another limitation is that the records were retrieved via online search. Thus, no study from before the 1990s is included in the analysis of study sites. However, the distribution of SGD study sites from the 1960s to 1990s (Taniguchi et al. 2002) is very similar to our findings, while the number of publications per year has multiplied since the early 2000s (Figure S4).

We compare the basin characteristics of coastal subbasins (i.e., subbasins draining into the ocean) with study sites to all coastal subbasins in the BasinATLAS dataset (Linke et al. 2019; https://www.hydrosheds.org/hydroatlas; average area of coastal basins: 136 km^2). To account for the high variability at the coast, the most detailed delineation of coastal subbasins available in BasinATLAS, Pfafstetter level 12 (Verdin and Verdin 1999), was used. Besides the basin shapes, BasinATLAS provides many hydroenvironmental variables, including terrain slope (Robinson, Regetz, and Guralnick 2014), aridity index (Zomer et al. 2008), population density (CIESIN 2016) and gross domestic product (GDP) per capita in administrative areas (Kummu, Taka, and Guillaume 2018). Two variables from other data sources were added to the analysed dataset: hydraulic conductivity by Huscroft et al. (2018) and fresh SGD estimates by Luijendijk, Gleeson, and Moosdorf (2020). Topographic slope and hydraulic conductivity are used as proxies for groundwater flow. The aridity index, defined as $\frac{\text{Mean Annual Precipitation}}{\text{Mean Annual Potential Evapotranspiration}}$ (Zomer et al. 2008), is used as a surrogate for (ground)water recharge. High population density has been associated with SWI since it is related to increased groundwater extraction (Cao, Han, and Song 2021). GDP per capita is used to assess economic productivity in basins where researchers study coastal groundwater flows. Fresh SGD estimates by Luijendijk, Gleeson, and Moosdorf (2020) are used to compare locations of SGD and SWI studies. Terrain slope, aridity index, population density, GDP per capita, hydraulic conductivity and fresh SGD show low-to-moderate correlation between each other both for the entire set of coastal basins and for the subset of basins with a study site (Text S3, Tables S2 and S3). After filtering coastal basins with very high hydraulic conductivities (above 1 m/s) and negative SGD values, 43 213 coastal basins remained.

3 | Studied Coastal Aquifers Are Characterised by High Anthropogenic Action

We identified 841 different study sites in the 1298 records (Figure 1). Most of the analysed SGD studies estimated/measured the amount of SGD or its chemical content, not distinguishing between fresh and saline SGD. Hence, we do not distinguish between SGD components here either, SGR is often studied implicitly in both SGD and SWI studies. We find that many investigations were performed in proximity to coastal megacities (> 10 million inhabitants), especially in China and India, while large parts of the global coastline, especially South America and Sub-Saharan Africa, are understudied. Together with groundwater pumping and sea-level rise, reducing GWR (severe in red areas of Figure 1) could change the focus of coastal studies from SGD to SWI, for example, at the US East Coast.

SGD and SWI study sites are often far apart (Figure 1), and just 5% of all analysed studies looked at SGD and SWI simultaneously. Studies of both SGD and SWI are scattered around the world and most of them focus either on sea-level rise or fluctuating drivers like tides and seasonality of precipitation. While the vast majority of SWI studies are in North Africa and East India, SGD studies dominate the eastern coasts of the United States and Australia. 75% of coastal groundwater studies that identified a coastal ecosystem at the study site (i.e., lagoons, mangroves, salt marshes, estuaries and coral reefs) were SGD studies (46% of analysed SGD studies). Regions with large ecosystems (green areas in Figure 1, see also Figure S5) are frequently studied, especially when they are close to highly populated areas (i.e., Great Barrier Reef, Florida Mangroves, Pichavaram Mangrove Forest).

Table 2 and the cumulative density functions of selected attributes (Figure S6) show that study sites of SGD and SWI are often characterised by anthropogenic activity. Approximately

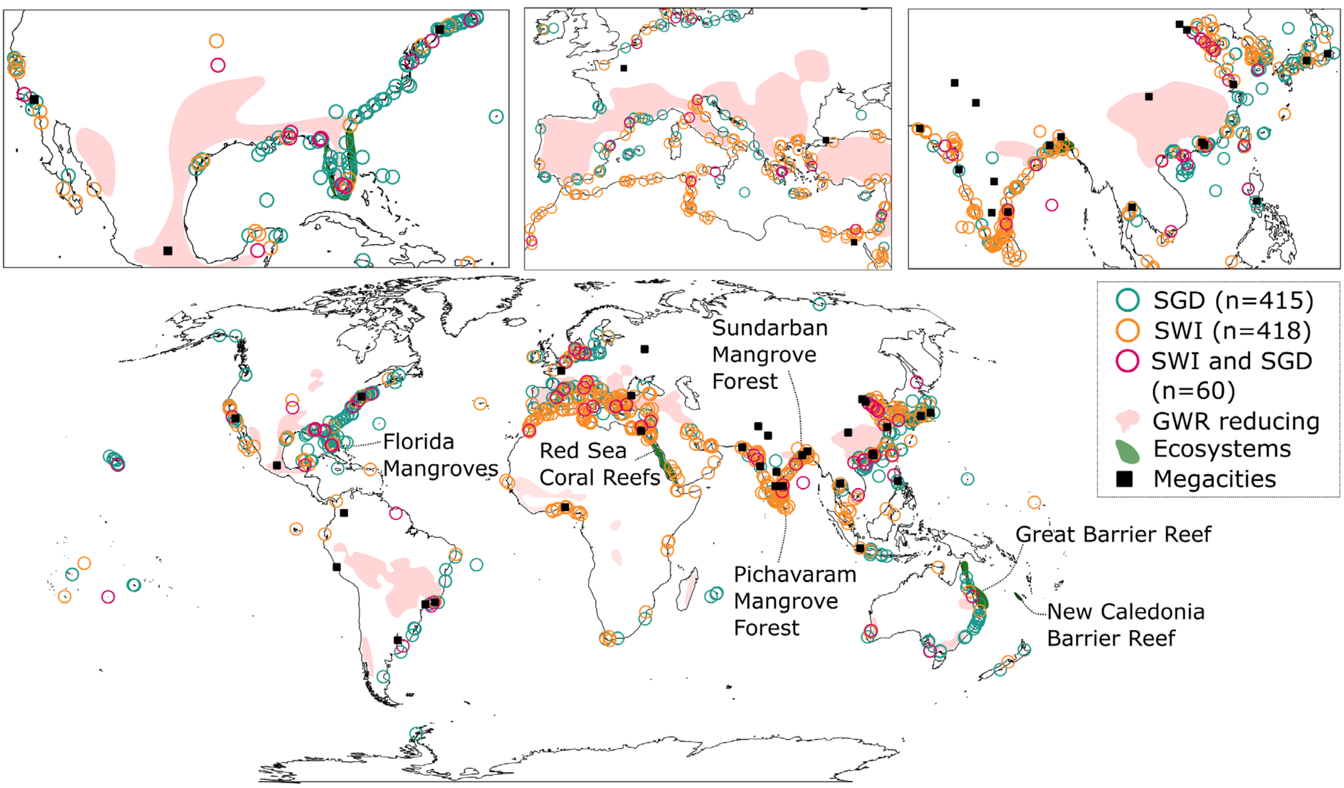

FIGURE 1 | Study locations of SGD, SWI and both. Zoom-ins at the top show frequently studied regions in North America, Mediterranean and Asia. In red areas, GWR per year is projected to be reduced by over 10 mm at global warming of 2°C (Reinecke et al. 2020). Green areas show large marine ecosystems (see also Figure S5). Black squares mark megacities (> 10 million inhabitants). Numbers add up to more than the number of study sites (sum here: 893, study site number: 841) since at some locations both SGD and SWI were studied. Markers placed far inland (in North America and India) are subcontinental studies.

TABLE 2 | Shares of basins with SGD/SWI/SGD and SWI sites where population density, GDP per capita, hydraulic conductivity and aridity index are above/below their respective thresholds. Thresholds are shown in Figure S6. *Median GDP of coastal basins.

	Population density		GDP per capita		Hydraulic conductivity		Aridity index		Estimated SGD	
	Rural	Urban	Below median*	Above median*	Low	High	Water-limited	Energy-limited	Low	High
Basins with SGD site	60%	40%	33%	67%	35%	65%	40%	60%	58%	42%
Basins with SWI site	42%	58%	80%	20%	19%	81%	76%	14%	76%	24%
Basins with SGD & SWI site	47%	53%	45%	55%	23%	77%	53%	47%	68%	32%
All basins	87%	13%	50%	50%	35%	65%	44%	56%	68%	32%

70%/80% of SGD/SWI studies were located in coastal basins (i.e., draining into the ocean) with a population density of over 100 people/km^2, which occurs only in 20% of the 43 213 coastal basins (Figure S6). While more than half (58%) of the SWI studies are performed in urban (population density ≥ 300 people/km^2) coastal basins (Eurostat 2021), only 13% of all coastal basins are urban. This is sensible since high population densities have been linked to the occurrence of SWI (Post, Eichholz, and Brentführer 2018; Cao, Han, and Song 2021).

GDP per capita strongly separates the lines of SGD and SWI study site locations (Figure S6): GDP is below the median of all coastal basins in just a third of SGD studies, and in 80% of the coastal SWI studies (Table 2). Groundwater salinity issues related to SWI, which can be decisive for agricultural and domestic water use, seem prioritised over SGD-related topics (e.g., coastal ecosystems) in regions with lower GDP. Another reason may be that shallower wells, vulnerable to SWI, have been installed in regions with lower GDP, but while international compilations of well data contain many data points in the United States and Australia, just few are in less developed regions (e.g., Jasechko, Perrone, and Seybold 2020; Thorslund and van Vliet 2020; Jasechko, Seybold, and Perrone 2024).

Compared to the cumulative density function of all coastal basins, basins with SWI and/or SGD studies have rather low terrain slopes, frequently below 2°. Among the SWI studies, 81% were done in basins with a relatively permeable aquifer (hydraulic conductivity > 10^{-5} m/s) (Bear 1972). SGD often is a surficial process and the assessed hydraulic conductivity data (GLHYMPS 2.0) rather reflects deeper layers. This may explain why basins associated with SGD studies show lower hydraulic conductivity values than basins associated with SWI studies. As expected, water-limited basins (aridity index below 1) make up a large part (76%) of SWI study sites (Zomer et al. 2008). Meanwhile, energy-limited basins make up 60% of SGD studies sites. SGD estimations from Luijendijk, Gleeson, and Moosdorf (2020) match reasonably with the occurrence of SWI and SGD studies: just 24% of SWI studies were conducted in coastal basins where they estimated high fresh SGD (above 10 m^2/year), and 42% of SGD studies (Table 2).

4 | A Perceptual Model of Drivers and Limiters of Coastal Groundwater Dynamics

Many perceptual (or conceptual) models have been published in the literature. Although the influence of anthropogenic action and climate change on coastal groundwater is diverse, perceptual models rarely include drivers besides groundwater pumping and sea-level rise. Theoretical numerical models, reviews, and publications after August 2022 were excluded from the literature for the analysis of study sites. No literature was excluded in the development of our perceptual model (Figure 2), which takes a rather holistic view on coastal groundwater flows. Besides natural processes and geologic conditions driving or limiting coastal groundwater flows, it shows that many drivers of coastal groundwater flows are affected by anthropogenic action and climate change. The perceptual model is editable and intended to be adjusted and reused by the community (https://zenodo.org/records/13762771).

Since scales of impact are rarely reported, the scales at which drivers act remain uncertain (Text S5). Figure S8 shows the spatiotemporal scales at which drivers impact SWI and SGD according to the assessed literature, ranging from hours to millennia and from centimetres to tens of kilometres. This wide range of spatial and temporal scales was included in our perceptual model, targeting to create a holistic reflection of coastal groundwater flows and their drivers. Thus, bioirrigation and sea-level rise, impacting coastal groundwater at very different scales, are both in the perceptual model.

Causal relations exist between many drivers of coastal groundwater changes. Consequently, processes increasing the amount of groundwater flowing towards the coast (e.g., GWR) can increase fresh SGD and reduce vulnerability to SWI (Michael, Russoniello, and Byron 2013). On the other hand, geological settings allowing for high SGD rates (e.g., high hydraulic conductivity) allow for high SGR, too. In the following, we use our perceptual model to discuss coastal groundwater processes, flows and their major drivers of change (see overview in Table 3).

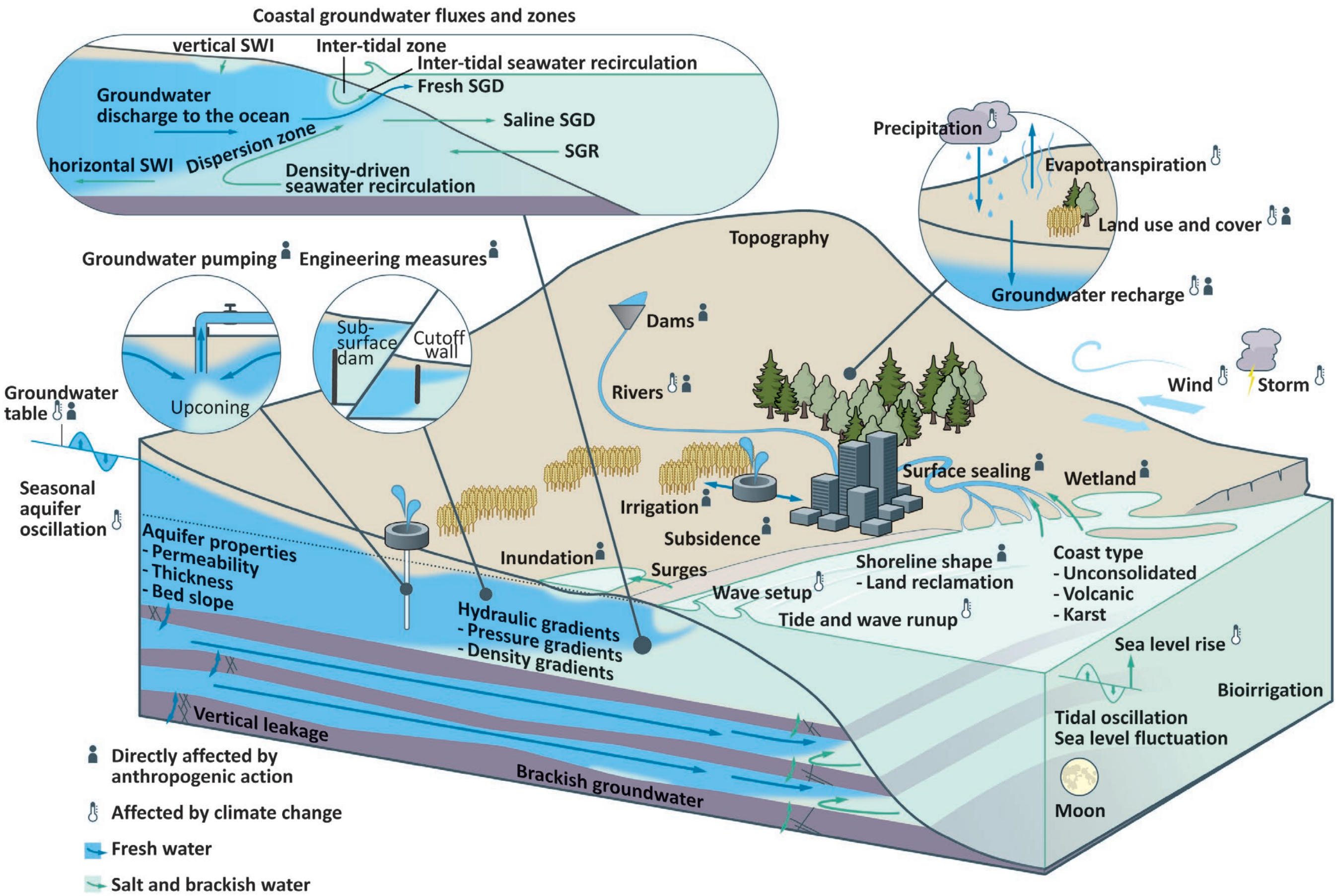

FIGURE 2 | A perceptual model of groundwater flows in coastal basins, including factors that drive and limit change (Kretschmer and Reinecke 2024). Many of those factors are impacted by anthropogenic action and/or climate change and may be causally related. SGD—submarine groundwater discharge, SGR—submarine groundwater recharge, SWI—seawater intrusion.

TABLE 3 | Coastal groundwater processes, respective flows and their major drivers of change.

Coastal groundwater dynamics	Coastal groundwater flows	Major drivers of change
Coastal aquifer interaction with the ocean (4.1)	Fresh SGD (4.1.1)	GWR, groundwater pumping
	Saline SGD and SGR (4.1.2)	Tides, waves, seasonality of GWR, winds, storms, salinity distributions
Seawater recirculation (4.2)	Density-driven seawater recirculation (4.2.1)	Salinity and temperature differences between meteoric and saline water
	Intertidal seawater recirculation (4.2.2)	Change in tidal amplitude between spring and neap tide, wave height
SWI (4.3)	Horizontal SWI (4.3.1)	Groundwater pumping, sea-level rise, seasonality of GWR
	Vertical SWI (4.3.2)	Storm surge overwash, tidal inundation, river salinisation

4.1 | Coastal Aquifer Interaction With the Ocean

4.1.1 | Fresh SGD

Driven by hydraulic gradients, meteoric groundwater (i.e., derived from precipitation) can enter the ocean as fresh SGD (top zoom-in in Figure 2). While topography influences the steepness of the hydraulic gradients, the amount of groundwater that can flow through an aquifer at a given gradient depends on its transmissivity (i.e., the product of hydraulic conductivity and saturated aquifer thickness) (Darcy 1856). Assuming uniform hydraulic gradient, hydraulic conductivity controls groundwater flow and determines how fresh SGD is distributed along the coast (Russoniello et al. 2013; Qu et al. 2014). Where heterogeneity in hydraulic conductivity enables preferential flowpaths, focussed areas of high fresh SGD rates may develop (Kreyns, Geng, and Michael 2020; Geng and Michael 2021). Particularly high rates of fresh SGD are associated with flow through conduits, for example, in volcanic rocks and permeable karst (Befus et al. 2014; Yu et al. 2021; Samani et al. 2021). At shorter temporal and smaller spatial scales, the morphology of a beach is a major control of fresh SGD distribution through the beach face (Zhang et al. 2017).

GWR (right zoom-in in Figure 2) can raise groundwater levels and increase fresh SGD rates (McKenzie, Dulai, and Fuleky 2021) at moderate-to-high hydraulic conductivities. However, low hydraulic conductivity limits GWR and groundwater flow irrespective of the groundwater head (Darcy 1856; Luijendijk, Gleeson, and Moosdorf 2020). Groundwater tables, and in turn fresh SGD, follow seasonally changing rates of GWR (Michael, Mulligan, and Harvey 2005; Fang et al. 2022) and precipitation (Gwak et al. 2014; Beebe et al. 2022) with a temporal lag. Individual precipitation events can induce higher fresh SGD with a lag of several days to weeks (Santos et al. 2009; McKenzie, Dulai, and Fuleky 2021; Yu et al. 2021). Investigations of monsoon seasons and El Niño Southern Oscillation events have shown the importance of precipitation events in rates of fresh SGD (Anderson and Emanuel 2010; Das et al. 2022). When the natural aquifer is disturbed by fresh groundwater pumping (Figure 2), this reduces the amount of fresh groundwater flowing towards the ocean and fresh SGD (Peng et al. 2008). Locally, GWR through rivers can also enhance fresh SGD (Yu et al. 2021).

While SGD is high and salty during ebbing tide, it was found to be less and fresher at low tide (Urish and McKenna 2004). Results from a coastal lagoon suggest that fresh SGD is particularly large at spring tide and decreases towards neap tides (Rocha, Ibanhez, and Leote 2009). Similarly, Glaser et al. (2021) found increased fresh SGD in a tidal creek at spring tides. However, these findings depend on the site: for example, fresh SGD at a beach was found to be higher at neap tides than at spring tides (de Sieyes et al. 2008) which is supported by simulations of different tidal amplitudes at another beach site showing higher fresh SGD at smaller tidal amplitudes (Li et al. 2009). This behaviour was found in aquifers with permeabilities below 0.1 cm/s, where saltwater may accumulate within the aquifer and low rates of fresh SGD occur at high tidal amplitudes (de Sieyes et al. 2008; Li et al. 2009; Abarca et al. 2013).

4.1.2 | Saline SGD and Recharge

Saline SGD and SGR (i.e., saline groundwater outflow to and inflow from the ocean) are oscillating counterparts (top zoom-in in Figure 2), driven by tidal pumping, sea-level changes, wave runup and changing density gradients (Taniguchi et al. 2002; Burnett et al. 2003; Robinson et al. 2018). However, persistent landward hydraulic gradients and density differences may cause SGR to exceed saline SGD beyond usual oscillations, causing horizontal SWI (Werner et al. 2013). Similar to fresh SGD, heterogeneity in hydraulic conductivity affects saline SGD and SGR (Russoniello et al. 2013; Kreyns, Geng, and Michael 2020; Geng and Michael 2021). The exchange of saline groundwater with the ocean at the scales of centimetres (i.e., porewater exchange) can be significantly increased by bioirrigation (i.e., deliberate burrow flushing by benthic organisms) (Meysman et al. 2006) and by the increased hydraulic conductivity from burrows dug by animals (Smith et al. 2016; Stieglitz, Clark, and Hancock 2013).

SGR and saline SGD incorporate the in/outflows from intertidal seawater recirculation and density-driven seawater recirculation, exceeding fresh SGD amounts by far (Li et al. 1999; Taniguchi, Ishitobi, and Saeki 2005). Saline SGD and SGR are particularly large at higher tidal ranges, and thus, can experience a reduction of flow volumes from spring tide towards neap tide (de Sieyes et al. 2008; Abarca et al. 2013; Wilson et al. 2015). Furthermore, due to the low slope allowing larger area per coastline to interact with ocean water, saline SGD per coastline length is larger from a coastal wetland than from a beach (Evans, White, and Wilson 2020).

Saline SGD and SGR are not independent of GWR to the aquifer. A coastal aquifer can be salinised by SGR during a season of low GWR and freshened in the following wet season when increased GWR upstream causes high saline SGD during the flushing of saltwater (Michael, Mulligan, and Harvey 2005). Similarly, seasonally in/decreased sea levels cause larger SGR/saline SGD rates (Michael, Mulligan, and Harvey 2005; Gonneea, Mulligan, and Charette 2013). The effect of sea-level changes can be much larger at coastal wetlands than at beaches (Wilson et al. 2015), because wetlands exist at low slopes.

SGR/saline SGD may increase/decrease during a storm event due to wind and waves pushing saline water into the aquifer, followed by a decrease/increase in the weeks after the storm, when the saline water is transported back into the ocean (Wilson et al. 2011; Xin et al. 2014). Similarly, where winds blow offshore, regionally depressed sea levels can cause significant SGD, likely from confined aquifers (George et al. 2020; Moore et al. 2022), potentially contributing to groundwater discharge at the size of river discharge (George et al. 2020).

4.2 | Seawater Recirculation

4.2.1 | Density-Driven Seawater Recirculation

Density-driven seawater recirculation begins where SGR enters the subterranean estuary in the lower subtidal zone (top zoom-in in Figure 2). Newly recharged saline groundwater flows downward towards the fresh-saline water mixing zone, and then upward along the freshwater–saltwater interface, eventually flowing back into the ocean as saline SGD (Taniguchi, Ishitobi, and Saeki 2005; Robinson et al. 2018). The circulation is limited by aquifer properties and the density gradient. Large values of horizontal (Qu et al. 2014) and vertical hydraulic conductivity (Smith 2004) have been shown to enable density-driven circulation, and large anisotropies (i.e., $\frac{\textit{horizontal hydraulic conductivity}}{\textit{vertical hydraulic conductivity}}$) reduce the circulation (Wilson 2005; Qu et al. 2014). Heterogeneity in hydraulic conductivity, creating preferential flowpaths and complex salinity distributions can greatly increase density-driven recirculation rates if multiple density-driven circulation cells develop (Michael et al. 2016; Kreyns, Geng, and Michael 2020). Assuming constant temperature in the aquifer, Smith (2004) showed the highest density-driven recirculation rates for intermediate dispersion values: (1) if there is no salt transport by dispersion, a sharp interface between fresh and saline water remains in the aquifer and (2) if dispersion is too large, freshwater and saline water mix rapidly, leaving no density gradients to circulate along. Higher freshwater temperatures, increasing the density gradient between fresh and saline groundwater, may increase density-driven seawater recirculation (Pu et al. 2020). Fresh SGD rates can enhance density-driven seawater recirculation when they create a stable dispersion zone with sufficient density gradients (Smith 2004).

4.2.2 | Intertidal Seawater Recirculation

In beach-like shores, seawater may circulate in the intertidal zone at the top, driven by wave setup and changing hydraulic gradients due to tidal oscillation (top zoom-in in Figure 2). SGR occurring at the top of the intertidal zone is pushed down along hydraulic gradients and is discharged back into the ocean as saline SGD (Taniguchi et al. 2002). At spring tide (i.e., when tidal amplitude is the highest), the intertidal seawater recirculation is exceptionally high (Taniguchi et al. 2002; Nguyen et al. 2020).

A consequence of intertidal seawater recirculation is the upper saline plume—a zone of saline water above the freshwater zone at the coastline (Robinson et al. 2007). Upper saline plume formation can be enabled by high hydraulic conductivity and beach slopes (Evans and Wilson 2016). The top zoom-in in Figure 2 shows the plume disconnected from the underlying saline zone, occurring at moderate-to-high fresh groundwater flows towards the ocean (Evans and Wilson 2016; Fang et al. 2021). Increasing tidal amplitudes can cause plume expansion (Robinson et al. 2007; Nguyen et al. 2020), mixing the plume with underlying fresh groundwater flowing to the ocean and potentially connecting it with the saltwater wedge below (Evans and Wilson 2016; Fang et al. 2021).

4.3 | SWI Processes

4.3.1 | Horizontal SWI

The perceptual model in Figure 2 shows a coastal groundwater system where the flows are in an approximate balance. Horizontal SWI (top zoom-in in Figure 2) occurs when the amount of SGR is larger than saline SGD, moving saline water inland, shifting the position of the saline wedge landward. Horizontal SWI is often caused by head gradient changes (i.e., lowering or shifting landward), allowing saline water to intrude the aquifer (Werner et al. 2013). Aquifer resilience against horizontal SWI can be increased by large GWR rates creating hydraulic heads that push against the saline wedge (Michael, Russoniello, and Byron 2013; Rajendiran et al. 2019; Costall et al. 2020; Jung et al. 2020). Consequently, land drainage, reducing the aquifer water table, can increase vulnerability to horizontal SWI (Barlow and Reichard 2010). Besides the head gradient change, horizontal SWI is driven by the density differences between freshwater and saline water (Pacheco-Castro et al. 2021).

Urbanisation, related surface sealing and other human activities significantly alter hydraulic gradients in coastal aquifers, often causing SWI (Deng et al. 2017; Uddameri, Singaraju, and Hernandez 2014). Infiltration of shallow coastal groundwater into ageing sewer systems can cause sewer overflows, discharging untreated sewage (Su et al. 2020). Where large volumes are withdrawn from the coastal aquifer, withdrawal is a major driver of SWI (Barlow and Reichard 2010; Shi and Jiao 2014; Lyra et al. 2021; Jeen et al. 2021), potentially causing horizontal SWI at scales of kilometres within a few years (Langevin and Zygnerski 2013; Chang et al. 2016; Dibaj et al. 2020). Strategies to mitigate horizontal SWI often use artificial or managed GWR, to change the hydraulic gradient (García-Menéndez et al. 2018; Jarraya Horriche and Benabdallah 2020). Alternatively, physical barriers within the aquifer (i.e., cutoff walls or subsurface dams) can be used to effectively reduce the horizontal extent of SWI, but they are highly expensive (Hussain et al. 2019).

Sea-level rise may locally cause horizontal SWI to reach kilometres inland (Sherif and Singh 1999; Giambastiani et al. 2007; Guha and Panday 2012). The impact of sea-level rise on horizontal SWI depends strongly on the aquifer's capability to level out the newly developing hydraulic heads at the coast (Rasmussen et al. 2013): aquifers, whose water table is limited by flux into the system or GWR and not limited by topography, can develop higher groundwater levels balancing the new sea levels, and are thus more resilient to horizontal SWI from sea-level rise (Michael, Russoniello, and Byron 2013). However, such aquifers are also prone to experience SWI due to reducing GWR (Richardson et al. 2024).

Horizontal hydraulic conductivity is a key factor for the SWI rate (Qu et al. 2014; Deng et al. 2017; Costall et al. 2020). Low hydraulic conductivities limit the rate of SWI but also the recovery from it (Shi and Jiao 2014). While aquifers extending deep below the ocean show higher vulnerability to SWI, higher seaward slopes at the aquifer bed increase resilience against horizontal SWI (Mazi, Koussis, and Destouni 2013; Ketabchi et al. 2016).

4.3.2 | Vertical SWI

Vertical SWI occurs when seawater recharges an aquifer from above, on the landward side of the intertidal recirculation zone (top zoom-in in Figure 2). River flow reduction by dams and groundwater pumping (Loc et al. 2021; Shi and Jiao 2014) can enable seawater to move further into coastal rivers and deltaic estuaries (Mikhailova 2013; Peters et al. 2022). Where the coastal aquifer is recharged from the coastal river, vertical SWI from surface water salinises aquifers significantly faster and further landward than horizontal SWI (Hingst et al. 2022; Smith and Turner 2001). Groundwater pumping can even cause vertical SWI from below: in proximity to groundwater wells, saline water may be pulled upwards into the well, called upconing (Werner et al. 2013; Alfarrah and Walraevens 2018). Furthermore, seawater may flood coastal plains after subsidence (Ketabchi et al. 2016; Eslami et al. 2021), often caused by anthropogenic groundwater abstraction (Giambastiani et al. 2007). Another key driver is seawater inundation caused by storm surges (Terry and Falkland 2010; Xiao and Tang 2019), which is exacerbated by land-surface connectivity (Yu et al. 2016) and sea-level rise (Hoque et al. 2016; Gingerich, Voss, and Johnson 2017; Cantelon et al. 2022).

5 | Conclusions

The expected growth of coastal communities, GWR changes with climate change and sea-level rise pose serious threats to coastal fresh groundwater resources worldwide. Analysing the study sites of over 1200 publications, we show that coastal groundwater study sites are biased towards coastal basins with high population density. We further find that while 80% of SWI studies are conducted in basins with GDP per capita below the median of coastal basins, 67% of SGD studies are conducted in basins with GDP per capita above the median of coastal basins. This shows that the availability of fresh groundwater is elemental for coastal regions but threatened in many regions with low GDP per capita. Many of the assessed publications show the strong impact of anthropogenic action on coastal groundwater (e.g., groundwater pumping) causing SWI and altering SGD flows. Since perceptual models in the literature rarely include anthropogenic drivers, we present a literature-informed perceptual model taking a rather holistic view on coastal groundwater flows. We use our perceptual model of coastal groundwater flows to discuss drivers and limiters of coastal groundwater flows, highlighting impacts by anthropogenic action. The perceptual model is editable and can be modified to any study focus. It is intended to continuously improve over time with increasing knowledge about the shown processes and impacts. We call for researchers to use holistic perceptual models of environmental processes to guide their decisions (e.g., in study design, site selection and simulation model development) and to communicate their research.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The table of publications with extracted information is available as a supplemental CSV file (TableOfPublications.csv), the perceptual model (in Figure 2) is published at https://zenodo.org/records/13762771 (as PDF and SVG). The BasinATLAS dataset (contains hydro-environmental data for sub-basins, including slope, aridity index, GDP per capita, and population density used in this analysis) is available at https://www.hydrosheds.org/hydroatlas. Fresh submarine groundwater discharge data by Luijendijk et al. (2020) is available at https://store.pangaea.de/Publications/Luijendijk-etal_2019/S3_global_geospatial_data.zip, hydraulic conductivity data of the GLHYMPS 2.0 product is available at https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU.

Novelty and International Appeal Statement

Analysing over 1000 publications, we found that coastal groundwater studies are highly biased towards highly populated areas. Based on this extensive literature review, we developed a comprehensive graphical perceptual model of coastal groundwater dynamics. We invite the community to use this model to question current process understanding.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.