Submarine Groundwater Discharge and Seawater Intrusion: Two sides of the same coin that are rarely studied simultaneously

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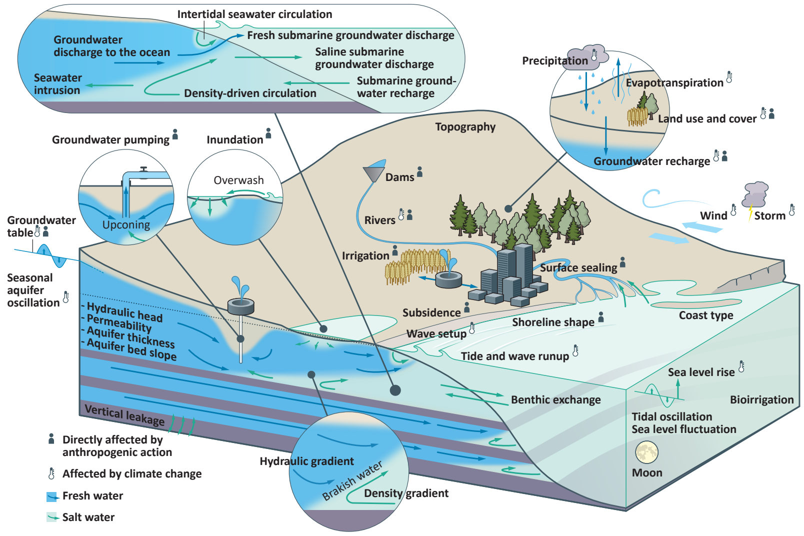
Abstract

Fresh submarine groundwater discharge (SGD) and seawater intrusion (SWI) are complementary processes at the interface of coastal groundwater and oceans. Multiple common drivers enable or limit SGD and SWI. However, we find that SGD and SWI are rarely studied simultaneously. In this meta-analysis, we synthesize 1298 publications, examining drivers of SGD and SWI, where and why they are studied, and at which scales they are impacted by their drivers. Studies of SGD and SWI accumulate in urban coastal basins with high gross domestic product (GDP), and high permeabilities, where measurable groundwater fluxes are expected. We find, that studies investigate various drivers, but rarely assess the scales they act at. Effects of temporally recurring processes (e.g., tides) are studied more often and are better known than effects of spatial variability (e.g., permeability). Future studies should investigate SGD and SWI simultaneously, report impact scales of drivers explicitly and explore unchartered coastlines.


Intertidal seawater circulation
Groundwater discharge to the ocean
Fresh submarine groundwater discharge
Saline submarine groundwater discharge
Seawater intrusion
Density-driven circulation
Submarine groundwater recharge
Precipitation
Evapotranspiration
Land use and cover
Groundwater recharge
Topography
Groundwater pumping
Inundation
Overwash
Upconing
Dams
Rivers
Irrigation
Wind
Storm
Groundwater table
Seasonal aquifer oscillation
Surface sealing
Subsidence
Shoreline shape
Coast type
Wave setup
Tide and wave runup
- Hydraulic head
- Permeability
- Aquifer thickness
- Aquifer bed slope
Sea level rise
Bioirrigation
Benthic exchange
Tidal oscillation
Sea level fluctuation
Moon
Vertical leakage
Hydraulic gradient
Brakish water
Density gradient
Directly affected by anthropogenic action
Affected by climate change
Fresh water
Salt water

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Key Points:

- Coastal groundwater flow drivers interact (hydraulic and density gradients, tides, and waves) but fluxes are rarely studied simultaneously.
- Submarine groundwater discharge and seawater intrusion are understudied in regions with low gross domestic product or population density.
- Drivers of coastal groundwater fluxes act across scales. Standard frameworks for reporting impact scales could help close knowledge gaps.

Abstract

Fresh submarine groundwater discharge (SGD) and seawater intrusion (SWI) are complementary processes at the interface of coastal groundwater and oceans. Multiple common drivers enable or limit SGD and SWI. However, we find that SGD and SWI are rarely studied simultaneously. In this meta-analysis, we synthesize 1298 publications, examining drivers of SGD and SWI, where and why they are studied, and at which scales they are impacted by their drivers. Studies of SGD and SWI accumulate in urban coastal basins with high gross domestic product (GDP), and high permeabilities, where measurable groundwater fluxes are expected. We find, that studies investigate various drivers, but rarely assess the scales they act at. Effects of temporally recurring processes (e.g., tides) are studied more often and are better known than effects of spatial variability (e.g., permeability). Future studies should investigate SGD and SWI simultaneously, report impact scales of drivers explicitly and explore unchartered coastlines.

Plain Language Summary

The interaction between underground water and the ocean in coastal areas is influenced by two processes: fresh submarine groundwater discharge (SGD) and seawater intrusion (SWI). However, these processes are rarely studied together. We examined 1298 publications to understand why and where SGD and SWI are studied and the scales at which they are impacted by their drivers, the factors that enable or limit flow. Most studies focus on urban coastal areas with high economic activity and permeable soil, where measurable water flow between groundwater and the ocean is expected. Although different drivers are investigated, their impact scales are seldom examined. Temporal variations, like tides, are more commonly studied and understood compared to spatial variations, such as soil permeability. Future studies should investigate SGD and SWI concurrently, explicitly report driver impact scales, and explore unstudied coastal areas.

1 Introduction

Groundwater is essential to meet coastal freshwater demand and strongly impacts coastal ecosystems. Compared to surface water, groundwater is more resilient to droughts and less vulnerable to contaminants. Making up 99% of the world's available freshwater (Gleeson et al. 2016), groundwater is a major source of water for domestic and agricultural purposes in African (Steyl and Dennis 2010), US American (Barlow and Reichard 2010), South American (Bocanegra et al. 2010), Indian (Pandian et al. 2016), Chinese (Shi and Jiao 2014) and European (Custodio 2010) coastal regions. Water resources at the coast are crucial to reach sustainable development goals (2) "zero hunger" and (6) "clean water and sanitation", since 40% of the global population live within 100 km of the coast (Crossland et al. 2005; UN 2017). Besides humans, coastal ecosystems are affected by coastal groundwater (Herbert et al. 2015). Submarine groundwater discharge (SGD) - the flow of groundwater into oceans - can be critical for coastal ecosystems, enhancing primary production and attenuating pollutants, but can also be detrimental, causing eutrophication and ocean acidification (Santos et al. 2021). Seawater intrusion (SWI), the landward movement of saline water into coastal aquifers, is a major threat to stygofauna in freshwater aquifers (Saccò et al. 2022).

High freshwater demand and climate change have already reduced hydraulic gradients, decreasing SGD, and causing SWI. Already, 32% of the global coastal metropolitan cities have been threatened by SWI (Cao et al. 2021), and many cities facing severe water shortages are located at the coast (Savelli et al. 2023). This situation is exacerbated by the expected doubling of the coastal city population from 2000 to 2060 (Neumann et al. 2015). Anthropogenic activity reduces groundwater flow to the coast in various ways, e.g., through river dams, urbanization, 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 comes from groundwater pumping, which is also considered the main cause of SWI (Ferguson and Gleeson 2012; Post et al. 2018). Sea level rise from global climate change will further reduce the amount of fresh groundwater at the coast (Alsumaiei and Bailey 2018; IPCC 2022; Oude Essink et al. 2010) and likely increase the threat of over-wash and storm surges (Oberle et al. 2017; Gingerich et al. 2017; Cantelon et al. 2022).

Current process understanding is limited, and global estimates of SGD are highly uncertain. Luijendijk et al. (2020) show that global fresh SGD may lie between 0.4 and 210 km^3/year and available large-scale assessments of SWI are limited to countries or global assessments of vulnerability (Michael et al. 2013; Sawyer et al. 2016). Recent studies show the attribution of SGD to enhanced primary production in coastal ecosystems (Kobayashi et al. 2017; Andrisoa et al. 2019; Maher et al. 2019; Starke et al. 2020), but assessing its importance remains challenging (Liu et al. 2021).

SGD and SWI are complementary processes driven by hydraulic gradients at the land-sea boundary (Robinson et al. 2018; Taniguchi et al. 2002). Hydraulic gradients determine fresh SGD rates and the position of the salt-fresh water mixing zone. Fresh SGD still occurs when seawater intrudes – they are not exclusive processes. But changes in hydraulic gradients create changes in SGD and the mixing zone position (Michael et al. 2005; Heiss et al. 2020). However, here we show that scientific communities studying the two processes tend to be separate – with water resources scientists focusing on SWI and coastal ecologists/oceanographers focusing on SGD and its impacts on coastal waters.

In this meta-analysis, we synthesize 1298 publications to delineate drivers of SGD and SWI, understand where and why they are studied, and at what spatial- and temporal-scales drivers impact SGD and SWI.

2 Materials and Methods

In this meta-analysis of publications on coastal groundwater fluxes, we retrieved 5896 publications from Web of Science by searching in all fields terms related to coastal groundwater, SWI and SGD (Text S1). Criteria for inclusion are (1) the main topic is related to coastal groundwater fluxes, (2) the study was conducted in proximity to an ocean coast, hence, excluding reviews and theoretical modeling studies, (3) the language is English, (4) it was published online before 2022. The screening process was assisted by AS Review, a software using artificial intelligence to propose publications based on our previous decisions on the relevance of publications (https://asreview.nl/ and Text S2). Due to time constraints, not all 5896 records could be screened. Instead, screening was concluded after 1502 records. Of those, 1332 were deemed relevant and only 170 were excluded, mostly because the topic was not related to coastal groundwater fluxes (Figure S1). The use of AS Review increased the share of relevant records among the retrieved publications from about 25% to almost 90% according to AS Review (Figure S2).

The 1332 records classified as relevant in the screening were complemented by 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 analyzed 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). Additionally, spatial and temporal scales of driver impact on SGD and SWI were extracted from records that focused on flow drivers as their main topic.

The coastal basins of the BasinATLAS dataset, providing hydro-environmental data for sub-basins, are the baseline for the analysis (Linke et al. 2019, https://www.hydrosheds.org/hydroatlas). We used the coastal sub-basins at Pfafstetter level 12 (Verdin and Verdin 1999). Terrain slope (Robinson et al. 2014), aridity index (Zomer et al. 2008), population density (CIESIN 2016), and gross domestic product (GDP) per capita in administrative areas (Kummu et al. 2018) were taken from BasinATLAS. More information about BasinATLAS attributes can be retrieved from its documentation.

Topographic slope serves as a proxy for groundwater flow since it often relates to hydraulic gradients. The aridity index, defined as *Mean Annual Precipitation / Mean Annual Potential Evapotranspiration*, is used as a surrogate for (ground)water recharge. High population density is associated with SWI (Cao et al. 2021) since it comes with increased water demand and potentially increased groundwater extraction. GDP per capita is used to assess economic productivity in basins where researchers study coastal groundwater fluxes. Two variables were added to the dataset: the hydraulic conductivity by Huscroft et al. (2018) since it determines how far groundwater can flow per time, and fresh SGD estimates by Luijendijk et al. (2020) to compare locations of SGD and SWI studies with existing estimates. Terrain slope, aridity index, population density, GDP per capita, hydraulic conductivity, and fresh SGD show low to moderate correlation both for the entire set of coastal basins and for the subset of basins with a study site (Text S3, Tables S2 and S3).

3 A multitude of drivers impact coastal groundwater fluxes

Coastal groundwater fluxes are impacted by various causally-related drivers (Figure 1). Driven by hydraulic gradients, groundwater can enter the ocean as fresh SGD. In the reverse direction, ocean water may enter the aquifer, recharging it with saline water. This process is called submarine groundwater recharge (SGR) (Taniguchi et al. 2002). There are various potential pathways for ocean water in a coastal aquifer: (1) 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. However, specific conditions regarding permeability, beach slope, and groundwater flux are necessary (Evans and Wilson 2016). (2) Most SGR occurring in the subtidal zone circulates driven by density gradients (from differences in temperature or salinity). (3) Landward hydraulic gradients may cause horizontal intrusion of seawater that entered through SGR in the subtidal zone, moving the zone of brackish water landward. Thus, lateral SWI is driven by changes in land-sea hydraulic gradients. Hydraulic gradients are the result of aquifer hydraulic heads balancing semi-diurnal tidal changes, spring-neap tidal amplitude changes, seasonally changing sea levels, and sea level rise. Vertical SWI occurs when seawater recharges an aquifer from above through inundation caused by storm surge (Xiao and Tang

2019) or seawater flooding after subsidence (Eslami et al. 2021), and when seawater intrudes coastal rivers (Smith and Turner 2001). Causal relations exist between the drivers of coastal groundwater fluxes (e.g., precipitation and evapotranspiration impact GWR, which impacts the hydraulic head and, in turn, the hydraulic gradient) and thus the fluxes themselves. Since SWI is counteracted by drivers of SGD, all drivers that impact fresh SGD may also impact SWI.

Most drivers of coastal groundwater fluxes are affected by anthropogenic action and climate change (Figure 1). River flow reduction by dams and groundwater pumping lowers hydraulic gradients in coastal aquifers, reduces the amount of groundwater flowing to the ocean (Loc et al. 2021; Shi and Jiao 2014), and enables surface saltwater to intrude further into coastal rivers and deltaic estuaries (Mikhailova 2013; Peters et al. 2022). Such saltwater intrusion from surface water can occur more quickly than SWI into aquifers and induce vertical saltwater intrusion into the coastal aquifer if the adjacent aquifer is recharged from the coastal river (Hingst et al. 2022; Smith and Turner 2001). Generally, SWI into coastal aquifers is common in regions with high population densities (Cao et al. 2021) and groundwater pumping is likely the main driver of SWI (Ferguson and Gleeson 2012). Moreover, sea level rise slowly changes hydraulic gradients at the coast. Coastal basins with groundwater levels close to the surface (i.e., topography-limited) are expected to experience large increases in lateral SWI (Michael et al. 2013) because the water table cannot rise significantly in response to sea level rise. Additionally, sea level rise exacerbates flooding of coastal lowland and consequences of storm surges (Hoque et al. 2016). Few drivers experience minor or no impact of humans or climate change on them (e.g., topography, permeability).

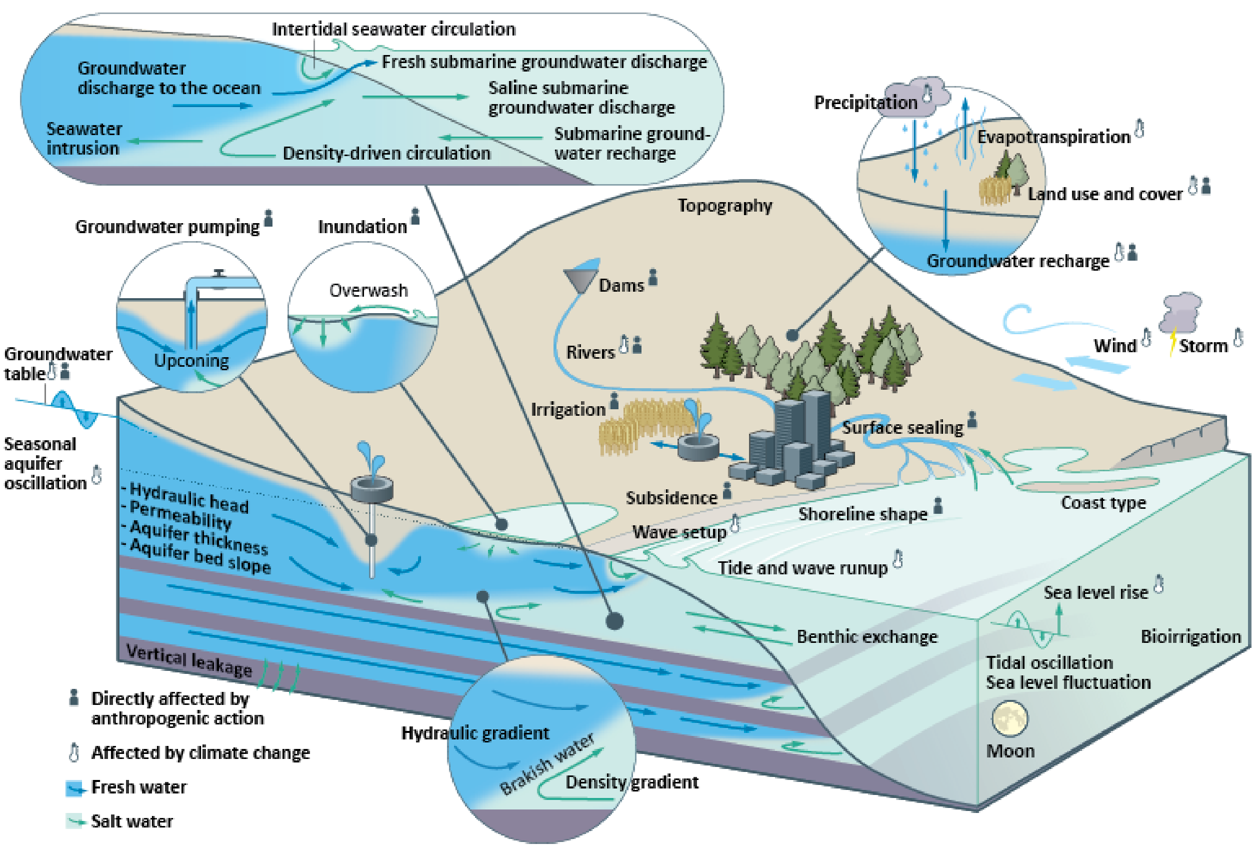

Figure 1. A perceptual model of coastal groundwater fluxes showing drivers of SGD and SWI, including which of these are impacted by anthropogenic action and/or climate change (Kretschmer & Reinecke 2023). The zoom-in at the top presents a detailed view of groundwater flows in the coastal subsurface, and the mixing zone of fresh and saline water.

4 Submarine groundwater discharge and seawater intrusion are rarely studied together while study site locations correlate with anthropogenic factors

The global distribution of coastal groundwater studies is uneven (Figure 2). In the 1298 records included in this meta-analysis, 841 different study sites were identified. Of these 841 sites, 26% were studied more than once, and 5% were studied five times or more. More than ten studies were found at Florida State University Coastal and Marine Laboratory, Indian River Lagoon (FL), Waquoit Bay (MA), Spiekeroog Island (Germany), Jeju Island (South Korea), and Laizhou Bay (China). Meanwhile, large parts of the global coastline, especially South America and Sub-Saharan Africa, remain unstudied. We find that regions close to large ecosystems (green areas in Figure 2, see also Figure S4), such as the Great Barrier Reef, may be frequently studied. However, less populated regions, like at the New Caledonia Barrier Reef, are less frequently studied. Many investigations were performed in proximity to coastal megacities (> 10 million inhabitants), especially in China and India.

SGD and SWI study sites are often far apart, and they are rarely studied in conjunction. In Southern Europe, and in proximity to the Yellow Sea, both SGD and SWI studies were found. While SGD studies dominate the eastern coasts of the USA and Australia (e.g., in proximity to the Great Barrier Reef and Florida Mangroves), SWI studies obtain the vast majority in North Africa and East India. SGD/ SWI study sites match with regions where total water storage estimations from GRACE are stable or increasing (East USA, East Australia)/ decreasing (e.g., East of India, North-East of China, North Africa) (Scanlon et al. 2023). SGD studies make up almost 75% of all coastal studies conducted at a coastal ecosystem (i.e., lagoons, mangroves, salt marshes, estuaries, and coral reefs) (46% of all coastal SGD studies). As a result, SGD and SWI study sites rarely overlap and are often far apart. Just 5% of all analyzed studies looked at SGD and SWI simultaneously. Areas for which global hydrological models project severe reductions (> 10 mm/year) in GWR compared to pre-industrial times at a 2°C global warming are shown in light red (Reinecke et al. 2020). If GWR reduces as expected or groundwater pumping increases, SWI might become an issue in large parts of the US East Coast, South Europe to the Middle East, and East China.

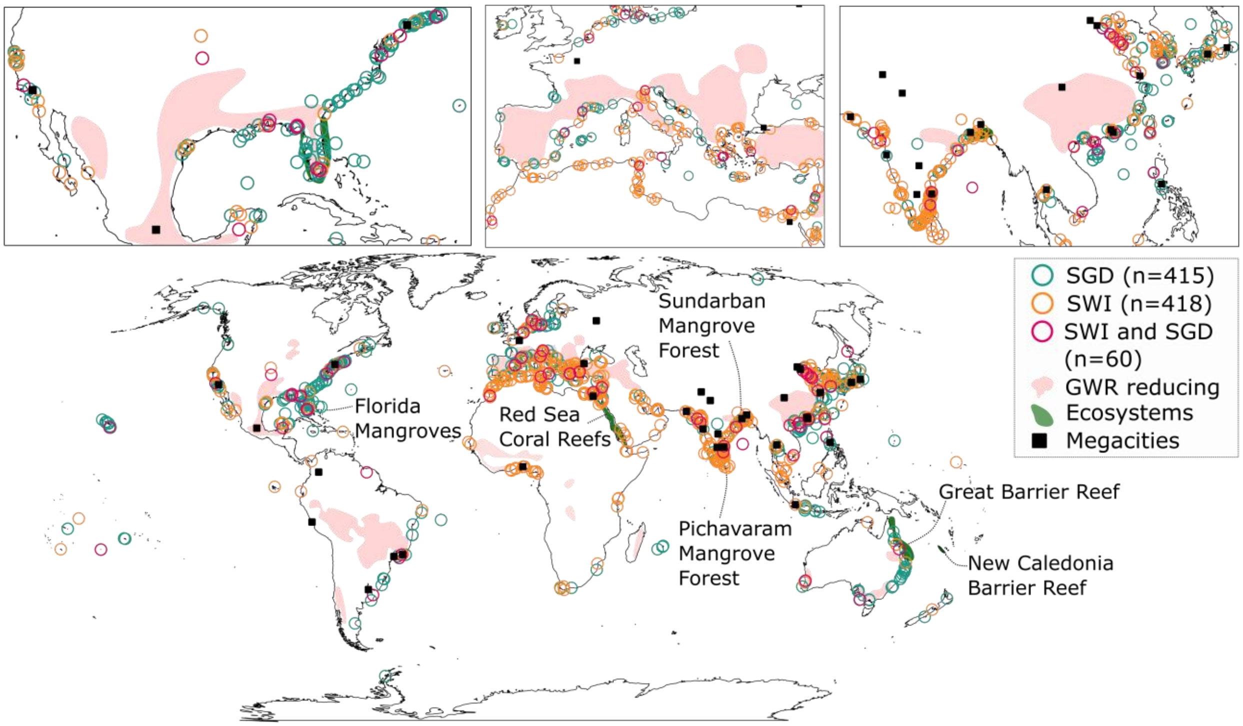

Figure 2. Study locations of SGD, SWI, and both. Zoom-ins at the top show frequently studied regions in North America, Mediterranean, and Asia in more detail. Red areas are regions with a projected reduction in GWR due to climate change (adapted from Reinecke et al. (2020)). Green areas show large marine ecosystems (better visible in Figure S4). Black squares mark the location of 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

SGD and SWI are studied where they are likely to be observed. Figure 3 displays cumulative density functions (CDF) of selected attributes of all coastal basins (in grey) and those coastal basins with SGD and/or SWI study sites in proximity. The plots show that, compared to the CDF of all coastal basins, basins with SWI and/or SGD studies have rather low terrain slopes, frequently below 2°. Among the SWI studies, 80% were done in basins with a relatively permeable, or “good“ aquifer (hydraulic conductivity >10^{-5} m/s) (Bear 1972). Very few SGD studies are conducted where hydraulic conductivity is below 10^{-7} m/s, and the CDF strongly rises between 10^{-6} m/s and 10^{-4} m/s. Since SGD often is a surficial process (like SGD through a beach) and the assessed permeability data do not necessarily reflect this surficial aquifer, it makes sense that SGD studies are done already at basins with lower hydraulic conductivity values than SWI studies. While water-limited basins (aridity index below 1) make up 75% of SWI study sites (Zomer et al. 2008), approximately 90% of SGD studies were done where the aridity index is above 0.5. SGD estimations from Luijendijk et al. (2020) match well with the occurrence of SWI or SGD studies. Among all studies in coastal basins with fresh SGD estimation above 10 m^2/year, SWI/SGD studies make up 33%/57%. Overall, this is not very surprising since study site selection is either based on an existing problem (e.g. rising groundwater salinity levels) or requires the expectation of measurable flows or tracers.

Approximately 70%/80% of SGD/SWI studies were made in basins with a population density over 100 people/km^2, which occurs only in 20% of all coastal basins. Over half of SWI studies are performed in urban (population density ≥ 300 people/km^2) coastal basins (Eurostat 2021), which occurs in only 13% of all coastal basins. GDP strongly separates the lines of SGD and SWI study site locations: Only 15% of all SGD studies took place in regions with a GDP per capita below the global mean (~12’200 USD), but 50% of all coastal SWI studies (Worldbank 2022). Also, 80% of SWI/SGD studies were located at basins with GDP per capita over 6’000 USD/20’000 USD. Groundwater salinity issues related to SWI, which can be decisive for agricultural and domestic water use, seem to be more pressing than SGD-related topics (e.g., coastal ecosystems). Located between the lines of SGD and SWI, the CDFs of joint studies are close to those of all coastal basins. The CDFs of GDP and population density reflect the global spatial distribution of the study sites (Figure 2). Overall, population density and GDP per capita are important anthropogenic indicators of study site locations. This may be due to the increased use of groundwater in highly populated regions, and due to the increased number of studies published in international literature in highly populated and developed areas. However, this is largely unknown since no global groundwater pumping dataset exists (Reinecke et al. 2023).

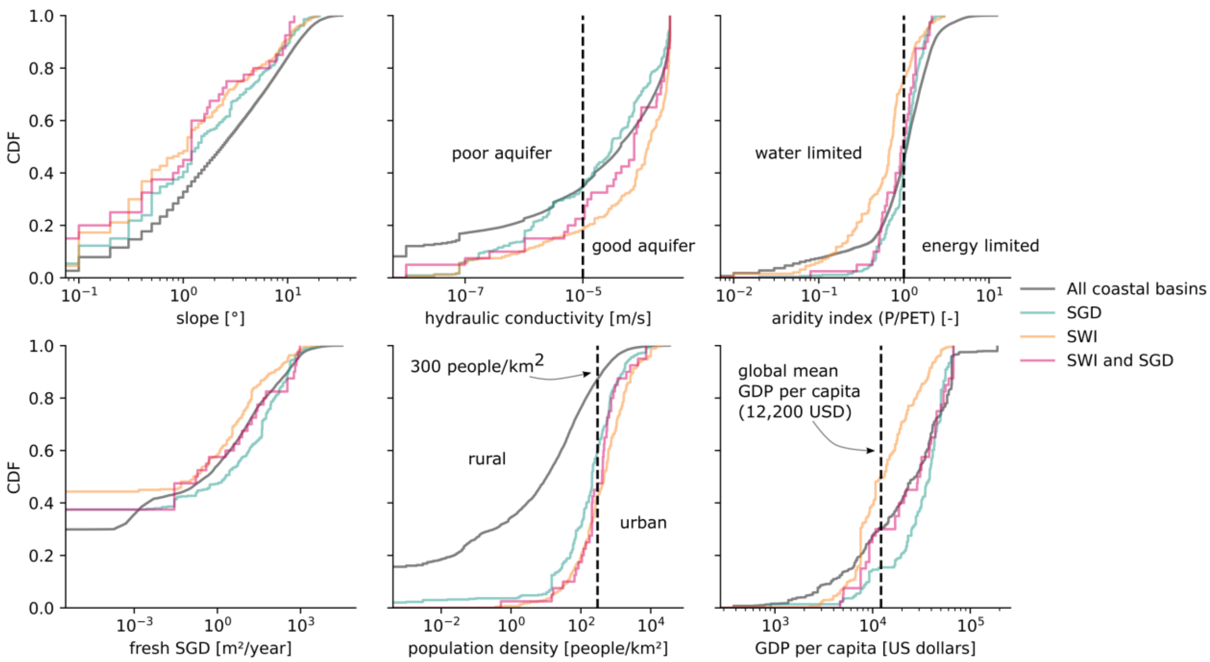

Figure 3. Cumulative density functions (CDFs) of selected attributes (slope, hydraulic conductivity, aridity index, fresh SGD, population density, and GDP per capita) of coastal basins (grey lines). Colored lines show the CDF of coastal basins assigned to studies on SGD (cyan lines), SWI (orange lines), or both (pink lines).

The pronounced separation of SGD studies from SWI studies has numerous reasons, and conducting more joint investigations of SGD and SWI could improve our understanding of both processes. Figure 3 displays the differences in study sites between SWI and SGD publications, with GDP, aridity index, and hydraulic conductivity showing strong separations. This separation exists due to the low interaction between scientific communities: a network analysis using all 5896 records shows that communities within some countries (e.g. South Korea, India) tend to cluster together and that only few SGD and SWI researchers publish together regularly (Figure S5). Of the 3527 different authors of publications included in this analysis, just 123 were found on a publication about SWI and about SGD; of the 276 authors that studied SWI and SGD simultaneously, 122 were also found on SWI or SGD studies. Only 18 authors were assigned to all three study types in this analysis, which demonstrates the scarcity of interdisciplinarity. Since SGD and SWI are connected, studying SWI together with SGD can help understanding the underlying processes and trends. Half of the evaluated studies focus on hydrochemistry or the transport of substances through SGD and/or SGD. Chemical reactions can be induced by saltwater (Slomp and van Cappellen 2004) and a regular change between fresh and salty environments (Santos et al. 2021), changing the groundwater composition. Thus, SGD studies may benefit from considering the spatial distribution of SWI in coastal aquifers.

5 Spatial and temporal scales of drivers of SGD and SWI are uncertain

Drivers of SWI and SGD act over a wide range of spatial and temporal scales. Figure 4 shows the spatiotemporal scales at which drivers impact SWI and SGD, based on all included records in this meta-analysis which focus on drivers of SWI or SGD. We take a similar approach to the scales figure by Taniguchi et al. (2019), but instead of expert knowledge, our plot is based on the available literature (65 publications). The plotted scales span from half a day to millennia and 1 meter to 10’000 meters perpendicular to the coastline. The scales of the impact of sea level change on SWI span across multiple temporal and spatial scales, from seasonal to millennia and from 100 m to 10 km scale. More drivers than shown here were assessed in the analyzed literature, but often the assessed publications do not report both spatial and temporal scales (Text S4). The full table of drivers (Table S4) shows that knowledge of spatial scales significantly lacks behind knowledge of temporal scales. Comparing the presented findings with the many drivers in the perceptual model (Figure 1) shows that influence scales of drivers are rarely investigated.

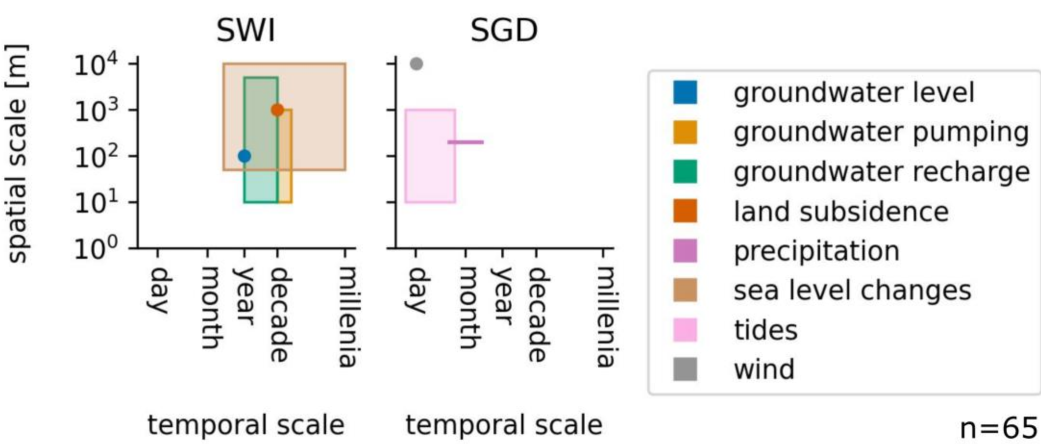

Figure 4. Spatiotemporal scales of the impact of drivers on SWI and SGD based on included publications focusing on drivers of SWI or SGD (n=65). Rectangles are drawn for drivers known to span across spatial and temporal scales, lines for drivers known to act across one of these scales. Dots are shown for drivers that were found to act at one spatiotemporal scale only in the

literature. For further drivers (having information only on either spatial or temporal scale), see Table S4. Spatial scale is perpendicular to the coastline. Both axes show logarithmic scale.

Our process understanding is limited due to study site selection practices and the small number of studies exploring impact scales of drivers. We find that published studies of SGD and SWI are generally conducted in basins with conditions enabling their measurement - with SWI study sites that often are dry, flat, or have a high hydraulic conductivity - and with high population density or GDP. This practice has created a strongly imbalanced distribution of study sites across the globe where some regions are studied many times and most parts of the global coastline remain unstudied (Figure 2). We presume that the scales investigated in the analyzed literature are biased by existing research and established methods. Also, the results of this meta-analysis are biased due to its setup focusing on published journal articles, adopting an inherent publication bias (Dickersin and Min 1993). Since many studies of SGD and SWI are conducted in regions that are strongly impacted by anthropogenic action, their results should be interpreted cautiously in terms of process understanding. Exploration of driver scales is a knowledge gap in coastal groundwater research. To gain further process understanding, particularly spatial scales of drivers impacting SGD and SWI need to be addressed more explicitly. Establishing standard frameworks for assessing and reporting driver influences and scales is necessary to enhance transferability and statistical analysis. Jointly studying coastal groundwater, assessing remote locations of Sub-Saharan Africa and South America, exploring spatiotemporal scales of driver impact, and a standard of reporting impact scales are key to closing knowledge gaps.

6 Conclusions

A global understanding of coastal groundwater is vital in tackling current and future water resource challenges. Therefore, we have conducted a meta-analysis of studies on coastal groundwater fluxes, their drivers, study locations, and driver scales. We find that SGD and SWI are controlled by interacting drivers, but are rarely studied in conjunction. Both are mostly studied in coastal basins with high population densities, where we can expect to measure fluxes (SGD at high permeabilities, SWI in water-limited regions) and at large-scale coastal ecosystems (mainly SGD). Economic development is another key factor: 80% of SWI studies were conducted at basins with GDP per capita over 6’000 USD, and 80% of SGD studies at basins with GDP per capita over 20’000 USD. Hence, current research rarely addresses coastal groundwater issues where GDP is lower. The African coast, while having the highest population growth rates around the world (Neumann et al. 2015), remains understudied in the international literature, with just a few hotspots of severe SWI which are well known (Steyl and Dennis 2010). Given the relatively low GDP in many African coastal basins, international research funding is key to enable studies in this region. Drivers impact SGD and SWI at a wide range of spatial and temporal scales, which are uncertain since coastal configurations are diverse and because driver scales are rarely explored. Future SWI and SGD studies need to focus on process understanding and joint assessments, explicitly report driver impact scales, and explore unchartered coastlines.

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Author Contributions

Daniel Kretschmer performed conceptualization, methodology, formal analysis, writing – original draft, and visualization. Robert Reinecke performed conceptualization, methodology, writing – review and editing, supervision, project administration, and funding acquisition. Thorsten Wagener performed supervision, writing – review and editing. Nils Moosdorf, Holly Michael, Gualbert Oude Essink and Mark Bierkens performed writing – review, and editing.

Availability statement

- The table of publications with extracted information is available as a supplemental CSV file: TableOfPublications.csv
- The perceptual model (in Figure 1) is available as a supplemental PDF file and published at https://doi.org/10.5281/zenodo.8004309
- 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
- The hydraulic conductivity data of the GLHYMPS 2.0 product is available at: https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU

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Submarine Groundwater Discharge and Seawater Intrusion: Two sides of the same coin that are rarely studied simultaneously

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Key Points:

- Coastal groundwater flow drivers interact (hydraulic and density gradients, tides, and waves) but fluxes are rarely studied simultaneously.
- Submarine groundwater discharge and seawater intrusion are understudied in regions with low gross domestic product or population density.
- Drivers of coastal groundwater fluxes act across scales. Standard frameworks for reporting impact scales could help close knowledge gaps.

Abstract

Fresh submarine groundwater discharge (SGD) and seawater intrusion (SWI) are complementary processes at the interface of coastal groundwater and oceans. Multiple common drivers enable or limit SGD and SWI. However, we find that SGD and SWI are rarely studied simultaneously. In this meta-analysis, we synthesize 1298 publications, examining drivers of SGD and SWI, where and why they are studied, and at which scales they are impacted by their drivers. Studies of SGD and SWI accumulate in urban coastal basins with high gross domestic product (GDP), and high permeabilities, where measurable groundwater fluxes are expected. We find, that studies investigate various drivers, but rarely assess the scales they act at. Effects of temporally recurring processes (e.g., tides) are studied more often and are better known than effects of spatial variability (e.g., permeability). Future studies should investigate SGD and SWI simultaneously, report impact scales of drivers explicitly and explore unchartered coastlines.

Plain Language Summary

The interaction between underground water and the ocean in coastal areas is influenced by two processes: fresh submarine groundwater discharge (SGD) and seawater intrusion (SWI). However, these processes are rarely studied together. We examined 1298 publications to understand why and where SGD and SWI are studied and the scales at which they are impacted by their drivers, the factors that enable or limit flow. Most studies focus on urban coastal areas with high economic activity and permeable soil, where measurable water flow between groundwater and the ocean is expected. Although different drivers are investigated, their impact scales are seldom examined. Temporal variations, like tides, are more commonly studied and understood compared to spatial variations, such as soil permeability. Future studies should investigate SGD and SWI concurrently, explicitly report driver impact scales, and explore unstudied coastal areas.

1 Introduction

Groundwater is essential to meet coastal freshwater demand and strongly impacts coastal ecosystems. Compared to surface water, groundwater is more resilient to droughts and less vulnerable to contaminants. Making up 99% of the world's available freshwater (Gleeson et al. 2016), groundwater is a major source of water for domestic and agricultural purposes in African (Steyl and Dennis 2010), US American (Barlow and Reichard 2010), South American (Bocanegra et al. 2010), Indian (Pandian et al. 2016), Chinese (Shi and Jiao 2014) and European (Custodio 2010) coastal regions. Water resources at the coast are crucial to reach sustainable development goals (2) "zero hunger" and (6) "clean water and sanitation", since 40% of the global population live within 100 km of the coast (Crossland et al. 2005; UN 2017). Besides humans, coastal ecosystems are affected by coastal groundwater (Herbert et al. 2015). Submarine groundwater discharge (SGD) - the flow of groundwater into oceans - can be critical for coastal ecosystems, enhancing primary production and attenuating pollutants, but can also be detrimental, causing eutrophication and ocean acidification (Santos et al. 2021). Seawater intrusion (SWI), the landward movement of saline water into coastal aquifers, is a major threat to stygofauna in freshwater aquifers (Saccò et al. 2022).

High freshwater demand and climate change have already reduced hydraulic gradients, decreasing SGD, and causing SWI. Already, 32% of the global coastal metropolitan cities have been threatened by SWI (Cao et al. 2021), and many cities facing severe water shortages are located at the coast (Savelli et al. 2023). This situation is exacerbated by the expected doubling of the coastal city population from 2000 to 2060 (Neumann et al. 2015). Anthropogenic activity reduces groundwater flow to the coast in various ways, e.g., through river dams, urbanization, 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 comes from groundwater pumping, which is also considered the main cause of SWI (Ferguson and Gleeson 2012; Post et al. 2018). Sea level rise from global climate change will further reduce the amount of fresh groundwater at the coast (Alsumaiei and Bailey 2018; IPCC 2022; Oude Essink et al. 2010) and likely increase the threat of over-wash and storm surges (Oberle et al. 2017; Gingerich et al. 2017; Cantelon et al. 2022).

Current process understanding is limited, and global estimates of SGD are highly uncertain. Luijendijk et al. (2020) show that global fresh SGD may lie between 0.4 and 210 km^3/year and available large-scale assessments of SWI are limited to countries or global assessments of vulnerability (Michael et al. 2013; Sawyer et al. 2016). Recent studies show the attribution of SGD to enhanced primary production in coastal ecosystems (Kobayashi et al. 2017; Andrisoa et al. 2019; Maher et al. 2019; Starke et al. 2020), but assessing its importance remains challenging (Liu et al. 2021).

SGD and SWI are complementary processes driven by hydraulic gradients at the land-sea boundary (Robinson et al. 2018; Taniguchi et al. 2002). Hydraulic gradients determine fresh SGD rates and the position of the salt-fresh water mixing zone. Fresh SGD still occurs when seawater intrudes – they are not exclusive processes. But changes in hydraulic gradients create changes in SGD and the mixing zone position (Michael et al. 2005; Heiss et al. 2020). However, here we show that scientific communities studying the two processes tend to be separate – with water resources scientists focusing on SWI and coastal ecologists/oceanographers focusing on SGD and its impacts on coastal waters.

In this meta-analysis, we synthesize 1298 publications to delineate drivers of SGD and SWI, understand where and why they are studied, and at what spatial- and temporal-scales drivers impact SGD and SWI.

2 Materials and Methods

In this meta-analysis of publications on coastal groundwater fluxes, we retrieved 5896 publications from Web of Science by searching in all fields terms related to coastal groundwater, SWI and SGD (Text S1). Criteria for inclusion are (1) the main topic is related to coastal groundwater fluxes, (2) the study was conducted in proximity to an ocean coast, hence, excluding reviews and theoretical modeling studies, (3) the language is English, (4) it was published online before 2022. The screening process was assisted by AS Review, a software using artificial intelligence to propose publications based on our previous decisions on the relevance of publications (https://asreview.nl/ and Text S2). Due to time constraints, not all 5896 records could be screened. Instead, screening was concluded after 1502 records. Of those, 1332 were deemed relevant and only 170 were excluded, mostly because the topic was not related to coastal groundwater fluxes (Figure S1). The use of AS Review increased the share of relevant records among the retrieved publications from about 25% to almost 90% according to AS Review (Figure S2).

The 1332 records classified as relevant in the screening were complemented by 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 analyzed 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). Additionally, spatial and temporal scales of driver impact on SGD and SWI were extracted from records that focused on flow drivers as their main topic.

The coastal basins of the BasinATLAS dataset, providing hydro-environmental data for sub-basins, are the baseline for the analysis (Linke et al. 2019, https://www.hydrosheds.org/hydroatlas). We used the coastal sub-basins at Pfafstetter level 12 (Verdin and Verdin 1999). Terrain slope (Robinson et al. 2014), aridity index (Zomer et al. 2008), population density (CIESIN 2016), and gross domestic product (GDP) per capita in administrative areas (Kummu et al. 2018) were taken from BasinATLAS. More information about BasinATLAS attributes can be retrieved from its documentation.

Topographic slope serves as a proxy for groundwater flow since it often relates to hydraulic gradients. The aridity index, defined as *Mean Annual Precipitation / Mean Annual Potential Evapotranspiration*, is used as a surrogate for (ground)water recharge. High population density is associated with SWI (Cao et al. 2021) since it comes with increased water demand and potentially increased groundwater extraction. GDP per capita is used to assess economic productivity in basins where researchers study coastal groundwater fluxes. Two variables were added to the dataset: the hydraulic conductivity by Huscroft et al. (2018) since it determines how far groundwater can flow per time, and fresh SGD estimates by Luijendijk et al. (2020) to compare locations of SGD and SWI studies with existing estimates. Terrain slope, aridity index, population density, GDP per capita, hydraulic conductivity, and fresh SGD show low to moderate correlation both for the entire set of coastal basins and for the subset of basins with a study site (Text S3, Tables S2 and S3).

3 A multitude of drivers impact coastal groundwater fluxes

Coastal groundwater fluxes are impacted by various causally-related drivers (Figure 1). Driven by hydraulic gradients, groundwater can enter the ocean as fresh SGD. In the reverse direction, ocean water may enter the aquifer, recharging it with saline water. This process is called submarine groundwater recharge (SGR) (Taniguchi et al. 2002). There are various potential pathways for ocean water in a coastal aquifer: (1) 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. However, specific conditions regarding permeability, beach slope, and groundwater flux are necessary (Evans and Wilson 2016). (2) Most SGR occurring in the subtidal zone circulates driven by density gradients (from differences in temperature or salinity). (3) Landward hydraulic gradients may cause horizontal intrusion of seawater that entered through SGR in the subtidal zone, moving the zone of brackish water landward. Thus, lateral SWI is driven by changes in land-sea hydraulic gradients. Hydraulic gradients are the result of aquifer hydraulic heads balancing semi-diurnal tidal changes, spring-neap tidal amplitude changes, seasonally changing sea levels, and sea level rise. Vertical SWI occurs when seawater recharges an aquifer from above through inundation caused by storm surge (Xiao and Tang

2019) or seawater flooding after subsidence (Eslami et al. 2021), and when seawater intrudes coastal rivers (Smith and Turner 2001). Causal relations exist between the drivers of coastal groundwater fluxes (e.g., precipitation and evapotranspiration impact GWR, which impacts the hydraulic head and, in turn, the hydraulic gradient) and thus the fluxes themselves. Since SWI is counteracted by drivers of SGD, all drivers that impact fresh SGD may also impact SWI.

Most drivers of coastal groundwater fluxes are affected by anthropogenic action and climate change (Figure 1). River flow reduction by dams and groundwater pumping lowers hydraulic gradients in coastal aquifers, reduces the amount of groundwater flowing to the ocean (Loc et al. 2021; Shi and Jiao 2014), and enables surface saltwater to intrude further into coastal rivers and deltaic estuaries (Mikhailova 2013; Peters et al. 2022). Such saltwater intrusion from surface water can occur more quickly than SWI into aquifers and induce vertical saltwater intrusion into the coastal aquifer if the adjacent aquifer is recharged from the coastal river (Hingst et al. 2022; Smith and Turner 2001). Generally, SWI into coastal aquifers is common in regions with high population densities (Cao et al. 2021) and groundwater pumping is likely the main driver of SWI (Ferguson and Gleeson 2012). Moreover, sea level rise slowly changes hydraulic gradients at the coast. Coastal basins with groundwater levels close to the surface (i.e., topography-limited) are expected to experience large increases in lateral SWI (Michael et al. 2013) because the water table cannot rise significantly in response to sea level rise. Additionally, sea level rise exacerbates flooding of coastal lowland and consequences of storm surges (Hoque et al. 2016). Few drivers experience minor or no impact of humans or climate change on them (e.g., topography, permeability).

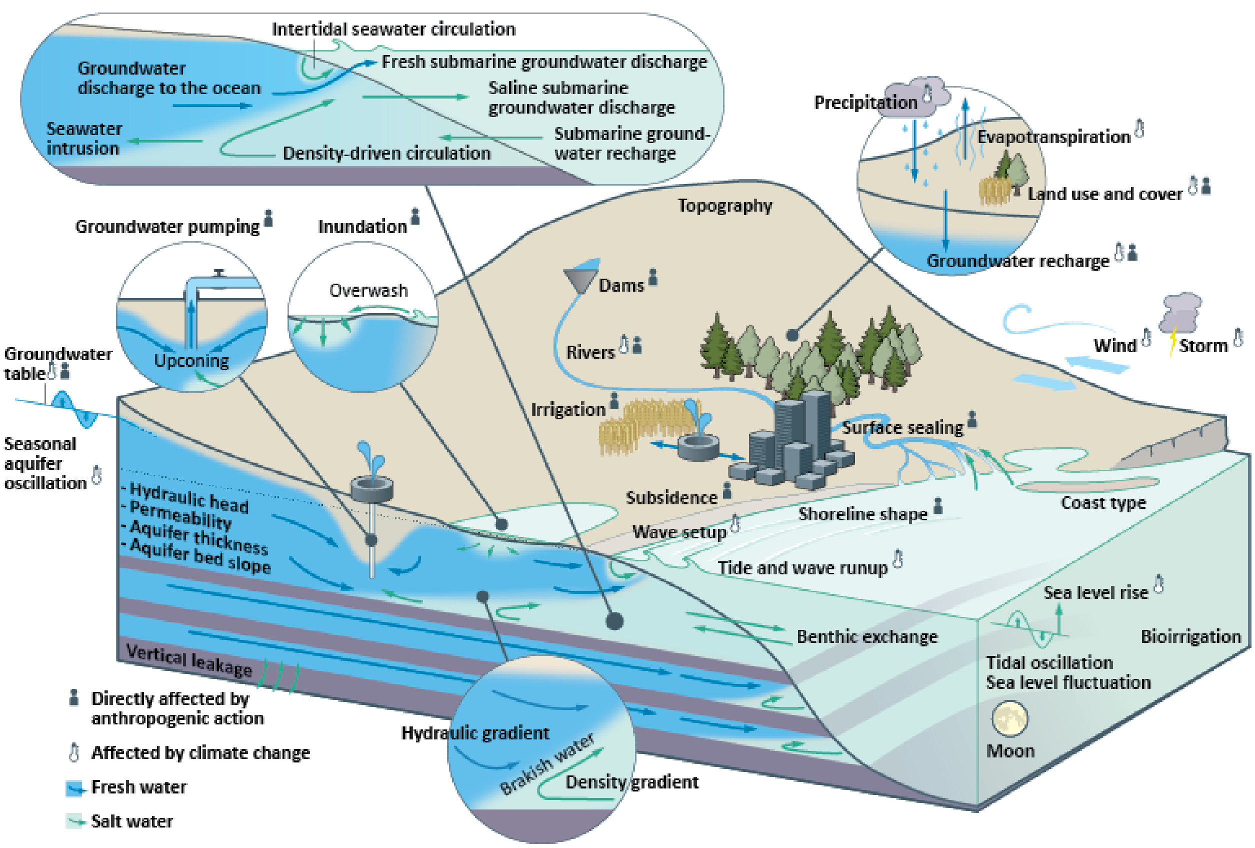

Figure 1. A perceptual model of coastal groundwater fluxes showing drivers of SGD and SWI, including which of these are impacted by anthropogenic action and/or climate change (Kretschmer & Reinecke 2023). The zoom-in at the top presents a detailed view of groundwater flows in the coastal subsurface, and the mixing zone of fresh and saline water.

4 Submarine groundwater discharge and seawater intrusion are rarely studied together while study site locations correlate with anthropogenic factors

The global distribution of coastal groundwater studies is uneven (Figure 2). In the 1298 records included in this meta-analysis, 841 different study sites were identified. Of these 841 sites, 26% were studied more than once, and 5% were studied five times or more. More than ten studies were found at Florida State University Coastal and Marine Laboratory, Indian River Lagoon (FL), Waquoit Bay (MA), Spiekeroog Island (Germany), Jeju Island (South Korea), and Laizhou Bay (China). Meanwhile, large parts of the global coastline, especially South America and Sub-Saharan Africa, remain unstudied. We find that regions close to large ecosystems (green areas in Figure 2, see also Figure S4), such as the Great Barrier Reef, may be frequently studied. However, less populated regions, like at the New Caledonia Barrier Reef, are less frequently studied. Many investigations were performed in proximity to coastal megacities (> 10 million inhabitants), especially in China and India.

SGD and SWI study sites are often far apart, and they are rarely studied in conjunction. In Southern Europe, and in proximity to the Yellow Sea, both SGD and SWI studies were found. While SGD studies dominate the eastern coasts of the USA and Australia (e.g., in proximity to the Great Barrier Reef and Florida Mangroves), SWI studies obtain the vast majority in North Africa and East India. SGD/ SWI study sites match with regions where total water storage estimations from GRACE are stable or increasing (East USA, East Australia)/ decreasing (e.g., East of India, North-East of China, North Africa) (Scanlon et al. 2023). SGD studies make up almost 75% of all coastal studies conducted at a coastal ecosystem (i.e., lagoons, mangroves, salt marshes, estuaries, and coral reefs) (46% of all coastal SGD studies). As a result, SGD and SWI study sites rarely overlap and are often far apart. Just 5% of all analyzed studies looked at SGD and SWI simultaneously. Areas for which global hydrological models project severe reductions (> 10 mm/year) in GWR compared to pre-industrial times at a 2°C global warming are shown in light red (Reinecke et al. 2020). If GWR reduces as expected or groundwater pumping increases, SWI might become an issue in large parts of the US East Coast, South Europe to the Middle East, and East China.

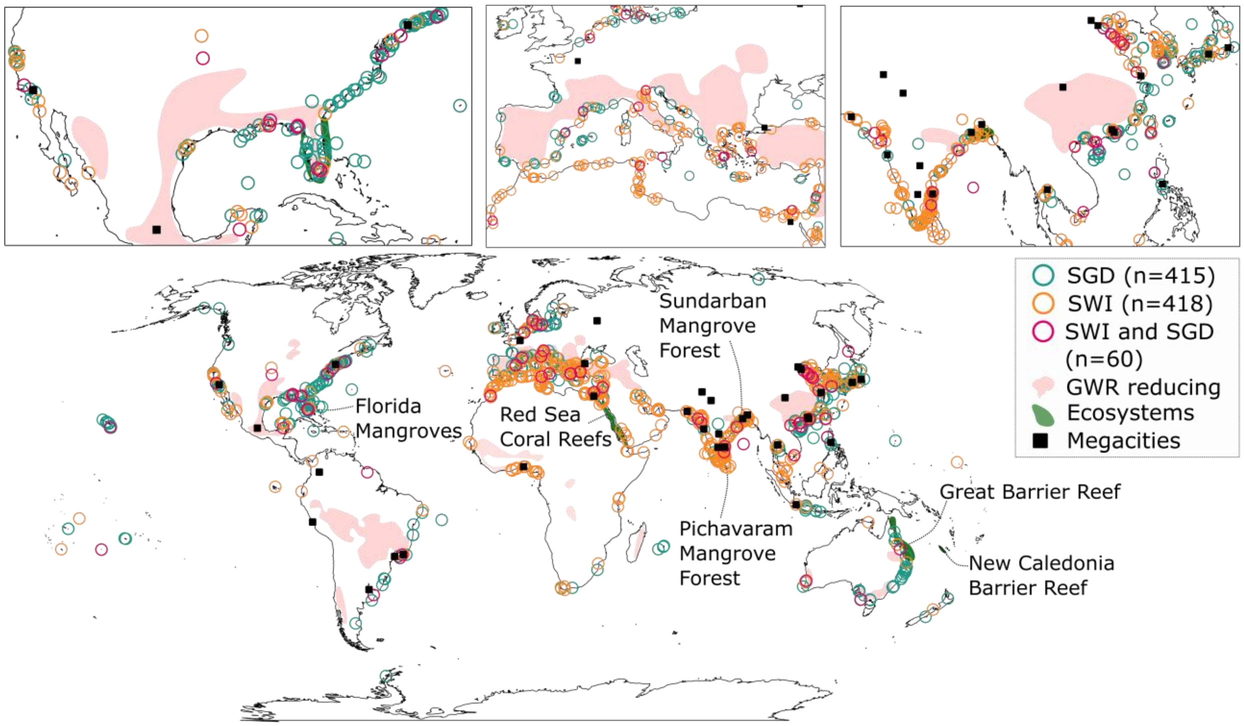

Figure 2. Study locations of SGD, SWI, and both. Zoom-ins at the top show frequently studied regions in North America, Mediterranean, and Asia in more detail. Red areas are regions with a projected reduction in GWR due to climate change (adapted from Reinecke et al. (2020)). Green areas show large marine ecosystems (better visible in Figure S4). Black squares mark the location of 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

SGD and SWI are studied where they are likely to be observed. Figure 3 displays cumulative density functions (CDF) of selected attributes of all coastal basins (in grey) and those coastal basins with SGD and/or SWI study sites in proximity. The plots show that, compared to the CDF of all coastal basins, basins with SWI and/or SGD studies have rather low terrain slopes, frequently below 2°. Among the SWI studies, 80% were done in basins with a relatively permeable, or "good" aquifer (hydraulic conductivity >10^{-5} m/s) (Bear 1972). Very few SGD studies are conducted where hydraulic conductivity is below 10^{-7} m/s, and the CDF strongly rises between 10^{-6} m/s and 10^{-4} m/s. Since SGD often is a surficial process (like SGD through a beach) and the assessed permeability data do not necessarily reflect this surficial aquifer, it makes sense that SGD studies are done already at basins with lower hydraulic conductivity values than SWI studies. While water-limited basins (aridity index below 1) make up 75% of SWI study sites (Zomer et al. 2008), approximately 90% of SGD studies were done where the aridity index is above 0.5. SGD estimations from Luijendijk et al. (2020) match well with the occurrence of SWI or SGD studies. Among all studies in coastal basins with fresh SGD estimation above 10 m^2/year, SWI/SGD studies make up 33%/57%. Overall, this is not very surprising since study site selection is either based on an existing problem (e.g. rising groundwater salinity levels) or requires the expectation of measurable flows or tracers.

Approximately 70%/80% of SGD/SWI studies were made in basins with a population density over 100 people/km^2, which occurs only in 20% of all coastal basins. Over half of SWI studies are performed in urban (population density $\geq$ 300 people/km^2) coastal basins (Eurostat 2021), which occurs in only 13% of all coastal basins. GDP strongly separates the lines of SGD and SWI study site locations: Only 15% of all SGD studies took place in regions with a GDP per capita below the global mean (~12'200 USD), but 50% of all coastal SWI studies (Worldbank 2022). Also, 80% of SWI/SGD studies were located at basins with GDP per capita over 6'000 USD/20'000 USD. Groundwater salinity issues related to SWI, which can be decisive for agricultural and domestic water use, seem to be more pressing than SGD-related topics (e.g., coastal ecosystems). Located between the lines of SGD and SWI, the CDFs of joint studies are close to those of all coastal basins. The CDFs of GDP and population density reflect the global spatial distribution of the study sites (Figure 2). Overall, population density and GDP per capita are important anthropogenic indicators of study site locations. This may be due to the increased use of groundwater in highly populated regions, and due to the increased number of studies published in international literature in highly populated and developed areas. However, this is largely unknown since no global groundwater pumping dataset exists (Reinecke et al. 2023).

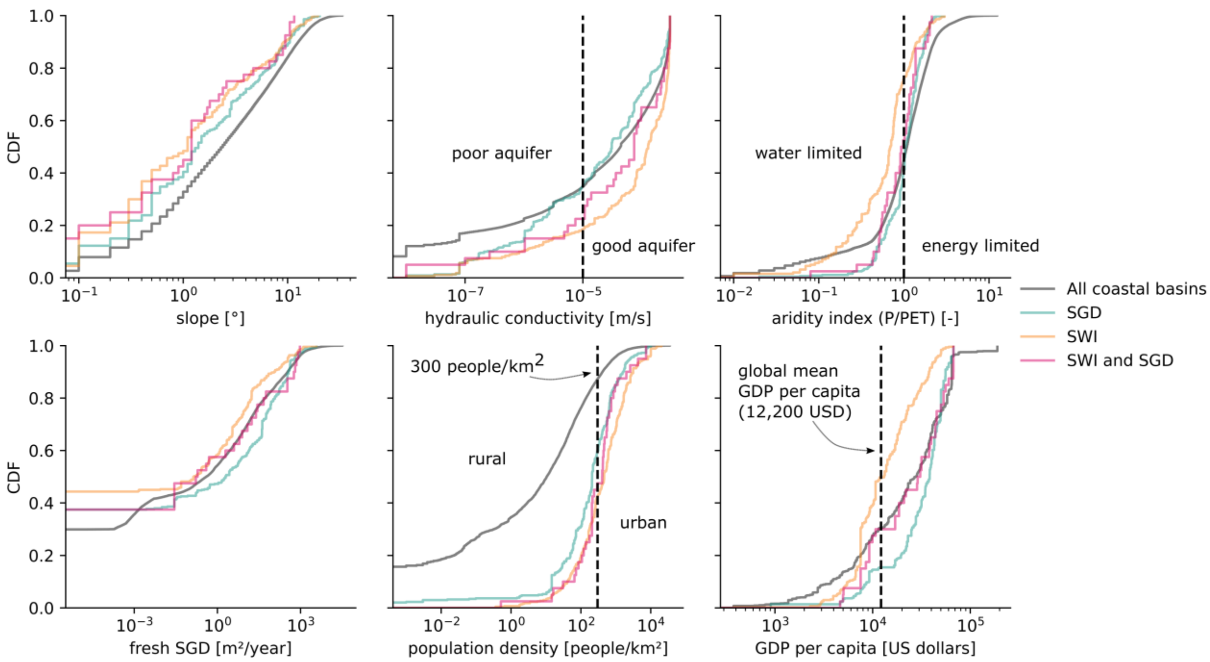

Figure 3. Cumulative density functions (CDFs) of selected attributes (slope, hydraulic conductivity, aridity index, fresh SGD, population density, and GDP per capita) of coastal basins (grey lines). Colored lines show the CDF of coastal basins assigned to studies on SGD (cyan lines), SWI (orange lines), or both (pink lines).

The pronounced separation of SGD studies from SWI studies has numerous reasons, and conducting more joint investigations of SGD and SWI could improve our understanding of both processes. Figure 3 displays the differences in study sites between SWI and SGD publications, with GDP, aridity index, and hydraulic conductivity showing strong separations. This separation exists due to the low interaction between scientific communities: a network analysis using all 5896 records shows that communities within some countries (e.g. South Korea, India) tend to cluster together and that only few SGD and SWI researchers publish together regularly (Figure S5). Of the 3527 different authors of publications included in this analysis, just 123 were found on a publication about SWI and about SGD; of the 276 authors that studied SWI and SGD simultaneously, 122 were also found on SWI or SGD studies. Only 18 authors were assigned to all three study types in this analysis, which demonstrates the scarcity of interdisciplinarity. Since SGD and SWI are connected, studying SWI together with SGD can help understanding the underlying processes and trends. Half of the evaluated studies focus on hydrochemistry or the transport of substances through SGD and/or SGD. Chemical reactions can be induced by saltwater (Slomp and van Cappellen 2004) and a regular change between fresh and salty environments (Santos et al. 2021), changing the groundwater composition. Thus, SGD studies may benefit from considering the spatial distribution of SWI in coastal aquifers.

5 Spatial and temporal scales of drivers of SGD and SWI are uncertain

Drivers of SWI and SGD act over a wide range of spatial and temporal scales. Figure 4 shows the spatiotemporal scales at which drivers impact SWI and SGD, based on all included records in this meta-analysis which focus on drivers of SWI or SGD. We take a similar approach to the scales figure by Taniguchi et al. (2019), but instead of expert knowledge, our plot is based on the available literature (65 publications). The plotted scales span from half a day to millennia and 1 meter to 10’000 meters perpendicular to the coastline. The scales of the impact of sea level change on SWI span across multiple temporal and spatial scales, from seasonal to millennia and from 100 m to 10 km scale. More drivers than shown here were assessed in the analyzed literature, but often the assessed publications do not report both spatial and temporal scales (Text S4). The full table of drivers (Table S4) shows that knowledge of spatial scales significantly lacks behind knowledge of temporal scales. Comparing the presented findings with the many drivers in the perceptual model (Figure 1) shows that influence scales of drivers are rarely investigated.

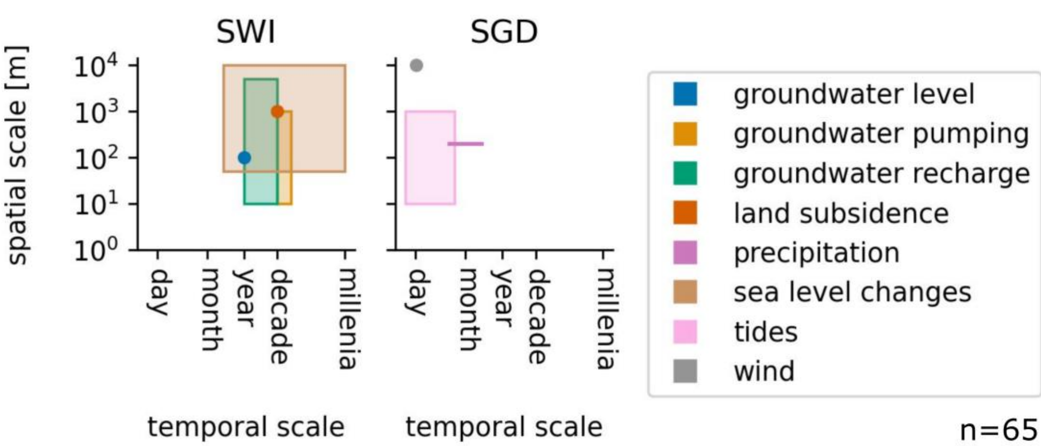

Figure 4. Spatiotemporal scales of the impact of drivers on SWI and SGD based on included publications focusing on drivers of SWI or SGD (n=65). Rectangles are drawn for drivers known to span across spatial and temporal scales, lines for drivers known to act across one of these scales. Dots are shown for drivers that were found to act at one spatiotemporal scale only in the

literature. For further drivers (having information only on either spatial or temporal scale), see Table S4. Spatial scale is perpendicular to the coastline. Both axes show logarithmic scale.

Our process understanding is limited due to study site selection practices and the small number of studies exploring impact scales of drivers. We find that published studies of SGD and SWI are generally conducted in basins with conditions enabling their measurement - with SWI study sites that often are dry, flat, or have a high hydraulic conductivity - and with high population density or GDP. This practice has created a strongly imbalanced distribution of study sites across the globe where some regions are studied many times and most parts of the global coastline remain unstudied (Figure 2). We presume that the scales investigated in the analyzed literature are biased by existing research and established methods. Also, the results of this meta-analysis are biased due to its setup focusing on published journal articles, adopting an inherent publication bias (Dickersin and Min 1993). Since many studies of SGD and SWI are conducted in regions that are strongly impacted by anthropogenic action, their results should be interpreted cautiously in terms of process understanding. Exploration of driver scales is a knowledge gap in coastal groundwater research. To gain further process understanding, particularly spatial scales of drivers impacting SGD and SWI need to be addressed more explicitly. Establishing standard frameworks for assessing and reporting driver influences and scales is necessary to enhance transferability and statistical analysis. Jointly studying coastal groundwater, assessing remote locations of Sub-Saharan Africa and South America, exploring spatiotemporal scales of driver impact, and a standard of reporting impact scales are key to closing knowledge gaps.

6 Conclusions

A global understanding of coastal groundwater is vital in tackling current and future water resource challenges. Therefore, we have conducted a meta-analysis of studies on coastal groundwater fluxes, their drivers, study locations, and driver scales. We find that SGD and SWI are controlled by interacting drivers, but are rarely studied in conjunction. Both are mostly studied in coastal basins with high population densities, where we can expect to measure fluxes (SGD at high permeabilities, SWI in water-limited regions) and at large-scale coastal ecosystems (mainly SGD). Economic development is another key factor: 80% of SWI studies were conducted at basins with GDP per capita over 6'000 USD, and 80% of SGD studies at basins with GDP per capita over 20'000 USD. Hence, current research rarely addresses coastal groundwater issues where GDP is lower. The African coast, while having the highest population growth rates around the world (Neumann et al. 2015), remains understudied in the international literature, with just a few hotspots of severe SWI which are well known (Steyl and Dennis 2010). Given the relatively low GDP in many African coastal basins, international research funding is key to enable studies in this region. Drivers impact SGD and SWI at a wide range of spatial and temporal scales, which are uncertain since coastal configurations are diverse and because driver scales are rarely explored. Future SWI and SGD studies need to focus on process understanding and joint assessments, explicitly report driver impact scales, and explore unchartered coastlines.

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Author Contributions

Daniel Kretschmer performed conceptualization, methodology, formal analysis, writing – original draft, and visualization. Robert Reinecke performed conceptualization, methodology, writing – review and editing, supervision, project administration, and funding acquisition. Thorsten Wagener performed supervision, writing – review and editing. Nils Moosdorf, Holly Michael, Gualbert Oude Essink and Mark Bierkens performed writing – review, and editing.

Availability statement

- The table of publications with extracted information is available as a supplemental CSV file: TableOfPublications.csv
- The perceptual model (in Figure 1) is available as a supplemental PDF file and published at https://doi.org/10.5281/zenodo.8004309
- 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
- The hydraulic conductivity data of the GLHYMPS 2.0 product is available at: https://borealisdata.ca/dataset.xhtml?persistentId=doi%3A10.5683/SP2/TTJNIU

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Geophysical Research Letters

Supporting Information for

Submarine Groundwater Discharge and Seawater Intrusion: Two sides of the same coin that are rarely studied simultaneously

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Contents of this file

Additional Supporting Information (Files uploaded separately)

TableOfPublications.csv
PerceptualModelCoastalGroundwaterFluxes.pdf

Introduction

The supporting information is presented following the outline of the main text. First, the search string for the initial literature search on Web of Science is presented (Text S1), followed by the PRISMA flow diagram of the meta-analysis is displayed (Figure S1). Further details on the machine learning supported review with the software AS Review, are explained in Text S2, Figure S2, and Figure S3. In Table S1, the information extracted from the literature is shown. The Pearson correlation of the datasets used in the analysis are presented in Text S3, Table S2 and Table S3. Figure S4 shows the global plot without study site locations. Figure S5 displays the author network of all retrieved records. While Text S4 present additional information about the scarcity of spatiotemporal scales of impact of submarine groundwater discharge and seawater intrusion drivers, Table S4 displays the plotting input table for Figure 4.

Text S1. Search string for Web of Science search

"saltwater intrusion" OR "salt water intrusion" OR "seawater intrusion" OR "sea water intrusion" OR "coastal salinization" OR "coastal salinisation" OR "salinization of coastal" OR "salinisation of coastal" OR "subterranean estuar*" OR "coastal groundwater" OR "submarine groundwater discharge" OR "submarine ground water discharge" OR "submarine spring"

Text S2. Software assisting screening process: AS Review

AS Review is a software using artificial intelligence to sort a list of publications, which is continuously trained by the user's decisions about in/exclusion. This is used to increase the rate of relevant literature per total literature read. Figure S2 shows that the share of relevant records was significantly higher using AS Review (~90%), compared to the random relevance without AS Review (~25%). Figure S3 shows that the number of relevant records among the past 10 screened records dips at around 600 screened records, where the transition from submarine groundwater discharge papers to seawater intrusion papers happened, and that there is a slight decline of the number of relevant papers as the number of screened records increases. The software for AS Review was developed at the University of Utrecht (https://asreview.nl/).

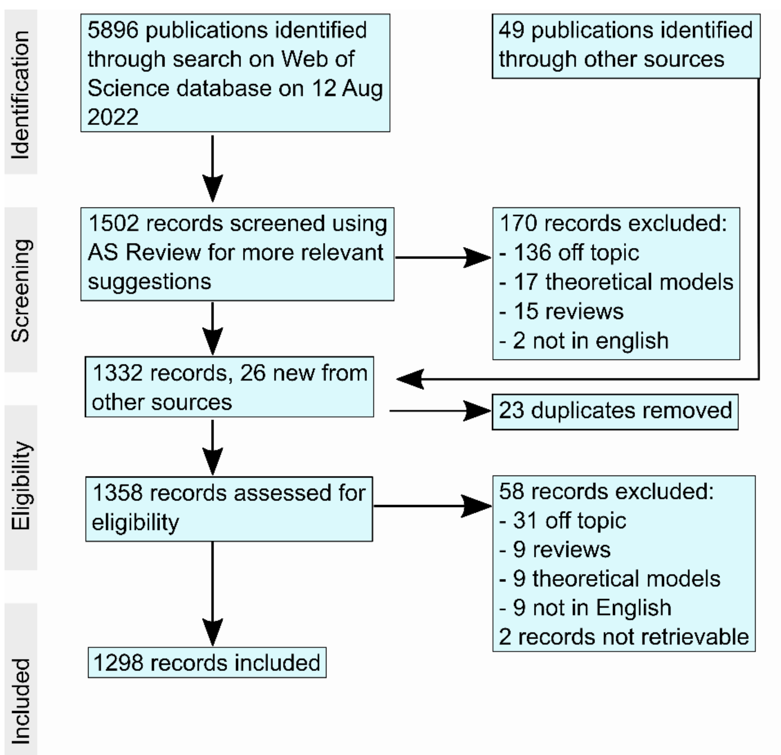

Figure S1. Flow diagram of the meta-analysis showing the number of records from identification of publications to record screening, eligibility assessment and inclusion along with number of excluded publications.

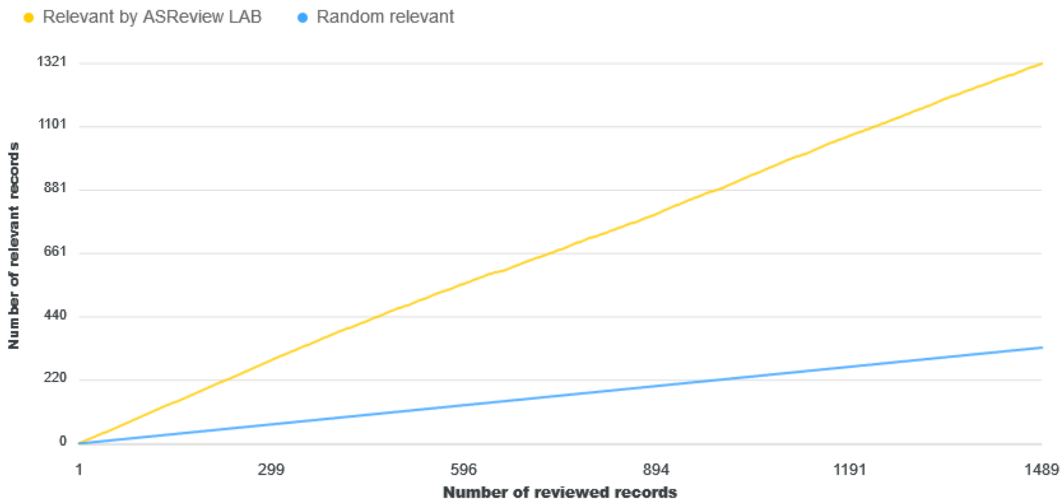

Figure S2. Comparison of number of relevant screened (reviewed) records using AR Review compared to the number of records that would have been randomly relevant (i.e., without the use of AS Review)

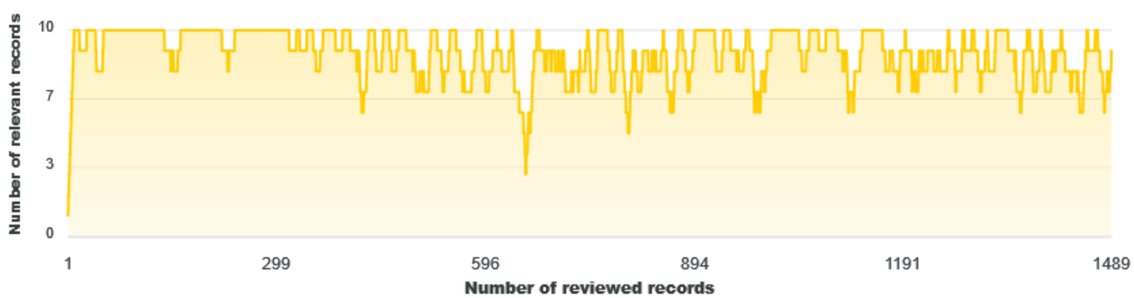

Figure S3. The number of relevant records among the past 10 records (y-axis) along with the number of screened (reviewed) records (x-axis). The dip at around 600 screened records shows the switch from submarine groundwater discharge literature to seawater intrusion literature.

Table S1. Information extracted from the literature (see also supporting file TableOfPublications.csv).

Extracted information	**Note**
Flow type	Options: porewater exchange, SGD, SWI, SWI and SGD
Topic or Objective	Options: multiple, other, anthropogenic impact, factors influencing flow type, GW resources (amount, sustainability…), GW flow rates, hydrogeochemistry / solute transport / quality, GW detection/distribution, large-scale

	estimation, mixing of fresh & saline GW, salinity distribution / interface, source of GW salinity / contamination, vulnerability to SWI
Shore type	Options: not sure, multiple, coral reef, estuary / lagoon, karst, mangrove / marsh, muddy shore, rocks, rocks and unconsolidated, unconsolidated, permafrost
Study site	Multiple entries are separated by a semicolon
Country or Region	
Continent or Region	
Lat and Lon	

Text S3. Pearson correlation between the variables used for the analysis of studies in coastal basins

The highest overall correlation values were found for the terrain slope with the aridity index (0.44) and with hydraulic conductivity (-0.38). Among the basins with an associated study site, the strongest correlation values were found for slope with hydraulic conductivity (-0.45), slope with fresh SGD (0.29) and hydraulic conductivity with GDP per capita (-0.29). All other variable combinations resulted in values below 0.2.

Table S2. Pearson correlation of variables - among all coastal basins

	Slope	**Permeability**	**Aridity Index**	**Fresh SGD**	**Population density**	**GDP per capita**
Slope	1	-0.38	0.44	0.15	-0.08	0.05
Permeability	-0.38	1	-0.12	-0.03	0.07	-0.16
Aridity Index	0.44	-0.12	1	0.13	-0.03	0.02
Fresh SGD	0.15	-0.03	0.13	1	-0.01	-0.11
Population density	-0.08	0.07	-0.03	-0.01	1	-0.08
GDP per capita	0.05	-0.16	0.02	-0.11	-0.08	1

Table S3. Pearson correlation of variables - among coastal basins with associated studies

	Slope	**Permeability**	**Aridity Index**	**Fresh SGD**	**Population density**	**GDP per capita**
Slope	1	-0.45	0.11	0.29	-0.07	-0.01
Permeability	-0.45	1	-0.17	-0.13	0.08	-0.29
Aridity Index	0.11	-0.17	1	0.21	0.05	0.10
Fresh SGD	0.29	-0.13	0.21	1	-0.05	-0.03
Population density	-0.07	0.08	0.05	-0.05	1	-0.11
GDP per capita	-0.01	-0.29	0.10	-0.03	-0.11	1

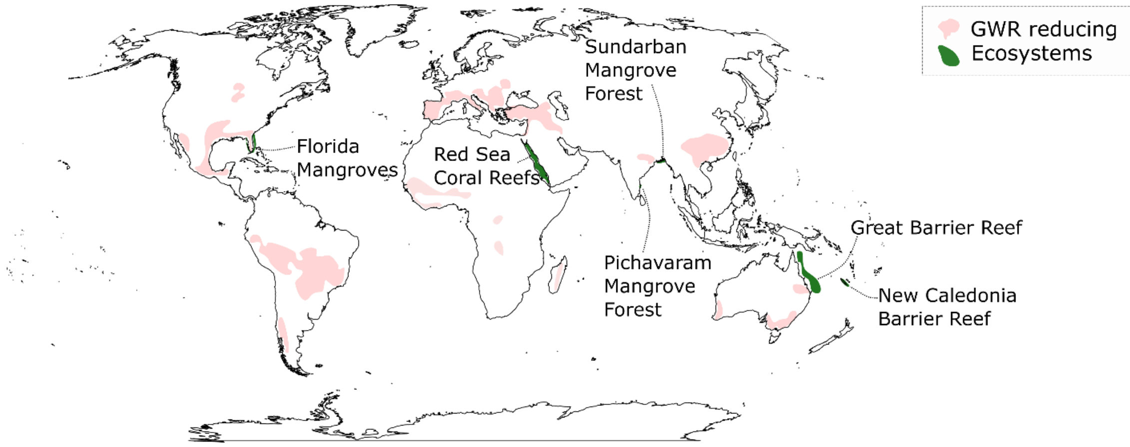

Figure S4. Global plot without study site locations (compare with Figure 2). Red areas are regions with projected reduction in groundwater recharge (GWR) due to climate change (adapted from Reinecke et al. (2020)). Green areas show large marine ecosystems.

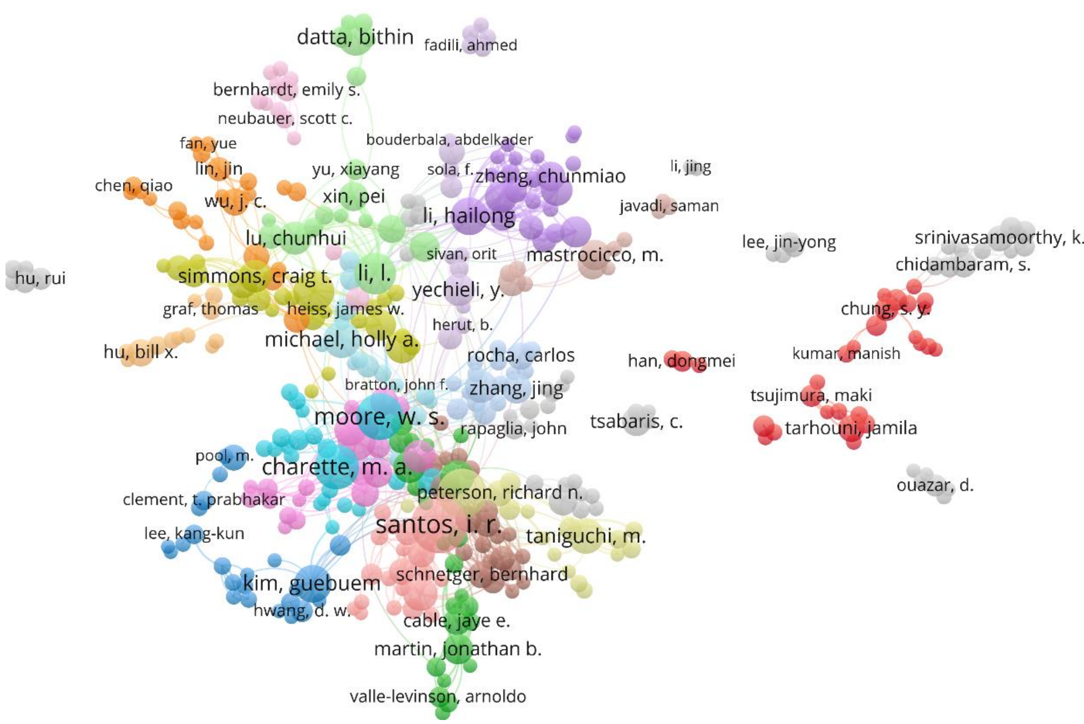

Figure S5. Author network based on all authors among the retrieved publications. Created with the VOSViewer software (https://www.vosviewer.com/). Authors with less than five appearances in the records were filtered as well as authors with no connections. Maximum number of authors per record were 25.

Text S4. Spatiotemporal scales of impact of submarine groundwater discharge and seawater intrusion drivers

Driver scales are highly uncertain, especially in spatial scales. Just 7% (91 studies) of records investigate the drivers of SWI or SGD, and they mostly evaluate the impact of indirect (e.g. sea level rise) instead of direct (e.g., hydraulic gradient) drivers. Temporal scales of impact of tides, precipitation, groundwater recharge and pumping are known, and information about their spatial impact scale on SWI and SGD would be important for water management. For other drivers of SWI and SGD, temporal scales are poorly known; especially spatial scales of influence should be communicated more clearly and explored more thoroughly. The table S4 shows that among the 91 publications focusing on factors, 24 combinations of driver (e.g., groundwater level) with groundwater flow (e.g., SWI) were found.

Of those 24, no scale was found for three driver-groundwater flow combinations: impact of rivers on SGD, impact of groundwater amount flowing to the ocean on SWI, and the impact of the density gradient on SWI. For 4 driver-flow combinations, no temporal scale was assigned (i.e., impact of beach morphology on SGD) and for nine driver-flow combinations no spatial scale assigned (i.e., impact of groundwater level on SGD).

Figures showing temporal patterns or spatial changes were of great value for our evaluation. In many cases however, this information was extracted from the text, and, instead of ranges, single values were retrieved.

Table S4. Plotting input table for Figure 4. The second column ("Plot") indicates whether the driver's scale of impact on the groundwater flow should be plotted using the last for columns. Drivers in lines with "no" in column "Plot" have only temporal OR spatial information.

Driver	Plot	Impacted GW flow	String temporal from-to	Temporal from [s]	Temporal to [s]	Spatial from [m]	Spatial to [m]
beach morphology	no	SGD	nan	nan	nan	10	10
groundwater level	no	SGD	day to 3 weeks	864000	1814400	nan	nan
groundwater level	yes	SWI	year	31463000	31463000	100	100
groundwater pumping	no	SGD	nan	nan	nan	nan	nan
groundwater pumping	yes	SWI	decade to 25 years	314630000	777600000	10	1000
groundwater recharge	no	SGD	season	7776000	7776000	nan	nan
groundwater recharge	yes	SWI	year to decade	31463000	314630000	10	5000

hydraulic conductivity	no	SGD	nan	nan	nan	1	20000
hydraulic conductivity	no	SWI	nan	nan	nan	100	100
land subsidence	yes	SWI	decade	314630000	314630000	1000	1000
Precipitation	yes	SGD	day to season	864000	7776000	200	200
Precipitation	no	SWI	season to year	7776000	31463000	nan	nan
sea level changes	no	SGD	day to week	86400	604800	nan	nan
sea level changes	yes	SWI	season to millennia	7776000	31463000000	50	10000
storm surge	no	SGD	day	86400	86400	nan	nan
storm surge	no	SWI	5 months	12960000	12960000	nan	nan
Tides	yes	SGD	2 weeks	1209600	1209600	10	20
Tides	yes	SGD	semi-diurnal to 2 weeks	43200	1209600	1000	1000
Wind	yes	SGD	day	86400	86400	10000	10000
Wind	no	SWI	day	86400	86400	nan	nan
Rivers	no	SGD	nan	nan	nan	nan	nan
hydraulic gradient	no	SGD	hour	3600	3600	nan	nan
groundwater amount flowing to the ocean	no	SWI	nan	nan	nan	nan	nan
density gradient	no	SWI	nan	nan	nan	nan	nan