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Advances of Submarine Groundwater Discharge in the Coastal Aquifers of India: A Review

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ABSTRACT

Groundwater is a crucial freshwater source for coastal communities. However, population growth, urbanization, industrial activities, and the discharge of polluted sewage water have led to the contamination of coastal groundwater with nutrients, metals, and organic compounds. This contaminated groundwater and terrestrial groundwater discharges into the ocean through a process known as Submarine Groundwater Discharge (SGD). This study aims to review (i) the driving forces behind SGD across coastal barriers, (ii) methods for identifying and quantifying SGD sites, and (iii) the status of SGD in Indian coastal aquifers and groundwater resource availability. The study indicates that groundwater discharge is higher on the east coast of India than on the west coast. Data on groundwater resources in India's coastal states show an increase in annual groundwater extractions for irrigation, industry, and domestic use, with a decreasing trend in net groundwater availability for future use between 2011, 2013, and 2017. Despite this, there is limited evidence on the quantity of SGD flux along the Indian coastline. However, preliminary studies by the Mission SGD project have made some progress in understanding this phenomenon. This research aims to improve the estimation of water resources in India and highlight the volume of SGD entering the ocean. A comprehensive understanding of hydrogeological settings, computational methods, coastal aquifer geometries, and other factors is essential for accurately estimating SGD along the Indian coastline.

INTRODUCTION

Groundwater is a vital source of fresh water for coastal communities globally. The rising population, urbanization, and industrial activities increase the demand for coastal resources, including groundwater. This increased extraction often leads to seawater intrusion (SWI) and submarine groundwater discharge (SGD). SWI, the movement of saline water into coastal aquifers, degrades groundwater quality, while SGD involves the flow of fresh groundwater and nutrient-rich recirculated brackish water from coastal aquifers into the ocean. Both processes are interconnected and significantly impact coastal environments. Studies on SGD and SWI have been conducted worldwide, highlighting their influence on coastal ecosystems, water quality, and resource management.

For instance, research in Biscayne Bay, Florida (Langevin 2003), the New York coast (Tamborski, 2015), Kinvara Bay in Ireland (McCaul 2016), the French Mediterranean coast (Bejannin et al. 2017), and the Gulf of Mexico (Burnett et al. 2003) has provided valuable insights into the mechanisms and impacts of SGD. Similar studies have been carried out in Tianjin, China (Liu, 2015), the Western Mediterranean coast of Spain (Mejías et al. 2012), coastal karst aquifers in southern Spain (Montiel et al. 2018), the Aquitanian coast in France (Anschutz et al. 2016), the Dead Sea (Akawwi et al. 2008), and various other regions, including Antarctica

(Uemura et al. 2011). These investigations utilized diverse methodologies such as hydraulic head variation, numerical groundwater modeling, thermal infrared remote sensing (TIRS), hydrograph separation techniques, resistivity surveys, and geochemical tracers like radon, radium, and strontium.

India's coastal districts and island territories have 171 million and 0.44 million (Sanil Kumar 2006), accounting for 14.2% of the total population. The population density in the coastal states of India ranges from 600 per km^2 to 2000 per km^2 (as in Kerala state), which is twice India's average population density. The increase in population has led to biodiversity, marine environment, coastal ecosystems, landscape changes, and the increased demand for coastal resources, mainly groundwater. In the coastal region, groundwater is one of the significant sources of freshwater, but the increased extraction of groundwater due to rising demand for water for different purposes such as domestic, industries, and agriculture causes Seawater Intrusion (SWI) inland, resulting in a deterioration of groundwater quality, with the potential to undermine the coastal aquifer as a source of freshwater. Furthermore, unconfined and confined coastal aquifers discharge fresh groundwater due to increased groundwater levels (GWL) from rainfall and saltwater recharge. This phenomenon is called SGD.

SWI and SGD are the complementary processes occurring in coastal areas whenever coastal aquifers are hydraulically connected with the ocean (Charette et al. 2004). SWI is a movement of saline water (due to changes in GWL and tidal fluctuation) into the coastal landmass, which makes aquifers unfit for urgent demand. SGD is precisely contrary to SWI. The flow of fresh groundwater, nutrient-enriched water, and recirculated brackish water between land and ocean through porous sediment is called SGD. SGD occurs along coasts where GWL is much higher than the mean sea level (Bear 1972, Suresh Babu 2009, Manivannan et al. 2020). The downward gradient of GWL contour lines towards the ocean can be suspected as SGD zones. In addition, SGD not only discharges freshwater but also discharges nutrient-enriched water due to the recharge of agriculture and industries' polluted water. The effect of these discharged groundwaters as SGD influences the coastal environment and its chemistry. E.g., nutrients, metals, and nitrogen loading into ocean environments can result in eutrophication, which can lead to an effect on available oxygen content, lead to an algal bloom, kill fish, and also affect flora (Valiela et al. 1992, Slomp and Van Cappellen 2004).

In India, research on SGD and SWI includes studies on the west coast (Bhagat et al. 2021, George et al. 2018, Lino et al. 2023, Suresh Babu et al. 2009), east coast (Chakrabarti et al. 2018, Nandimandalam et al. 2023, Prakash et al. 2018), and island regions. Notable investigations have utilized various methods such as hydraulic head variation, numerical modeling (Unnikrishnan et al. 2021), TIRS, resistivity surveys, and geochemical tracers to understand SGD processes and impacts. The identification and quantification of SGD are crucial for effective coastal zone management and assessing freshwater resources in coastal aquifers. This work contributes to understanding the occurrence and extent of SGD in the coastal zone by reviewing several representative studies conducted on SGD. These studies illustrate the state-of-the-art advances and current knowledge based on new analytical techniques and numerical models. Hence, this study explores the relationship between SGD and CO_2 disposal, which was not explored earlier. The study focuses on current and recent research conducted in India, supplemented with a few top-notch, recently released studies that address other parts of the globe, emphasizing areas for which no prior data were available. The objectives of the study are to (i) explain drivers of SGD and methods to assess SGD by considering various methodologies and management implications and (ii) assess coastal state-wise groundwater resources, including groundwater draft and net groundwater availability across Indian coastal states for the period 2011, 2013 and 2017, and (iii) the present status of SGD in the Indian coastline.

Drivers of SGD

The SGD and SWI are spatially and temporally variable components, and it is difficult to identify their zones and quantify flux. However, a few marine and terrestrial processes drive the SGD and SWI along the shore (Zektser & Dzhamalov 1981, Moore 2010). According to Corbett et al. (1999), Charette et al. 2007, Taniguchi et al. 2007, Moore 2010, and Szymczycha & Pempkowiak 2016), the forces are topographical elevation, the hydraulic head differential across coastal barriers, excessive pumping (freshwater extraction), tidal fluctuation, wave set-up, and land-use changes. The combined impact of drivers and their effects, causing SGD into the ocean and SWI to the coastal aquifer, as shown in Figs. 1 and 2.

GWL Difference Across Coastal Barriers

Groundwater head is one of the crucial factors driving SGD across the coastal areas. Generally, water flows from a higher gradient to a lower gradient due to hydraulic head differences (Zektser & Dzhamalov 1981). In the monsoon season, the rise of GWL with respect to the above mean sea level (AMSL) due to the recharge of precipitation has induced pressure on the coastal aquifer system (Uemura et al. 2011). Due to

Table 1: SGD studies reported on the Indian coastline.

Sl. No.	References	Location/Coast	Methodology	Interfaces
1.	(Mukherjee et al. 2007)	Western Bengal Basin, India	Water balance study	SGD flux estimated at 1.2×10^8 m^3/y
2.	(Suresh Babu et al. 2009)	West Coast, Kerala, India	Satellite data analysis, Resistivity surveys, GWL EC measurement	SGD zones are identified between Kovalam and Muttam coastal promontories. Utilized satellite data, fieldwork, water quality checks, and resistivity surveys.
3.	(Jacob et al. 2009)	Thiruvananthapuram District, Kerala, India	Transient radon mass balance	Radon is used to estimate submarine groundwater discharge in coastal regions. The average SGD rate is estimated at 10.9 ± 6.1 cm/day.
4.	(Rahaman & Singh 2012)	Gujarat coast, India	Inverse model calculations	The inverse model is utilized to quantify SGD flux. The estimated SGD is 5 to 280 cm/day.
5.	(Antony Ravindran & Ramanujam 2014)	Manapad, Tuticorin, India	Geophysical resistivity imaging	Higher resistivity layers with values 31 to 690 Ohm act as Permeable pathways for freshwater discharge toward the sea.
6.	(Krishan et al. 2015)	West Bengal, India	Radon (222Rn) and Hydrogeological analysis	Water quality parameter signature.
7.	(Rengarajan & Sarma 2015)	Kakinada Bay, Andra Pradesh, India	228Ra isotopes	Significant submarine groundwater discharge in coastal areas. Gautami Godavari estuary: $5{\times}10^6$ m^3 d^{-1}, Vasishta Godavari estuary: 20 to $43{\times}10^6$ m^3 d^{-1}, Kakinada Bay: $300{\times}10^6$ m^3 d^{-1}.
8.	(Chidambaram et al. 2017)	Cuddalore district, Tamil Nadu, India	Seepage meter and Radon, water level, Electrical Conductivity (EC), and pH	The estimated SGD rate from the seepage meter is 37.24 to 79.16 cm/day.
9.	(Prakash et al. 2018)	Coleroon Estuary, Tamil Nadu, India	Radon mass balance estimation	Radon isotope assessment in Coleroon River Estuary, Tamil Nadu, India, reveals submarine groundwater discharge rates ranging from 2.37 to 7.47 m day^{-1}, influenced by distance from the coast, tides, and hydrological factors.
10.	(Prakash et al. 2018)	Coleroon Estuary, Tamil Nadu, India	Water budget, Darcy law, manual seepage meter	The estimated SGD rate from the water budget was 8.94 to 12.12 m^3 d^{-1}.
11.	(George et al. 2018)	Kozhikkode, Kerala, India	Thermal imagery Hydrogeological, hydrochemical, and ERT surveys	Three potential groundwater discharge zones in the Kozhikode coastal aquifer were identified. Utilized thermal remote sensing and field surveys for investigation techniques.
12.	(Chakrabarti et al. 2018)	Bay of Bengal, India	Isotope analysis	Direct evidence of SGD-Sr flux to the Bay of Bengal. SGD Sr flux estimated at $13.5–40.5{\times}10^5$ mol/yr.
13.	Srinivasamoorthy et al. 2019	Sankarabarani basin, Villupuram district of Tamil Nadu, India	Radon mass balance	Submarine groundwater discharge in the Sankarabarani River Basin, India, is significant, with fresh groundwater fluxes reaching 0.88 m/day, higher than global averages, as indicated by continuous radon monitoring.
14.	(Yadav et al. 2019)	Mumbai Harbour Bay, Mumbai, India	Hydrodynamic method, tracer techniques Isotopic measurements:	Imbalance in Ra isotopes in the bay is attributed to submarine groundwater discharge. Submarine groundwater discharge is estimated at $33.4{\times}10^9$ L Day^{-1} and $64.9{\times}10^9$ L Day^{-1}.
15.	(Manivannan & Elango 2019)	Both the west and the East coasts of India	Water Table elevation and Salinity profiling	The East Coast is more affected by seawater intrusion than the West Coast. 7% of coastal areas are affected by seawater intrusion below sea level.
16.	(Manivannan et al. 2020)	Coastal parts of South Chennai, India	Hydrochemical analysis and groundwater level	Geochemical signature and Groundwater level gradient analysis.

Table cont....

Sl. No.	References	Location/Coast	Methodology	Interfaces
17.	(Debnath et al. 2015, Das et al. 2020)	Odisha, India	Seepage meter, stable-isotopic signature, geophysical techniques	SGD impacts coastal ecology through nutrient fluxes, triggering N and P-sensitive algal blooms, enhancing understanding of eco-hydrological responses in the region. The estimated SGD rate was $0.6–0.8\times10^7$ m^3/y for pre-monsoon and $0.8–1.5\times10^7$ m^3/y for post-monsoon.
18.	(Singh & Chander 2020)	Okha coast, Gujarat, India	Thermal images of groundwater and porewater temperature and salinity anomalies	freshwater Temperature anomalies from Landsat-derived thermal Images
19.	(Purandara et al. 2021)	Uttara Kannada District (West Coast), Karnataka, India.	Groundwater head and in-situ water quality analysis	Significant submarine groundwater discharge in coastal areas.Rare seawater influence due to high groundwater recharge.
20.	(Selvam et al. 2021)	Punnakayal Estuary, Tamil Nadu, India	Radon and radium tracers	SGD fluxes ranged from 0.04 to 0.15 m^3 m^{-2} d^{-1}. MNutrient embellishments are highest where meteoric elements are present in groundwater.
21.	(Bhagat et al. 2021)	Valsad and Navsari districts of South Gujarat, India	GWL fluctuation, In-situ water sampling, Thermal images	Higher EC in groundwater and lower EC in Porewater indicate the presence of SGD and SWI
22.	(Nandimandalam et al. 2023)	Southeastern coast of Andhra Pradesh, India	GWL, In-situ water sampling, Thermal images	SGD and SWI were identified using salinity, EC, and TDS signatures in groundwater and porewater samples.
23.	(George et al. 2023)	West coast of Kanyakumari, India	Thermal images, water table fluctuations, and water quality analysis	Identified zones of submarine groundwater discharge and seawater intrusion. High SGD in areas with thermal contrast, low groundwater for SWI.
24.	(Rajaveni et al. 2021)	Rani-Korttalaiyar river basin, north of Chennai, India.	Finite element modeling	Submarine groundwater discharge (SGD) in the Arani-Korttalaiyar river basin, India, is impacted by over-exploitation, with predicted rates of 85,243 m^3/day from the unconfined aquifer and 22,414 m^3/day from the semi-confined aquifer by 2030.
25.	(George et al. 2021)	Kanyakumari west coast, India	Radon mass balance	Submarine groundwater discharge contributes to trace element fluxes.
26.	(Prakash et al. 2020)	Coleroon River estuary, Bay of Bengal, India	Radona isotope	Surface, seepage, and groundwater chemistry altered from fresh (NaK-CaMg-NO_3Cl) to mixed (NaK-NO_3Cl) to saline water (NaCl) type.
27.	(Prakash et al. 2021a)	Bay of Bengal, India	Radon mass balance	Submarine groundwater discharge in the Bay of Bengal, India, was estimated to contribute significant nutrient fluxes, potentially impacting algal blooms and hypoxia due to SGD-derived nutrients.
28.	(Prakash et al. 2021b)	Southeastern Bay of Bengal, India	mass balance analysis	Submarine groundwater discharge contributes to trace element fluxes. Various factors influence variations in fluxes.
29.	(Gopinath et al. 2023)	South East coast of India	Radon and nutrient flux assessment	Oxic and anoxic conditions influence SGD and nutrient fluxes. Radon in groundwater: 0.1-7.9 $Bq.L^{-1}$, average 2.2 $Bq.L^{-1}$, SGD flux: 0.11-15.03 $m.d^{-1}$, average 3.42 $m.d^{-1}$
30.	(Nayak et al. 2023)	Odisha, India	GWL fluctuations and sea surface temperature anomalies	3 SWI zones and 6 SGD zones were identified along the Odisha coast.Preliminary study for detailed groundwater-seawater interaction process investigation.
31.	(Unnikrishnan et al. 2023)	South West India	ERT surveys and Numerical modeling approach	Evaluation in SW India reveals dynamic submarine groundwater discharge. Electrical resistivity tomography surveys and beach well monitoring aid in understanding fresh SGD flux and coastal variations.
32.	(Lino et al. 2023)	Udupi District, Karnataka Coast	Seepage meters	High seepage rates: 754 cm/day, 572 cm/day, 296 cm/day Recirculated SGD dominates, and fresh SGD increases post-monsoon.
33.	(Satyaji Rao et al. 2023)	Odisha, India	GWL and hydrochemical analysis	Seven potential Submarine Groundwater Discharge (SGD) zones in Odisha were identified. Pore water samples showed low salinity and elevated nutrient levels.

the high hydraulic gradient in the unconfined aquifers, there could be chances of water flowing into the ocean (Cable et al. 1997) as SGD. Similarly, groundwater depletion (lack of rainfall) below the mean sea level during summer leads to SWI (Prusty & Farooq 2020). Furthermore, the coastal (unconfined and confined) aquifers discharge groundwater due to changes in hydraulic head across coastal barriers and differences in topographical elevation. Therefore, the fluctuation in GWL in the shallow, unconfined coastal aquifers is the primary driving force that drives SGD to the ocean.

Geological Factors

Generally, coastlines consist of unconfined and confined aquifer systems (Povinec et al. 2012). The various geological factors, such as geology, geomorphology, hydrogeology, and lithology, play an important role in the result of SGD

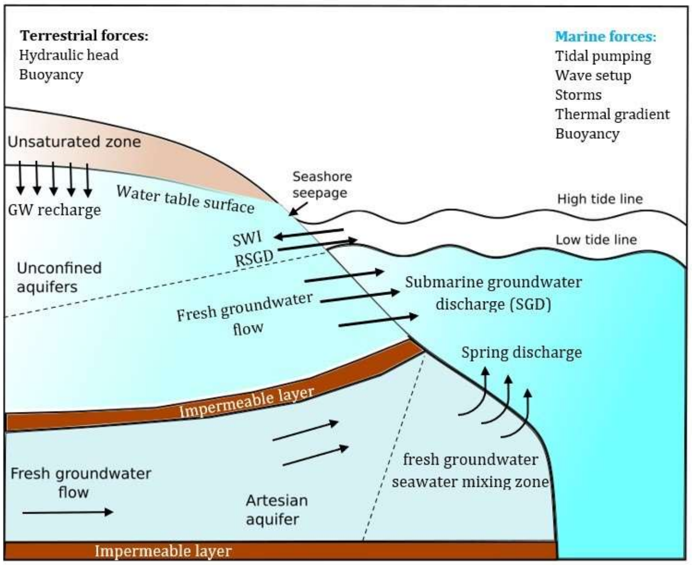
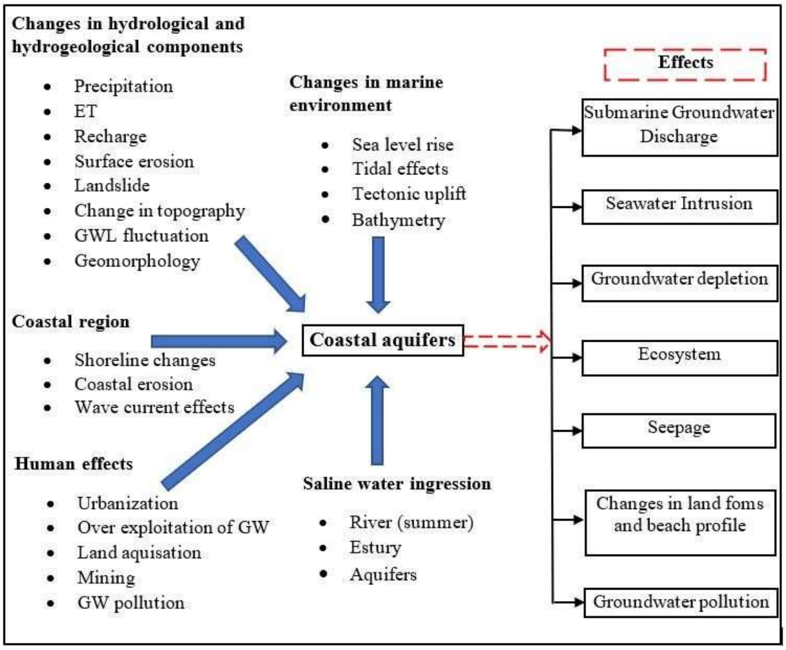


Fig. 1: Map illustrating the forces driving the SGD at the coast and also the SGD and SWI mixing zones.



(Source: modified from Kumar et al. 2006, Prusty & Farooq 2020)

Fig. 2: Factors influencing coastal aquifers and their effects.

(Shaban et al. 2005). SGD is a spatially and temporally variable component, and the location of SGD zones and the SGD rate vary based on the type of aquifer materials. The type of aquifers with laterite, coarse gravel, sand, and sandy soil release more groundwater as SGD into the ocean and hold less water than clay, the type of aquifer with sandy clay (Langevin 2003). Clay-type aquifers act as a permeable barrier to control the SGD rates (Burnett et al. 2003, Lee & Kim 2007). However, these clay patches may form perched aquifers in non-seawater flooding areas and accumulate freshwater (Yousif & Bubenzer 2012, Ali et al. 2015).

Many studies have reported that geological structural elements such as dyke, faults, fractures, and lineaments act as permeable pathways for SGD to the ocean and create an impact on the marine environment due to the discharge of nutrient loading as SGD (Taniguchi et al. 2002, Bokuniewicz et al. 2003, Tait et al. 2013).

However, discharge varies with geological features and types of aquifer material (Li et al. 1999). Mulligan & Charette (2006) conducted an SGD investigation on a sandy and gravel dominant aquifer in Waquoit Bay, and the estimated SGD rate was 5.6 m^3/m/day. Similarly, the estimated SGD rate in the clayey aquitard at the Mauritius Islands was 26 m^3/m/day (Povinec et al. 2012). The quantified SGD rate in unconsolidated loose and gravel aquifers was 1.2 m^3/s (Rapaglia et al. 2015). The estimated SGD rate in limestone and dolomite aquifers was 0.23 to 4 m^3/s (Cable et al. 1997). The reported SGD rate in clay and sandy clay aquifers was 0.8 to 1.5×10^7 m^3/year (Das et al. 2020). Considering the above quantified SGD rates, the sandy, gravel, and unconsolidated aquifers release more SGD than clayey and consolidated-type aquifers. So the rate of SGD mainly depends on the type of geology, lithology, lineaments, etc.

Tidal Pumping

The tidal effect is another major marine component that causes SGD at the coast. Generally, first high tide, first low tide, second high tide, and second low tide are four sets of tides that occur daily in the ocean environment. Tidal changes, wave set-up, and wind force could all cause sea-level variations. Tidal pumping, significant storms, current-induced gradient, and changes in the wave set up at the beach create a pressure gradient and cause SGD (Riedl et al. 1972, Huettel & Gust 1992, Huettel et al. 1996, Li et al. 2002, Burnett et al. 2003). During high tide, due to the rise of wave currents (Werner and Simmons 2009), the ocean tends to move saline water into coastal aquifers, leading to saltwater intrusion. Similarly, during low tide, the seawater goes back up to some distance towards the ocean, creating an intertidal zone (Szymczycha et al. 2018). The pressure gradient in the intertidal zone tends to attract fresh groundwater present in the pores of the coastal landmass (Stieglitz 2005, Niencheski et al. 2007). SGD sites can be seen easily during the intertidal zone (Vouillamoz et al. 2012).

Worldwide, various investigation methods, including tidal time series analysis, experimental analysis, field-oriented study, and simulation-based analysis, have been used to report on tidal activity and its impact on SGD and coastal groundwater quality. Using time series analysis, Hwang et al. (2005) found that the groundwater quality in Kimje, Korea's coastal region, follows periodic variations in tidal activity. In 2006, Won et al. 2006 conducted research that determined how the tides affect the coastal groundwater up to 3 km inland of Jeju Island, Korea. Carr and van der Kamp (1969) observed that periodic variations in the groundwater table impact the oscillation in tide movement controlled by groundwater heads along the shoreline. The freshwater-seawater mixing zone is greatly impacted by this shift in the groundwater table (Bear 1972, Strack 1976, Wang & Tsay 2001). This alteration in the freshwater-saltwater interface causes an influx of seawater into the pumping wells during the high tide period (Shalev et al. 2009). The natural channels that supply water to the tube wells may also function as routes for transit, according to Einsiedl et al. (2012). (Ataie-Ashtiani et al. 2001, Li et al. 2002) state that tidal oscillations significantly impact the shallow aquifer's GWL. The beach's slope is vital for releasing groundwater into the ocean. Combining numerical models with laboratory tests, Kuan et al. (2012) found a strong correlation between SWI in the intertidal zone and tidal action. SWI results from a saltwater plume in the intertidal zone that is created by tide-induced seawater movement that reduces freshwater flow into the sea.

Human-Influenced Fact

Human activity is the most essential component that is interconnected to all other elements that affect SGD results, either directly or indirectly. More than half of the world's population now lives within 100 km of the shore, with this number projected to rise by 25% in the next two decades (Xu 2015). Groundwater use has been increasing at an alarming rate as a result of rapid urbanization and industrialization. In addition, groundwater is polluted by discharging point and non-point source effluents from industries, agriculture, and domestic activities, resulting in natural imbalances like decreased flora, fauna, and phytoplankton. Numerous activities taking place in coastal regions can be greatly affected by groundwater flow into the marine ecosystem. As a result, a deeper understanding of the process is required.

The most important human-induced factor that increases SWI in coastal areas is the overexploitation of groundwater resources. The groundwater is the primary water source for domestic, agricultural and industrial uses at the coastline. Groundwater aquifers are being overexploited as a result of rising water demand, resulting in SWI. The SWI in many places around the world, such as Australia (Narayan et al. 2007), the United States (Misut & Vos 2007), Europe (Shi and Jiao 2014), Africa (Van Camp et al. 2014), China (Shi & Jiao 2014), Vietnam (Nguyen et al. 2015), and India (Kanagaraj et al. 2018), is mainly caused due to over overwithdrawal of groundwater. Moreover, this also increases the aquifer pressure and lowers the pore pressure of aquifer sediments, resulting in soil subsidence (Gambolati and Teatini 2015). The aquifer sediments are alternately exposed to freshwater and seawater due to periodic fluctuations in the freshwater–seawater interface. The hydraulic parameters of the aquifer are significantly influenced by this differential water flow (Dann et al. 2009). Groundwater extraction-induced subsidence on structures and coastal infrastructures has had serious consequences on several coastal regions globally (Feng et al. 2008, Minderhoud et al. 2017).

Research Gaps in SGD

The research gap in Submarine Groundwater Discharge (SGD) lies in the need for a comprehensive understanding and quantification of its impacts on coastal ecosystems and hydrological processes. While studies have identified SGD as a significant pathway for nutrient transport, contaminant dispersion, and freshwater input into coastal environments, there remains a lack of consensus on several key aspects. More detailed investigations into the spatial distribution (Burnett & Dulaiova 2003) and temporal variability of SGD fluxes are needed. Variations in geology, hydrology, and land use can influence SGD rates, yet these factors are not always adequately accounted for in current studies. Further research is needed to elucidate the biogeochemical processes occurring within submarine groundwater discharge zones (Sathish et al. 2011). Understanding the transformation and fate of nutrients, contaminants, and organic matter discharged through SGD is crucial for assessing its ecological impacts and potential contributions to coastal nutrient budgets. Integrating field observations, remote sensing data, and numerical modeling techniques can improve our ability to quantify SGD fluxes and predict their spatial and temporal dynamics (McCaul et al.2016). However, current modeling efforts often lack validation against comprehensive observational datasets, highlighting the need for coordinated monitoring campaigns and interdisciplinary collaboration. With climate change leading to alterations in precipitation patterns, sea level rise, and groundwater dynamics, there is a pressing need to investigate how these changes will affect SGD rates and associated ecological processes. Future research should explore the interactions between climate drivers and SGD dynamics to better anticipate the implications for coastal ecosystems and water resources. Addressing these research gaps will not only advance our fundamental understanding of SGD but also enhance our ability to manage and protect coastal environments facing increasing anthropogenic pressures and environmental uncertainties (Moore 2010).

MATERIALS AND METHODS

Groundwater flow is temporally and spatially varied, making quantifying groundwater discharge to the oceans difficult. There are several ways to assess SGD on the oceans from coastal aquifers. However, because of broad assumptions and inherent unpredictability, each approach has certain limits. In order to identify and quantify SGD, researchers typically employ multiple techniques or solve the limitations of the used method in a specific study area. A comprehensive overview of the many methods used to explore SGD was provided by Burnett et al. (2006). These approaches include seepage meter direct measurement, electromagnetic methods for SGD detection, natural tracers, infrared thermal imaging, numerical modeling, water balance equation, hydrograph separation technique, piezometers, etc. The amount of groundwater beneath the seafloor is challenging to perceive despite the widespread use of these techniques. Determining the precise location of the groundwater discharge becomes a difficult task.

GWL Monitoring and Evaluation of Aquifer Parameters

The GWL monitoring could be done manually as well as by using a Digital Water Level Recorder (DWLR). Hydraulic properties of aquifers and associated layers can be determined by a pumping test, which involves abstraction of water from a well at a controlled rate and observing, with respect to time, the water level changes in the pumped well and in one or more observations wells, pumping tests can also design to obtain information on the yield and drawdown of wells, for proper selection and positioning of pumps. The GWL hydrograph can be plotted to demarcate higher and lower GWL regions. Similarly, seasonal monitoring of GWLs can be used to plot the GWL contours. The obtained contours, which are shown ingression towards the sea, can be suspected as SGD zones.

GWL fluctuations and their contour showing downward movement toward the ocean have been used as a vital tool to locate probable SGD zones along the Indian west and east coast (Manivannan et al. 2020). Similarly, Zektser & Dzhamalov (1981) demarcated the SGD zones in the Pacific Ocean through hydraulic gradient variation obtained from the plotting of the GWL hydrograph. SGD zones were identified at Kozhikode coast in the Indian west coast by plotting seasonal GWL contours (George et al. 2018). The study found that more fresh SGD zones are found in the monsoon season due to the recharge of coastal unconfined aquifers by precipitation. In addition, a few recirculated SGD zones (the zones that recharge from SWI and again flow back as recirculated SGD to the ocean) were demarcated in summer, especially during low tide. Similarly, Suresh Babu et al. (2009) identified the probable SGD zones at Kovalam in Kerala and Muttam in Tamil Nadu using seasonal monitoring of GWLs. The SGD zones were suspected along the Northwestern coast of Gujarat in India using dynamic tools like GWL fluctuation (Bhagat et al. 2021). In order to define SGD and SWI zones, the shoreline has also been separated into five zones based on groundwater head. Almost GWL < 0 m indicates no SGD and a greater probability of SWI, 2) GWL 0 to 50 m indicates less SGD and moderate chances of SWI, 3) GWL 50.01–100 m indicates moderate SGD and less SWI chances, 4) GWL 100–150 m indicates high SGD and significantly lower SWI chances, 5) GWL>150 m indicates very high SGD and no possibility of SWI. Thus, one of the most important indicators of the SGD zones along the coast is the variation in GWL.

Thermal Infrared Remote Sensing (TIRS)

Once the SGD zone is identified through the hydraulic head difference, it must be cross-verified to better understand. Another method used to cross-verify is thermal infrared images that give Sea Surface Temperature (SST). The SGD flumes can be traced based on the temperature contrast between saltwater and coastal aquifers, where discharged groundwater is discharged over the intertidal zone and the sea surface. Generally, the seawater is warmer than the groundwater, and sites of SGD could be found in lower temperature regions compared to the surrounding warmer seawater (Mallast et al. 2013). Furthermore, one might see SGD barefoot wandering around the beach during low tide. The cool, wet beach sand on a hot day could reveal a potential SGD location, where cool water is discharged from an aquifer with a temperature lower than the seawater. Therefore, these zones can be captured through thermal infrared remote sensing (TIRS). These images give a better view of the coastal area that SGD has impacted. Similarly, during low tide in the summer, SGD sites appear as cooler locations (Roxburgh 1985).

Many studies have identified SGD locations using TIRS across the world. (Mallast et al. 2013) used aircraft surveys to capture thermal imagery at the Dead Sea, situated in Israel. The digital number (DN) obtained from thermal imageries was converted to radiance using Eq.1. Similarly, it was used as input to Eq.2 to estimate brightness temperature. In addition, Planck's law algorithm Eq.5 was used to map SST, and also study found that in the Monsoon season, SGD zones can be found in lower temperature regions, but in summer, they can be found in higher temperature regions. Landsat Enhanced Thematic Mapper (ETM+), Thermal Infrared (TIR) imagery, along with the geological study of sites prone to identifying SDG sites (Wilson & Rocha 2012). A nearshore survey of Radon (^{222}R) was also carried out to verify the occurrence of SGD.

Furthermore, Syariz's algorithm of the linear regression model was used by Bejannin et al. (2017) to map SST and SGD zones that were suspected along the French Mediterranean coastline. The study noted that the calculated SST from the Syariz algorithm was correlated with in situ SST (collected during the field survey) for better validation. Singh & Chander (2020) and Bhagat et al. (2021) identified SGD zones at Okha, Valsad, and Navsari districts of South Gujarat using a series of Landsat-08 OLI/TIRS thermal imageries along the Gujarat coastline. The zones were cross-verified with field and ship-based SST measurements (in situ temperature). The study found that the SGD site shows a cooler ocean surface than high tide during low tide conditions. Further, McCaul et al. (2016) mapped the SST using three sets of data, such as Earth Observation satellite (Landsat 8), high-resolution thermal imageries from aircraft surveys, and imageries of drone surveys. The pore water salinity ranges from 1 to 30 ppm, and also, the temperature of the porewater matches the groundwater temperature; these zones can be identified as SGD sites. Further, these zones were validated with the obtained thermal images. The difference in in situ temperature and salinity is an effective method to locate SGD zones.

The following three SST retrieval algorithms are more accurate methods to map SST. The value of DN will be converted to radians as the first step. The equation that was employed was as follows:

$$L_{\lambda} = \frac{[L_{MAX} - L_{MIN}][Q_{CAL} - Q_{CALMIN}]}{[Q_{CALMAX} - Q_{CALMIN}]} + L_{MIN\lambda} \quad \ldots(1)$$

$$BT = \frac{K_2}{\ln\left[\frac{K_1}{L_{\lambda}} + 1\right]} - 273.15 \quad \ldots(2)$$

Split Window Algorithm

$$T_s = BT_{10} + \left(2.946 \times (BT_{10} - BT_{11})\right) - 0.038 \ldots(3)$$

Where,

TS is the temperature of the surface

BT10 is the brightness temperature at band 10

BT11 is the brightness temperature at band 11

Syariz model

For band 10,

$$T_s = 31.192 - 0.0835 \times BT_{10} \qquad \ldots(4)$$

For band 11,

$$T_s = 30.899 - 0.0966 \times BT_{11} \qquad \ldots(5)$$

Where

TS is the temperature of the surface

BT10 is the band 10 brightness temperature

BT11is the band 11 brightness temperature

Planck's Algorithm:

$$T_S = \frac{BT}{1+[\frac{\lambda BT}{\rho}]ln\varepsilon} \qquad \ldots(6)$$

Where

Ts is SST in Kelvin (K)

BT is the Brightness Temperature at the sensor (K),

λ is the wavelength, $\rho = hc/\sigma = 1.438.10^{-2}$, mK, ε is the emissivity.

Geophysical Methods

The presence of a seawater-freshwater interface along the coast is determined by using geophysical methods such as electrical resistivity and electromagnetic measurements. It can be used to assess the thickness of the subsurface zone. The geophysical method has the advantage of obtaining subsurface data from the surface itself. For many decades, electrical resistivity measurements have been extensively used to detect seawater incursion. It can also be used to identify unconfined aquifers discharging freshwater lenses at the seabed (Ravindran & Ramanujam 2014, George et al. 2018). Aquifer discharge of fresh groundwater across the seabed is often indicated by high resistivity (>15 Ωm), which indicates the presence of SGD. In contrast, resistivity values between 3 and 15 Ωm indicate brackish water (a mixture of salty and freshwater), whereas resistivity values between 0.3 and 2 Ωm suggest groundwater impacted by saltwater, as opposed to freshwater above 15 Ωm (George et al. 2018). The resistivity techniques that are often employed to find SWI and SGD sites include Vertical Electrical Sounding (VES), two-dimensional (2D), and three-dimensional (3D) resistivity tomography (Taniguchi et al. 2007, 2019, Riwayat et al. 2018, Faleiro et al. 2019, Paepen et al. 2020).

SWI and SGD have been found in several studies in coastal areas worldwide. The VES can only collect data in 1D vertical information, which can only provide the depth of the transition zone. Several studies in coastal areas worldwide have found SWI and SGD zones. Commonly used resistivity methods are 2D resistivity tomography, 3D resistivity tomography, and VES. VES is a 1D research; the depth of the transition zone is measured, but the data collection is restricted to a single direction vertically downward. To determine the transition zone's lateral and vertical lengths, 2D resistivity studies were carried out later in the 1980s (Dahlin 2001). As stated by Sathish et al. (2011), this approach offers a distinct profile perspective of the transition zone's depth and distance. By employing high-resolution 2D resistivity tomography, the SWI was located at a depth of 10 m and extended up to 130 m in the southern areas of Chennai (Acworth & Dasey 2003). Additionally, SGD was discovered near Manapad, on the Indian coast of the Gulf of Mannar, through a 2D electrical resistivity survey (Ravindran & Ramanujam 2014). An inverse pseudo-section of the Earth's subsurface was mapped using the RES2DINV 3.56 program, utilizing apparent resistivity values. The fresh groundwater discharge to the ocean is also suspected by the resistivity value range of 31 to 174 Ohm. Similar to this, the subsurface formation of Zimbabwe's alluvial aquifers was mapped using the electrical resistivity approach (Burnett et al. 2003). The ABEM equipment was used to conduct the ERT survey. The resistivity ranges were utilized to determine the extent and interaction zones of the aquifers, as well as to estimate the 3D geometric extent of the aquifers. According to Kalisperi et al. (2009), the boundaries of the geological formations, boreholes, prior hydrogeological studies, and a trustworthy hydrogeological model were used to validate the 1D and 2D models for subsurface characteristics mapping using the Thermal Electromagnetic (TEM) and Vertical Electrical Sounding (VES) methods.

Groundwater Flow Paths

A variety of tools and data sources were used to calculate the groundwater discharge. Groundwater heads were specifically simulated using MODFLOW, a 3D finite-difference groundwater model intended for both steady-state and transient groundwater flow (Whittier et al. 2010). Furthermore, MODPATH was used, a model that uses groundwater head data generated by MODFLOW to solve 3D groundwater flow (Pollock 2012). Further, information on groundwater recharge, Local Meteoric Water Lines (LMWL) customized for various climatic zones, and data on the oxygen isotopic composition of water were included in the analysis (Fackrell et al. 2020). There are very few studies that report on SGD using MODFLOW-simulated groundwater heads. Wilson (2005) and Thompson et al. (2007) reported SGD flux ranges from 0 to 0.04 cm/d at the Mississippi Delta. Wilson (2005) performed the numerical method in the MODFLOW domain to quantify the SGD flux at Onslow Bay. Additionally, they cross-verified these numerically simulated SGD fluxes with the water budget estimated SGD to get better accuracy in the SGD flux.

Seepage Meters

Manual “seepage meters” are often used to measure groundwater seepage rates into oceans. This device was initially designed by Israelson and Reeve (1944) to quantify water loss from irrigation channels. Later, Lee (1977) modified a seepage meter by connecting one end of a 55-gallon (208-litre) steel barrel to a sample port and a plastic collection bag. The drum’s open end is immersed in the silt in the intertidal zone, creating a chamber. The seeped water through the sediment in the seepage meter is collected through plastic bags attached to the chamber. The flux is calculated using the change in volume of water in the bag over the predetermined time interval. Boyle et al. (1994) propose to install a seepage meter at a remote distance from the surface of various water bodies. In many places, fresh SGD has been quantified using a seepage meter e.g., Onslow Bay (0.6–2.0 cm/d) (Finkel et al. 1992), Biscayne Bay/Florida Bay (1 to 3 cm/d) (Corbett et al. 1999), Northeast Gulf of Mexico (2 to 24 L/m/min) (Cable et al. 1997), West Coast of Mauritius Island, central western Indian Ocean (35 m^3/m/d) (Povinec et al. 2012), Coleroon Estuary, Tamilnadu, India (0.7024 m/h at an average) (Prakash et al. 2018), Cuddalore district, Tamilnadu (37.24 to 79.16 cm/d) (Chidambaram et al. 2017). Although obtained SGD flux obtained through a manual seepage meter would be cross-verified with Darcy’s estimated SGD for a better assessment of the SGD flux.

Water Balance Approaches

The water balance method may be used to estimate the freshwater SGD, which can be written as P = ET + DS + DG + dS, where P stands for precipitation, ET for evapotranspiration, DS for surface discharge, DG for fresh groundwater discharge, and dS for the change in water storage. The dS is disregarded (or left out) when calculating the duration in years. To accurately evaluate DG using this approach, the precipitation, evapotranspiration and surface runoff must be precisely documented. The water balance approach has been used to quantify the SGD rate at several locations, including Perth, Australia (1.0 x 10^8 m^3/y) (Allen 1976), Santa Barbara (1.2 x 10^5 m^3/y) (Muir 1968), Long Island, New York (2.5 x 10^7 m^3/y) (Pluhowski and Kantrowitz 1964), and the Adriatic Sea (1.7x10^{11} m^3/y) (Sekulic and Vertacnik 1996). The fresh SGD flow cannot be estimated unless the area and volume of the SGD are established. The mean fresh SGD flow of 0.68 m/y is commonly determined using the expected fresh SGD volume and the Adriatic Sea discharge region (Sekulic & Vertacnik 1996). Since the SGD zone’s locations are usually uncertain, the water balance technique uses SGD volume, or the volume of SGD per unit length of the coast (Sellinger 1995). However, SGD estimates expressed as Darcy’s flow (such as cm^3/s, cm^2/s, cm/s, and m/y) could be challenging in the end. The water budget methodology is a fundamental method for determining estimated changes in groundwater basins according to Oberdorfer’s (1996). Numerical modeling offers a more precise quantitative assessment of climate change perturbations in basins with numerous sources and sinks. The water-balanced technique used for Tomales Bay, California, is based on a budget-based soil moisture change (Oberdorfer et al. 1990). The outcomes are compared to other conventional water balance predictions.

Hydrograph Separation Techniques

The hydrograph separation technique assumes that the quantity of groundwater entering the river can be estimated using the hydrograph separation method. The same can also be implemented in the coastal regions to quantify the SGD flux. A similar technique was adopted at the Pacific Ocean Rim by Zektser and Dzhamalov (1981), in eastern Russia by Boldovski (1996), and by Zektser et al. (1973) for global-scale estimation of fresh SGD. The method used to divide the hydrograph and calculate the fresh groundwater flow component is as simple as determining a base flow from the hydrograph’s form. There are other ways of carrying out this methodology, such as the unit hydrograph method (Bouwer 1978, Zektser et al. 1973). The problem with this simple method is figuring out baseline circumstances, which often change based on the space, time and hydrological parameters that exist.

Limitations of Assessment Methods For SGD

SGD is a significant process in coastal hydrology, yet assessing it comes with inherent challenges. Here are some limitations of the methods based on the literature survey. The dynamic nature of SGD makes it difficult to capture its spatial and temporal variability accurately (Singh & Chander 2020). Traditional assessment methods may not adequately account for fluctuations in discharge rates and locations over time. Moreover, Current sampling techniques often rely on point measurements or limited spatial coverage, which may not capture the full extent of SGD discharge areas. This limitation can lead to underestimation or misrepresentation of SGD fluxes. Many assessment methods for SGD rely on indirect measurements such as geochemical tracers, remote sensing, or numerical modeling (Moore 1996, Szymczycha et al. 2018). While these approaches provide valuable insights, they are prone to uncertainties and assumptions, which can affect the accuracy of SGD estimates. SGD can occur at various depths below the seafloor, ranging from nearshore shallow waters to deeper offshore regions. Assessing SGD across this depth range poses technical challenges, especially for methods limited to specific depth ranges or inaccessible depths. Subsurface hydrological processes, including groundwater flow dynamics, geology, and submarine topography, influence SGD patterns. Understanding and quantifying these processes remain challenging, impacting the reliability of assessment methods. SGD signals may be obscured or confounded by other coastal processes such as tidal pumping, surface runoff, or anthropogenic inputs. Distinguishing SGD contributions from these sources can be difficult, particularly in complex coastal environments (Tamborski et al. 2015).

Addressing these limits necessitates the development of novel approaches, the integration of numerous assessment methods, and multidisciplinary research collaboration. Meeting these problems is critical to increasing our understanding of SGD dynamics and their consequences for coastal ecosystems and water resource management. This study will help researchers and policymakers working in the SGD area to address the research gaps and to devise a sustainable solution.

RESULTS AND DISCUSSION

Status of SGD in India

SGD is a relatively emerging issue in Asian nations, particularly in the context of India. India's 7500 km vast coastline stretches along the three corners of the Indian subcontinent-the Arabian Sea to the west, the Bay of Bengal to the east, and the Indian Ocean to the south. Nine coastal states in India have 53 districts covering coastlines (Chachadi 2005). Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal are on the east coast, whereas Gujarat, Maharashtra, Goa, Karnataka, and Kerala are on the west coast. Moreover, there are four union territories: Lakshadweep Island is located in the Arabian Sea, Andaman and Nicobar, and Puducherry are on the mainland (Prusty & Farooq 2020). Naturally, cyclones are a common threat to the Indian coast. The northeast and southwest monsoons, which occur from October to November and June to September, respectively, provide rain to India's coastline. Rainfall on the west coast and therefore the northern half of the east coast is most abundant during the southwest monsoon, whereas the remaining part of the east coast has maximum rainfall during the northeast monsoon. From 300 to 4000 mm on the west coast and 1000 to 1500 mm on the east coast, respectively, is the average annual rainfall (CGWB 2014). Approximately 100 rivers pour into the sea along the Indian coast. Some of these rivers include the Ganges, Brahmaputra, Mahanadi,

Table 2: Describes the advantages and Limitations of methods for identifying and quantifying SGD flux.

Method	Technical Insights	Advantages	Limitations	References
Seepage Meters	Measures the direct flow rate of water from the sediment to the overlying water body. Typically involves placing a chamber on the sediment surface.	Direct measurement at specific locations	Labor-intensive and time-consuming, with limited spatial coverage	(Cable et al. 1997, Lee 1977)
Radon and Radium Isotopes	Utilizes the presence of naturally occurring radioactive isotopes as tracers for groundwater discharge. Requires water sampling and laboratory analysis.	Effective for tracing groundwater discharge over large areas, it provides integrated measurements over time.	Requires specialized equipment and expertise, handling and disposal issues with radioactive materials	(Burnett et al. 2006, Moore 1996)
Electrical Resistivity	Measures the electrical resistance of subsurface materials to infer groundwater flow paths and salinity. Uses electrodes placed on the ground or water surface.	Non-invasive, can distinguish between fresh and saline groundwater, and covers large areas.	Interpretation can be complex, sensitive to noise, and requires calibration.	(Stumm & Chu 2004)
Thermal Infrared (TIR) Imaging	Uses satellite or aerial imagery to detect changes in surface temperature that may indicate groundwater discharge.	Large-scale, non-invasive, covers inaccessible areas, and provides temporal data for change detection.	Limited to surface indications of SGD, requires ground-truthing, affected by surface conditions.	(Tamborski et al. 2015, Wilson & Rocha 2012)
Hydraulic Methods	Involves measuring hydraulic gradients and groundwater flow using wells and piezometers.	Directly measures hydraulic gradients and groundwater flow, and provides detailed local data.	Requires extensive and long-term monitoring wells, expensive and labor-intensive	(Bhagat et al. 2021, Oberdorfer 2003)
Numerical Modeling	Uses mathematical models to simulate groundwater flow and SGD based on physical and chemical data.	Integrates various data types and scenarios, and predicts future changes and scenarios.	Depending on the quality and availability of input data, it requires expertise in model development and validation.	(Rajaveni et al. 2021)

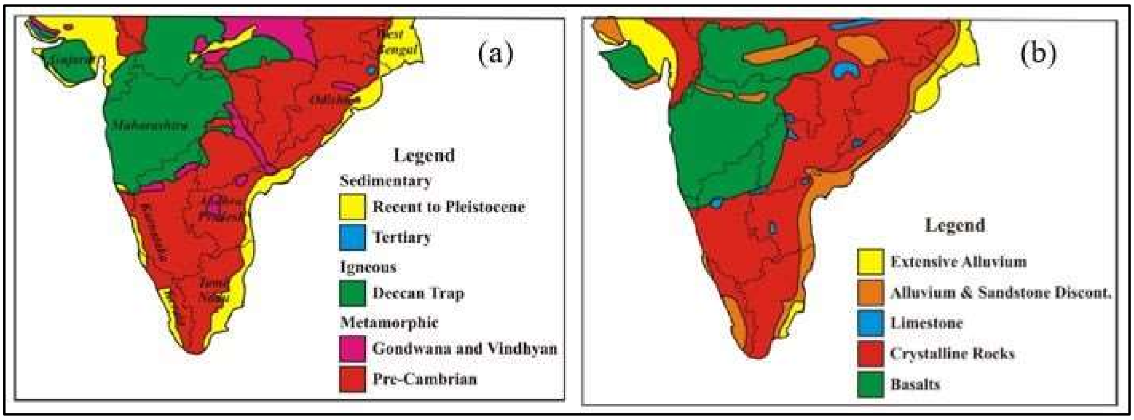
Krishna, Godavari, and Cauvery, which all discharge a significant quantity of water into the Bay of Bengal. In India's coastal zones, there have been wide fertile delta plains, industries, harbors, airports, land ports, tourism, etc. Mangroves, coral reefs, salt marshes, mud flats, estuaries, and lagoons are among the varied habitats found there (Central Water Commission 2017). The geological composition ranges from Archean crystalline rocks to modern river and marine deposits (Manivannan & Elango 2019). In contrast, the southeast coast comprises quaternary sediments, west with Deccan traps and southwest with Archean rocks. Fig. 3 (a) depicts a generalized geological map of the country with key geological formations, and Fig. 3 (b) represents the coastal state-wise aquifer systems of India.

The two types of aquifers present in India's coastal region are "sedimentary" and "weathered/ fissured igneous and metamorphic" formations (Fig. 3a). The sedimentary formations are found on Gujarat's western coast in coastal regions. The groundwater in this region is divided into multiple aquifer systems having many sandy confined aquifers at the top overlain by unconfined aquifers (Mahesha et al. 2012, Rina et al. 2013). Hydraulic conductivity and transmissivity in the Deccan trap aquifers range from 0.4 to 1.1 $m.d^{-1}$ and 18 to 38 $m^2.d^{-1}$, respectively (Saha & Agrawal 2006). The southern regions are home to lateritic aquifers, which are unconfined aquifers with considerable groundwater potential (Harshendra 1991, Lathashri & Mahesha 2015). According to Mahesha et al. (2012), the maximum transmissivity and specific yield of these aquifers are 461.4 $m^2.d^{-1}$ and 0.2805, respectively. In the southern portion of the western coast, groundwater may be found in shallow conditions and deeper Tertiary strata (Manjusree et al. 2009, Shaji et al. 2009, Kumar et al. 2015). The main water-bearing rocks in the eastern coastal region include gneisses, pink granites, weathered/fractured charnockites, and Quaternary and Tertiary sediments (Rao et al. 2005, Singaraja et al. 2014, Raju et al. 2016). Groundwater is found in the unconfined and semiconfined aquifers in several parts of the East Coast. There are shallow and deep aquifers within the sedimentary aquifers. Quaternary alluvium makes up shallow aquifers, whereas Tertiary to Permo-Carboniferous deposits comprise deep aquifers (CGWB 2014). Multi-layered aquifers may be found in Raj Naga, Visakhapatnam (Devadas et al. 2007), Puducherry (Thilagavathi et al. 2012) and Chennai (Nair et al. 2015). In the Andaman Islands, groundwater is found in worn, jointed, fractured, and sheared rocks of sedimentary and crystalline formations. High groundwater-bearing formations can be defined as the fractured volcanic and sandstone rocks (Maury & Balaji 2015). It has been determined that phreatic coral-sand aquifers in the Lakshadweep Islands contain groundwater (Mondal et al. 2012).

SGD and SWI into the coastal aquifer, as well as water scarcity, are the results of extensive urbanization and increasing population growth along the coast, which has put pressure on freshwater resources. In India, numerous coastal districts are directly affected by SWI (Fig. 4a). The coastal districts of India are depicted state-by-state in Fig.4b (MoEF and CC 2016). 70% of India's land is affected by salt, of which 21,000 km^2 are saline soil within the coastal belt, according to the Central Soil Salinity Research Institute (Karnal, India) (Farooqui et al. 2009). The state-wise SGD status and adopted mitigation measures, and their explanations, are covered in the ensuing subsections.

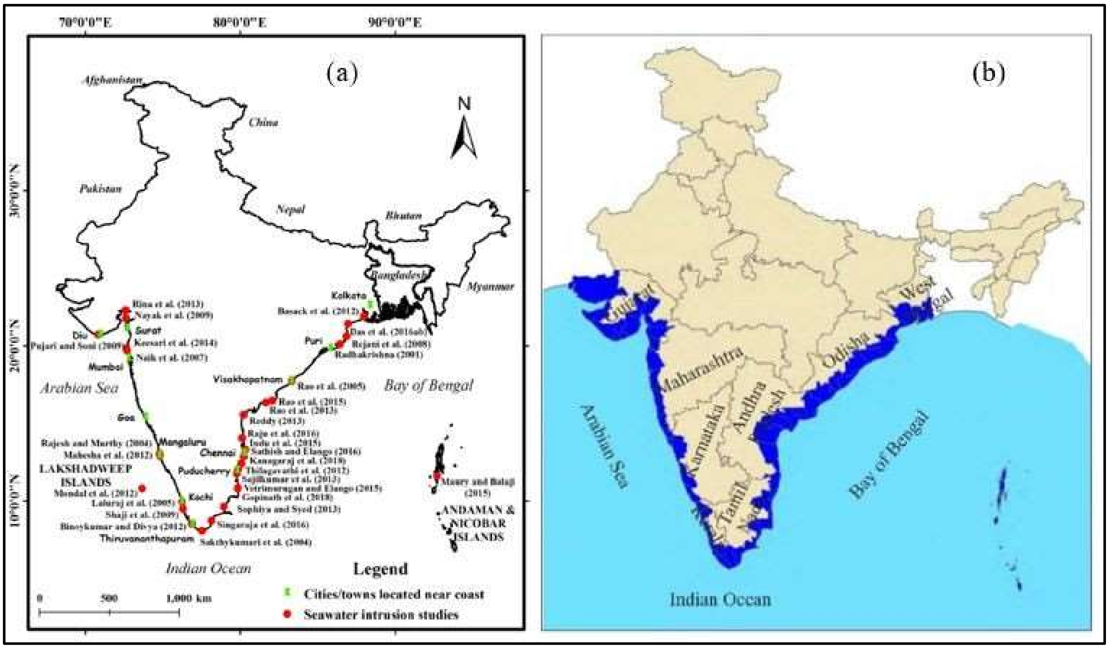
State-Wise SGD Status in India

Based on geomorphologic area, the Indian coast may be divided into two groups: the West Coast and the East Coast.



(Source: Kumar et al. 2006, CGWB 2014, Manivannan & Elango 2019)

Fig. 3: (a) Generalized geological map of the coastal states of India with key geological formations, and (b) Coastal state-wise aquifer systems in India.



(Source: Manivannan & Elango 2019), (b) Blue color area indicates coastal state-wise districts of India (Source: MoEF and CC 2016).

Fig. 4: (a) Major coastal towns/cities and reported SWI studies in India.

Well-defined deltaic plains and sedimentary deposits that originate at river mouths make up the eastern shoreline. The western coast, on the other hand, is primarily characterized by its islands, tidal creeks, flooded river channels, rock-cut surfaces, and other features (Central Water Commission 2017). The western coastal plains go from Gujarat's Rann of Kutch to Kerala's Malabar coast, while the eastern coastal plains connect the Sundarbans delta of West Bengal to the Coromandel coast of Tamil Nadu. The studies reported on SGD in India's east and west coasts are depicted in Fig. 5 and discussed subsequently.

Gujarat: Gujarat has the longest coastline of all other Indian states and is well notable for its coastal communities. In many sites near the shore, extensive groundwater driving for irrigation contraries the hydraulic gradient, causing SWI, according to hydrochemical and isotopic research (Pujari & Soni 2009, 2010, Rina et al. 2013, Maurya et al. 2019). As of now, only a few studies have been conducted on SGD along the Gujarat coastline. The inverse model was applied by Rahaman & Singh (2012), and the SGD rate has been quantified for Narmada, Tapi, and the Mandovi estuaries, Gujarat. The estimated SGD rate was 5 to 280 cm.d^{-1}. Similarly, Singh & Chander (2020) identified the SGD zones using thermal images obtained through Landsat 08 thermal band 10 of 30m resolution thermal images (both monsoon and post-monsoon) to delineate the sea surface temperature near Okha coast, Gujarat. The area of SGD sites was identified using the temperature difference of seawater and aquifer-discharged groundwater.

Further, the study found that during low tide conditions, the SGD site shows a cooler ocean surface than during high tide. However, the study also noted that the obtained SST was validated with field and ship-based seawater temperature measurements (in situ temperature). In the highly industrialized sectors of the state, Kale et al. (2012) projected seawater displacement up to 20 km from the shoreline.

Further, a 6.3 m increase in the water table at a groundwater recharge rate of $2.175x10^{-3}m^3.s^{-1}.m^{-1}$ will result in a 50% decrease in SWI. Similarly, in situ parameters of groundwater samples reveal that the south part of Gujarat has better water quality than Kutch and Saurashtra (Bhagat et al. 2021). Meanwhile, the SWI influenced the coastal areas of Jam Nagar and Kutch, whereas SGD dominated the south coast of Gujarat due to rising GWL during the monsoon. In addition to this, SGD zones were suspected at Navsari and Valsad districts of South Gujarat using seasonal monitoring GWL, In-situ hydrochemical analysis of GW samples, and Porewater samples (PW), Seawater samples (SW), and thermal images based on sea surface temperature. Still, many coastal districts of Gujarat have been affected by SGD due to the rise of groundwater tables from southwest monsoon rainfall (Rahaman & Singh 2012). There is a need to conduct a detailed investigation on SGD

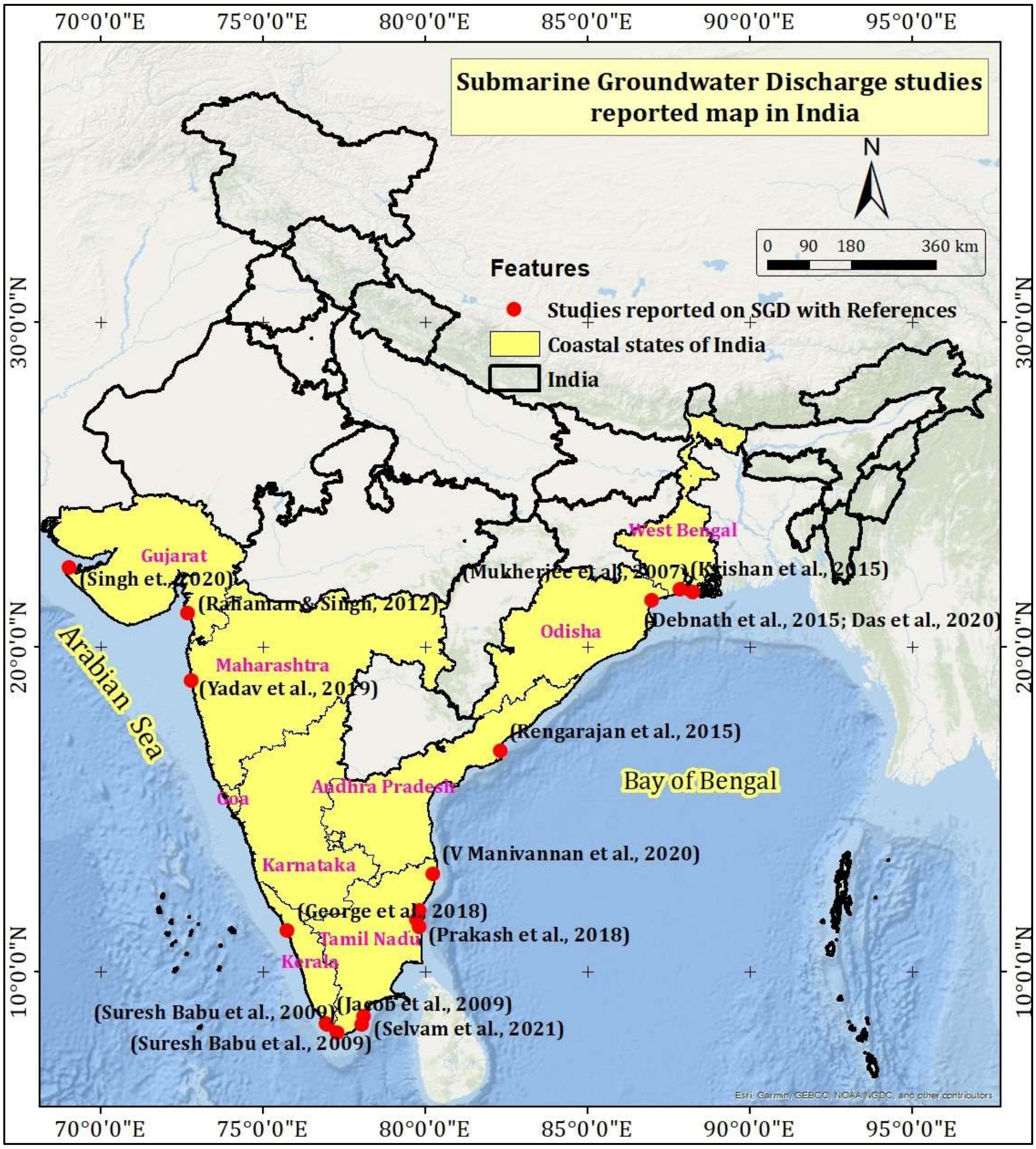


Fig. 5: Map showing the location of SGD studies reported along the Indian coastline.

to assess coastal groundwater resources and their impact on the marine environment.

Maharashtra: The coastline of Maharashtra state is located on the shoreline of the Arabian Sea on the west coast. As of now, only one study has been reported on SGD at Mumbai Harbour Bay (MHB), Mumbai, India (Yadav et al. 2019). The short-lived Ra isotopes (^{223}Ra and ^{224}Ra) were used to identify and quantify SGD flux. The measured SGD rate was $33.4\times10^{9} L.d^{-1}$ and $64.9\times10^{9} L.d^{-1}$. Many works have been conducted on saltwater intrusion using the ERT technique, hydrochemical analysis and numerical modeling (Naik et al. 2007, Gupta et al. 2010, Maiti et al. 2013, Keesari et al. 2014, Omprakash and Gadikar 2018). The Deccan traps, which are made up of basalts, cover much of the state's coastal regions. The volcanic rock has multiple cavities and lava flows, allowing seawater to enter several locations along the shoreline during the tidal cycle. Maharashtra has a long coastline, and there may be more SGD zones across the coast. To estimate the submarine groundwater outflow, there is a need to concentrate on areas where the GWL is above mean sea level and a high hydraulic gradient (Manivannan & Elango 2019)

Goa: Goa has the shortest coastline of all the Indian states. Till now, no work has been reported on SGD. To meet this demand, groundwater is one of the important sources over surface water. Assessment of coastal groundwater resources and SGD quantification and balanced use will effectively reduce water scarcity and saltwater intrusion across Goa. Researchers should concentrate more on SGD to analyze its impact on coastal communities and the marine environment. Many works have been conducted on saltwater intrusion. Chachadi (2005) has identified coastal aquifers' vulnerability due to saltwater intrusion using the GALDIT index. Similarly, Kumar et al. (2007) have predicted seawater movement up to 300 m away from the shoreline using the finite element model. Loveson et al. (2014) observed beach extension and widening due to marine deposition (influx of sediment) using the GPR technique. With a significant increase in tourism infrastructure development, groundwater withdrawals are increasing, potentially causing significant groundwater problems in the state.

Karnataka: The state of Karnataka also has a long coastline of about 280 km and covers three districts, mainly Uttara Kannada, Udupi, and Dakshina Kannada. The state receives an annual rainfall of around 4000 mm (CWC 2017) and experiences a maximum temperature of 35°C in summer and a minimum of 24°C in winter (CGWB 2014). The state is bounded by the Western Ghats in the east and the Arabian Sea in the west. Western ghat has thick biodiversity and are also the origin of many west-flowing rivers, namely, Nethravati, Gurupur, Pavanje, Udyavara, and Swarna rivers and the Arabian Sea in the west. The character of the beach is sandy and rocky, with a declining gradient from east to west. The coastline comprises alluvial soil, red soil, laterite soil, loamy soil with a medium grain, and sand, clay, and gravel. Still, no work has been reported on SGD.

Most of the studies were conducted on SWI and its modeling. Lathashri & Mahesha (2008) used the GALDIT index, which contains six parameters as groundwater occurrence (G), aquifer hydraulic conductivity (A), GWL above the sea (L), distance from the shoreline (D), the impact of existing SWI (I), and aquifer thickness (T), to assess the aquifer's vulnerability to SWI. Groundwater salinization has also been linked to over-exploitation during dry periods, according to the saturated-unsaturated transport model (SUTRA) (Vyshali et al. 2008). Several observations reflect the confinement of seawater to 200 m; however, it can reach up to 5 km during dry seasons. Sylus & Ramesh (2015) conducted a study on water quality sampling for electrical conductivity and total dissolved solids for each month in 2013. The results showed that the water quality and GWL were reduced in the pre-monsoon period due to the lack of precipitation. In monsoon, the water level rises due to ground recharge from rainfall, increasing water quality. According to studies, the state's coastline districts have adequate water resources appropriate for various uses. Continued development in the coastal region, on the other hand, may result in the salinization of the coastal aquifer in the near future. To protect the aquifer from SWI, constant monitoring of water resources and pumping activity is required.

Kerala: Limited studies were conducted on SGD along the Kerala coast, situated at the southern tip of India. The work carried out by George et al. (2018) characterizes potential groundwater discharge zones using GWL differences across coastal barriers and 2D electrical resistivity imaging. GWL contours have been used to identify possible zones of SGD in the Kozhikode coast in Kerala, where freshwater flows from the subsurface to the sea. Additionally, the presence of a water table and the underlying lithology may be clearly defined by measuring subsurface apparent resistivity using several electrode configurations, including Wenner, Schlumberger, Dipole-Dipole, and Pole-Dipole. According to the study's findings, the water-saturated laterite or lateritic soil aquifer layer is indicated by freshwater saturation values ranging from 20 to 700 Ω. Furthermore, the water table in wells is located 5–20 m below ground level. Suresh Babu et al. (2009) have demarcated the two SGD zones at Kovalam, Kerala, and Muttam, Tamil Nadu, using TIRS, hydrochemical analysis of groundwater porewater samples and geophysical methods. Initially, SGD zones were suspected of using a higher gradient of the GWL contour. Further, it has been verified with a brightness temperature of thermal images, which gives different temperature values for seawater and freshwater. Furthermore, hydrochemical parameters of groundwater and porewater, such as EC, TDS and salinity, the temperature, are used as critical parameters to locate SGD.

Tamil Nadu: The coastline of Tamil Nadu state is located in the Bay of Bengal on the east coast. As compared to other states, more studies have been reported on SGD in Tamil Nadu. Suresh Babu et al. (2009) have located the SGD zone at Muttam, Tamil Nadu, using thermal infrared remote sensing (TIRS), hydrochemical analysis of groundwater porewater samples, and geophysical methods. Similarly, Antony Ravindran and Ramanujam (2014) have applied the 2D electrical resistivity survey to identify SGD at Manapad, Tuticorin coast. In addition, it was concluded that the resistivity ranging from 31-174 Ωm behaves as a permeable pathway for freshwater discharge into the sea. The SWI and SGD zones were identified in the south part of Chennai in Tamil Nadu using Numerical groundwater modeling and electrical conductivity (EC) of in situ groundwater and porewater samples (Sathish and Elango 2015, Manivannan & Elango 2019). The estimated SGD fluxes and their nutrient effects on the marine environment have been traced using radon mass balance at the shoreline of Punnakayal Estuary, India (Selvam et al. 2021). They have quantified SGD rates for both estuaries (0.04 to 0.12 $m^3.m^{-2}.d^{-1}$) and groundwater sites (0.03–0.15 $m^3.m^{-2}.d^{-1}$), showing that groundwater sites discharge more SGD than estuaries. Further, the study found that the recirculation of seawater through the geological structure might move nutrients from the land to the coastal environment in many places. Similarly, Chidambaram et al. (2017) have attempted to identify and quantify SGD flux in Cuddalore district, Tamilnadu using a Seepage meter, Radon, GWL, Electrical Conductivity (EC), and pH parameter and estimated the daily SGD rate to be 37.24 to 79.16 $cm.d^{-1}$. They have used a seepage meter to measure SGD and Radon to identify groundwater anomalies in porewater samples to demarcate SGD zones. Prakash et al. (2018) have applied three approaches, viz water budget, Darcy law, and manual seepage meter, to quantify SGD at Coleroon Estuary, Tamil Nadu, India. The estimated SGD rate in the water budget equation was 6.9×10^6 $m^3.y^{-1}$, Darcy's law 3.2×10^3 to $308.3 \times 10^3 m^3.y^{-1}$, and similarly in the seepage meter 0.7024 $m.h^{-1}$. In addition to this, the obtained SGD rates were cross-verified with different results conducted worldwide and matched with the results. In another study at Sankarabarani basin, Villupuram district of Tamil Nadu, India (Srinivasamoorthy et al. 2019), Continuous radon isotope monitoring has been used to assess SGD, using groundwater, surface, and pore water samples taken at a distance perpendicular to the shore. The estimated average fresh SGD was 0.88 $m.d^{-1}$.

Andra Pradesh: Andhra Pradesh features India's second-largest coastline. The state's groundwater salinity is projected to be higher in an area of roughly 1760 km^2 (Farooqui et al. 2009). Groundwater quality is degrading, and agricultural land is eroding as a result of rising sea levels (Kantamaneni et al. 2019). Only one study has been reported on SGD in this state, at Godavari estuary, Vasishta Godavari, and the Kakinada Bay (Rengarajan and Sarma 2015). They have used ^{228}Ra isotopes to measure SGD in all three estuaries. The estimated SGD in the Gautami Godavari estuary: $5 \times 10^6 m^3.d^{-1}$, Vasishta Godavari estuary: 20 to $43 \times 10^6 m^3.d^{-1}$, Kakinada bay: $300 \times 10^6 m^3.d^{-1}$. Compared to the Vasishta and Gautham estuary, Kakinada Bay has recorded higher SGD rates due to higher precipitation and low topographical elevation along the coast. Most of the works have been conducted on saltwater intrusion using ERT technique, hydrochemical analysis, and numerical modeling in the state (Rao et al. 2011, Surinaidu et al. 2015, Janardhana Raju et al. 2013, Bobba 2002). These studies show that the state's deltaic regions are particularly vulnerable to SWI due to rising sea levels.

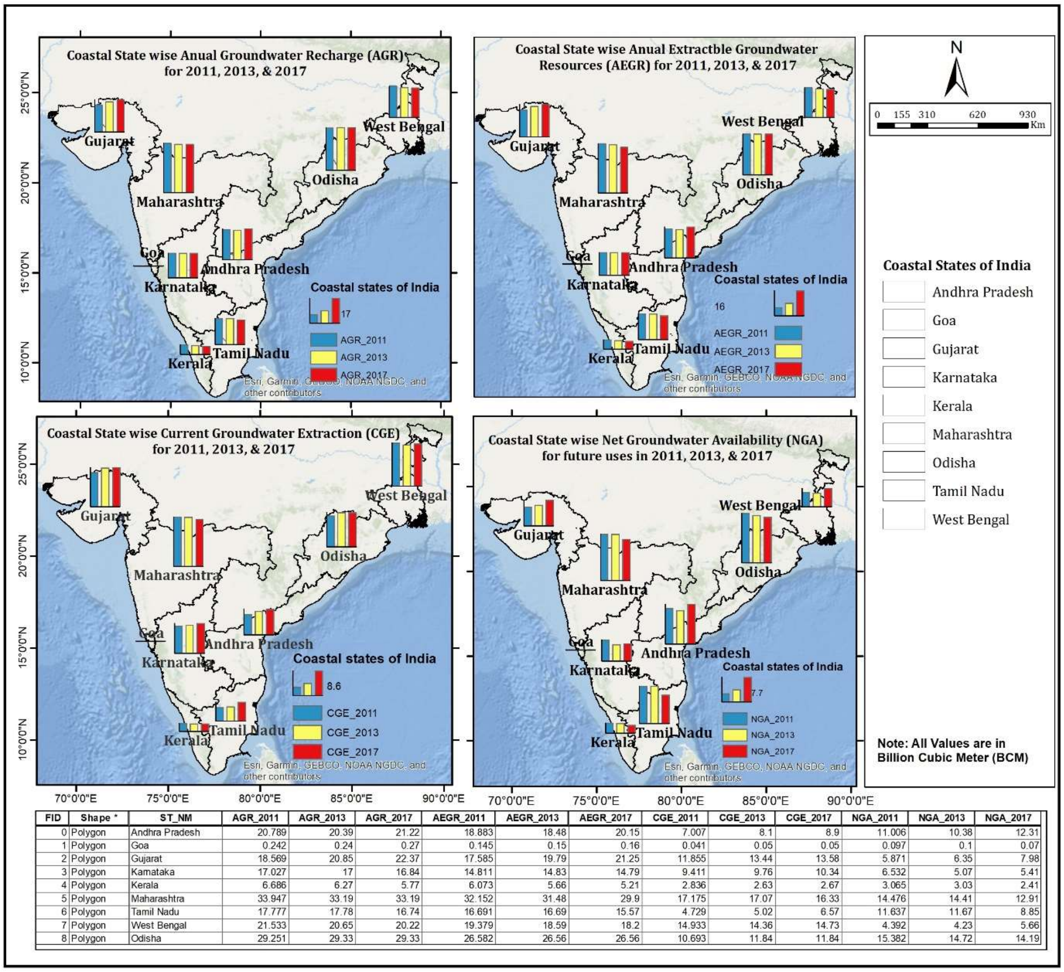
Odisha: India's state of Odisha is situated next to the Bay of Bengal on the country's east coast. The beach, which has a wide intertidal zone (> 4 km), is a tidal or marshy flat that appears at low tide and disappears at high tide (Mukherjee et al. 1987, Mukhopadhyay & Karisiddaiah 2014). Along with more recent alluvium deposits farther inland, palaeoaeolian dunes have shaped the shoreline. The area's coastal aquifers are covered with unconsolidated quaternary marine sediments and fluvial-deltaic deposits, which have grain sizes varying from medium sand to clay. Occasionally, there are iron nodules, calcareous concretions, and various fluvial and fluvial marine facies (Chakraborty 1991). By employing the ^{222}Radon measurement, Debnath et al. (2015) calculated the seasonal-wise SGD rate to the Bay of Bengal in Odisha, India. The estimated SGD rate in pre-monsoon was $0.6–0.8 \times 10^7 m^3.y^{-1}$ and post-monsoon $0.8–1.5 \times 10^7 m^3.y^{-1}$. It shows that the SGD flux to the Bay of Bengal is higher post-monsoon as compared to the pre-monsoon season. Furthermore, the study found that increased groundwater discharge induced by monsoonal activity causes significant porewater displacement from flat tidal sediments. Das et al. (2020) conducted a study on the impact of SGD on the Bay of Bengal's marine environment at Chandipur, Odisha, India. Further, the surface water–groundwater interaction zone, SGD rate, and nutrient flux were identified using solute chemistry, seepage meter studies, stable-isotopic signature, and geophysical approaches. The study also notes that the estimated nutrient flux was 240 and 224-$mMm^{-2}.d^{-1}$ for NO^{3-} and Fett.

West Bengal: West Bengal is an Indian state located between the Himalayas and the Bay of Bengal in eastern India. The stratigraphy of the coastline (Biswas 1963, Lindsay et al. 1991) starts with the deposition of pre-Jurassic Gondwana deposits, which cover the Rajmahal Group's 250 m thick late Cretaceous alternating sandstone and mudstone sequence and late Jurassic overlies to early Cretaceous amygdaloidal basalts and andesites. The rainfall induced by the southeast monsoon storm has a significant impact on the groundwater system in the Western Bengal basin. Minimal studies were reported on SGD in this state. Mukherjee et al. (2007) have used the water balance equation to estimate the SGD rate at four districts of West Bengal, namely Nadia, Murshidabad, South 24 Parganas, and North 24 Parganas. The estimated average SGD rate was $1.2 \text{ x } 10^8 m^3.y^{-1}$. Similarly, experimentation has been carried out at the two districts of waste Bengal, India, through in situ radon (^{222}Rn) monitoring (Krishan et al. 2015) to demarcate the locations of SGD. The investigations revealed intense ^{222}Rn activity in coastal waters (average: 4.98 $kBqm^{-3}$), indicating significant SGD. Further, Groundwater's EC location ranged from 850 to 5000 $\mu S.cm^{-1}$, with an average of 1385 $\mu S.cm^{-1}$, indicating the presence of saltwater zones. Finally, the study noted that the SGD is a mix of fresh groundwater and recirculated seawater that is influenced by the hydraulic gradient in the nearby aquifer and tide conditions in the coastal areas.

Coastal States' Groundwater Resources in India

In India, increased reliance on groundwater resources has resulted from rainfall uncertainty, lack of surface water in a few regions, and the onsite availability of fresh groundwater. In recent decades the land-use change and urban development have lead to the disruption of the natural groundwater recharge process and GWL drops (Mukherjee et al. 2018, Patra et al. 2018). However, the scenario turns severe during summer as the groundwater table drops drastically due to inadequate natural recharging. It results in water scarcity, particularly in coastal areas where groundwater overuse is frequent. But the scenario is different in the monsoon season due to an increase of the groundwater table from southwest monsoon rainfall, leading to high chances of SGD to occur to the sea from the ground water table increased coastal aquifers. Many states and central government bodies have assessed the groundwater resources of India every 3 or 4-year years, which started in 2004. The available groundwater resource datasets for the period are 2011, 2013, and 2017. The remaining years' datasets are not considered because they were not assessed. Fig. 6 shows coastal state-wise groundwater resources of India assessed by CGWB and have been collected from the Water resources information system (WRIS) (https://indiawris.gov.in/wris/#/GWResourcesweb portal) for the 2011, 2013, and 2017 periods. An analysis of coastal state-wise groundwater availability has been discussed below.

The annual replenishable groundwater resources that were evaluated in 2011 were 165.821 BCM, 165.7 BCM, and 165.95 BCM. These numbers indicate a little fluctuation in the groundwater supplies that can be replenished. Compared to 2011 and 2013, there was a notable rise in 2017. It is imperative to recognize, though, that these yearly



Note: All Values are in Billion Cubic Meter (BCM)

FID	Shape *	ST_NM	AGR_2011	AGR_2013	AGR_2017	AEGR_2011	AEGR_2013	AEGR_2017	CGE_2011	CGE_2013	CGE_2017	NGA_2011	NGA_2013	NGA_2017
0	Polygon	Andhra Pradesh	20.789	20.39	21.22	18.883	18.48	20.15	7.007	8.1	8.9	11.006	10.38	12.31
1	Polygon	Goa	0.242	0.24	0.27	0.145	0.15	0.16	0.041	0.05	0.05	0.097	0.1	0.07
2	Polygon	Gujarat	18.569	20.85	22.37	17.585	19.79	21.25	11.855	13.44	13.58	5.871	6.35	7.98
3	Polygon	Kamataka	17.027	17	16.84	14.811	14.83	14.79	9.411	9.76	10.34	6.532	5.07	5.41
4	Polygon	Kerala	6.686	6.27	5.77	6.073	5.66	5.21	2.836	2.63	2.67	3.065	3.03	2.41
5	Polygon	Maharashtra	33.947	33.19	33.19	32.152	31.48	29.9	17.175	17.07	16.33	14.476	14.41	12.91
6	Polygon	Tamil Nadu	17.777	17.78	16.74	16.691	16.69	15.57	4.729	5.02	6.57	11.637	11.67	8.85
7	Polygon	West Bengal	21.533	20.65	20.22	19.379	18.59	18.2	14.933	14.36	14.73	4.392	4.23	5.66
8	Polygon	Odisha	29.251	29.33	29.33	26.582	26.56	26.56	10.693	11.84	11.84	15.382	14.72	14.19

Fig. 6: Coastal state-wise groundwater resources of India for the 2011, 2013, and 2017 periods.

replenishable groundwater resources, which account for 64% of all annual replenishable groundwater resources, are primarily dependent on rainfall recharge during both monsoon and non-monsoon seasons (2011: 106.008 BCM, with monsoon rainfall at 93.107 BCM and non-monsoon rainfall at 12.901 BCM, 2013: 106 BCM, with monsoon rainfall at 93.38 BCM and non-monsoon rainfall at 12.67 BCM, 2017: 106.8 BCM, with monsoon rainfall at 93.1 BCM and non-monsoon rainfall at 13.75 BCM). The remaining amount (2011: 59.509 BCM, 2013: 59.68 BCM, 2017: 57.55 BCM) comes from a variety of sources, such as seepage via canals, recharge from tanks and ponds, irrigation return flow, and water-saving buildings, to name a few. While (2011: 152.301 BCM, 2013: 152.23 BCM, 2017: 151.79 BCM) is accessible for different uses, the remaining portion of the total naturally replenishable water (2011: 13.518 BCM, 2013: 13.48 BCM, 2017: 12.61 BCM) naturally discharges during the non-monsoon season. Additionally, the net annual groundwater extraction for residential, commercial, and industrial applications is projected to be (2011: 78.68 BCM, 2013: 82.27 BCM, 2017: 85.01 BCM), leaving (2011: 72.458 BCM, 2013: 69.96 BCM, 2017: 69.79 BCM) of groundwater accessible for future requirements. By 2050, given the present rates of population increase, India may have a serious water problem (Gupta & Deshpande 2004.

Management Measures

SWI and its associated processes, such as SGD, can impose significant water scarcity on coastal water resources worldwide. Conjunctive use of groundwater resources in coastal areas could avoid saltwater ingression, and nutrients enriched SGD into the ocean. Geochemical processes related to coastal groundwater are predominant, for e.g., Charette & Buesseler (2004) suggest that reducing conditions are common in groundwater, and Corbett et al. (1999) infer that denitrification rates are high in groundwater near the Florida Keys. However, at this time, our understanding of all these processes is limited. Additionally, the numerous studies focused on two alternatives for water discharge: 1) track groundwater outflow and related nutrient fluxes, and 2) cut back on inputs to the coastal groundwater system.

Best management practices (BMPs) have been shown to reduce nitrogen in surface water and groundwater (Mitsch et al. 1999). As a result, they should be effective in lowering nutrient concentrations entering the groundwater. Examples of BMPs include changing farming practices to use nitrogen more effectively and efficiently, creating and repairing wetlands and riparian zones, and increasing nitrogen controls on wastewater treatment plants. The scientific community has suggested monitoring the interactions between surface and ground waters in the coastal zone by modeling, geochemical tracers, and pressure sensor technologies. However, the issue has not received enough attention to merit management's attention. Similarly, Rainwater harvesting technology has been widely used to manage several groundwater problems in many areas of India. Havelis, Bndh, Bandhulia, Virda, Eri, Dhora, Khadins, Madakas, Ahar-pynes, Surangas, Taankas, and other historic rainwater harvesting techniques are being used in India (Rivera-Ferre et al. 2012). Rainwater harvesting adaptation and implementation are now mandatory in almost all Indian states, thanks to several legislative decisions. The Central Ministry of Drinking Water and Sanitation, in collaboration with the CGWB, has established several programs aimed at mitigating groundwater issues in India's rural and urban areas through constructing various rainwater harvesting structures and national projects on aquifer management and a pilot study on SGD along the India coastline and its islands. Implementing a series of check dams across rivers in coastal regions also seems to be quite effective in preventing SGD and SWI due to increased GWL.

Additional Discussion

The novelty of current research lies in several aspects, like SGD research contributes to a deeper understanding of coastal hydrology by investigating the exchange of groundwater and surface water in nearshore and offshore environments. This includes studying the fluxes, pathways, and dynamics of water, nutrients, and contaminants within coastal aquifers and marine ecosystems. Novel methods and technologies are continually being developed to improve the assessment and quantification of SGD. These include advancements in geochemical tracers, remote sensing techniques, numerical modeling, geophysical surveys, and in situ monitoring tools. Such methodological advances enhance the accuracy, resolution, and efficiency of SGD research. SGD research explores the ecological implications of submarine groundwater discharge on coastal habitats, including its role in nutrient cycling, primary productivity, biodiversity, and ecosystem health. Understanding these ecological connections is essential for effective coastal management and conservation efforts. SGD is a globally significant phenomenon with implications for coastal regions worldwide. Research on SGD addresses regional variations in discharge rates, drivers, and impacts, contributing to a broader understanding of coastal hydrological processes and their response to environmental changes, such as sea-level rise, land-use change, and climate variability. SGD research typically involves interdisciplinary collaboration among hydrologists, geochemists, oceanographers, geologists, biologists, and environmental scientists. This interdisciplinary approach allows for comprehensive investigations that integrate hydrological, geological, chemical, and biological processes, providing a more holistic understanding of SGD dynamics.

Overall, the novelty of SGD research lies in its contribution to advancing scientific knowledge, addressing environmental challenges, and informing management and policy decisions related to Indian coastal water resources and ecosystems.

CONCLUSIONS

SGD is a complex hydrogeological phenomenon that describes the exchange of fresh and recirculated saline groundwater from coastal aquifers into the ocean. In the majority of the west and east coast regions, the SGD outflow of nutrients and subterranean fluids to the coastal zone provides nutrients to continental shelf ecosystems. This study summarizes the results of various studies and the current status of SGD in Indian coastal aquifers. SGD's controlling factors, such as terrestrial forces and marines, were explained thoroughly, and quantification and identification methods such as seepage meter, groundwater modeling, thermal images, in-situ modeling, geophysical technique, and hydrograph separation technique have been reviewed. The following conclusions were formulated from the study.

- Studies indicate higher SGD rates on the east coast of India compared to the west coast.
- Net groundwater availability for future use declined in 2017 compared to 2011 and 2013.
- Accurate understanding and quantification of SGD are essential due to its significant impact on coastal eutrophication and freshwater discharge.
- Identifying and quantifying SGD is vital for marine environmental conservation, coastal zone management, and addressing water scarcity in coastal communities.
- Recent decades have seen substantial advancements in SGD studies, underscoring the need for further research on the description and quantification of SGD sources.
- Limited studies on SGD along the Indian coast are due to challenges in data monitoring, collection, and analysis, particularly in marine environments.
- SGD studies are crucial for auditing national water resources and marine ecosystems' health.
- Future research should focus on numerical modeling, identifying SGD signatures through marine ecosystem species, and quantifying fresh SGD flux using advanced methodologies.
- Identified SGD locations could be utilized for local drinking water during dry periods and enhance species productivity in the SGD zones.
- Understanding nutrient content and pollution levels in SGD is essential for aiding policymakers and government agencies in sustainable ocean management.
- Accurate nutrient estimation and contaminated SGD quantification are critical for developing sustainable marine environment management strategies.

The future scope of the study is to quantify the fresh SGD flux that was discharged annually into the ocean using numerical-based modeling or a series of isotope analyses. SGD not only discharges the fresh groundwater but also releases the enriched, polluted groundwater, impacting the marine environment. The nutrient estimation, quantification of contaminated SGD, and NPK analysis can be helpful for policymakers and government agencies in the sustainable management of the ocean environment.

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