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Review

State-of-the-art on the conceptual advancement of seawater intrusion: A comprehensive review, management, and possible future research direction

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ABSTRACT

The global need for freshwater resources by densely populated regions has resulted in the excessive exploitation of groundwater (GW), subsequently leading to seawater intrusion (SWI) predisposed to the influences of rising sea levels and changing climates. This research proposes a state-of-the-art review of SWI to develop proper coastal integrated water resource management. For these purposes, a detailed review of the long research period on SWI in terms of conceptual advancement, identification techniques, and protection and mitigation procedures is presented. Past, present, and future improvements of SWI were analysed from the available literature and comprehensive bibliographic analysis based on the largest available database (Scopus) was performed from 1970 to March 2022. We found that hydrogeological, hydrochemical, isotopic, and geophysical methods accounted for 7.2%, 8.1%, 3.7%, and 9.2% for SWI assessment studies, respectively. Moreover, SWI modelling, and simulation received the closest attention, accounting for 49.4% and 22.3%, respectively. The outcomes also revealed that China, the United States of America (USA), Australia, India, and Italy are the countries with the highest contributions to the field of SWI, accounting for 17%, 14%, 5.6%, 5%, and 4.5% of research, respectively. The obtained results also suggest further developments for enhancing the management of SWI in the affected regions. For Saudi Arabia, we found that more research is required for SWI assessment and management.

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1. Introduction

Groundwater (GW) plays a crucial role as the primary source of freshwater on Earth, accounting for over 90% of liquid freshwater resources globally. However, the depletion of vital freshwater resources poses significant challenges to water security and sustainable development. Moreover, the quality of groundwater is being degraded due to natural and artificial contaminants, further reducing the availability of exploitable freshwater. Climate change adds another layer of complexity by impacting freshwater reserves at national and global levels. In response, the United Nations Sustainable Development Vision 2030 and Saudi Arabia's 2030 sustainable vision aim to bridge the gap between water supply and demand, focusing on aquifer protection, water quality improvement, and sustainable groundwater withdrawal (KSA, 2020; SDGs, 2015).

Seawater intrusion (SWI) in coastal aquifers poses a substantial water security issue for coastal communities. It occurs when seawater infiltrates landward due to extensive groundwater abstraction and/or sea-level rise. The historical progression of SWI research and management is depicted in Fig. 1, which highlights the analytical solutions provided by early researchers such as Herzberg in the late eighteenth and early nineteenth centuries. Subsequent studies in the mid-nineteenth century further enhanced our understanding of SWI behaviour and shape through field investigations and analytical solutions (Dagan and Bear, 1968; Mualem and Bear, 1974). However, the delineation of the extent of SWI remained a challenge until recent decades, when computational tools and geophysical techniques enabled researchers to outline and simulate SWI in coastal aquifers (Chang and Clement, 2012).

SWI poses a significant threat to groundwater quality in coastal regions. The increased salinity of shallow groundwater not only impacts the availability of freshwater resources but also exerts pressure on deep groundwater, which is often fossil groundwater in arid regions by. The excessive extraction of deep groundwater ultimately compromises the sustainable use of freshwater in coastal areas and can lead to increased soil salinity, affecting food production (Hussain et al., 2019). SWI can also result in increased salinity pollution of fresh surface water through agricultural drainage, disrupting the local ecosystem. Therefore, mitigating and preventing SWI is crucial to ensuring a sustainable water resource and safeguarding both surface and underground freshwater bodies. Various methods and techniques, including conventional, physical, and hydraulic barriers, are employed for SWI management and prevention. Traditional approaches, such as reducing groundwater abstraction, are cost-effective and viable when alternative water supply sources are available. Physical barrier techniques are effective for shallow aquifers, but expensive processes are required for deep aquifers. Hydraulic barriers, involving aquifer recharge, brackish water abstraction, or a combination of both, represent the most recent approach to SWI management (Hussain et al., 2019).

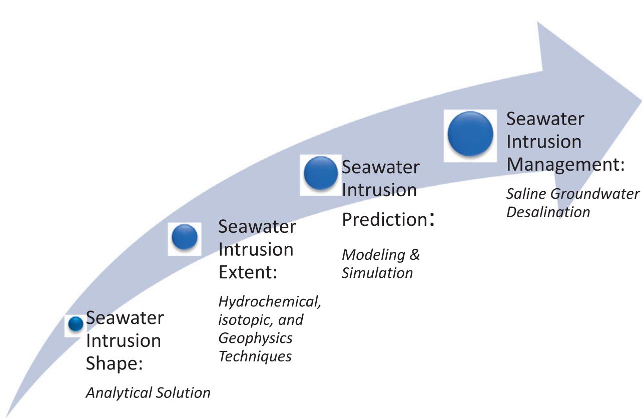

Fig. 1. Diagram showing the advancement of SWI research and management.

Recent reviews on SWI processes, management, and states in different regions have shed light on effective management strategies and detection techniques (Hussain et al., 2019; Jeen et al., 2021; Prusty and Farooq, 2020; Sankoh et al., 2022). Hydraulic methods have been identified as the most suitable for protecting coastal aquifers, while isotope techniques in combination with hydrochemical parameters offer effective means of identifying sources of contamination, including SWI. The vulnerability to SWI varies among different regions, with alluvial aquifers found to be more susceptible than crystalline aquifers. The status of SWI in Saudi Arabia's coastal aquifers remains largely unexplored, particularly along the eastern coast. This study aims to review the advancements in SWI conceptualization, management, and identification techniques over the past few decades, considering technological and computational tools as well as management practices. Furthermore, it identifies research gaps in SWI delineation, modeling, and management at regional and global scales. The coastal aquifers of Saudi Arabia serve as a case study to evaluate the current situation of SWI and existing management practices in the region. While some discrepancies have been identified in previous research on SWI, this review consolidates the developments in SWI research up to March 2022 and highlights the need for further.

2. Literature review and bibliometric analysis

Currently, SWI is a widespread environmental problem affecting over 100 countries globally. This article provides an overview of SWI in different regions, such as coastal, Mediterranean, and delta areas. The review utilizes bibliometric analysis and visualizations to explore the literature on SWI and highlights the significance of new technologies in managing this issue. Data for the review were obtained from various sources, including Scopus, Google Scholar, and Web of Science (WoS). Bibliometric software, particularly VOS viewer, was used for visualizing and analysing the data. The review focused on studies reported in the Scopus database from 1970 to 2022, using the primary index term "SWI." Different analysis methods, such as co-authorship, co-occurrence, and citations, were employed to examine the literature.

The network visualization of the conducted reviews on SWI showed a significant increase in attention towards this topic. The minimum number of keyword occurrences was 13,356, with

1,441 meeting the threshold, indicating the weight and significance of SWI in the literature (Fig. 2). A sieve analysis was performed to ensure focused and inclusive data, resulting in the selection of the 1,000 keywords with the highest total link strength. Similar approaches have been employed in previous studies using different databases, especially by Cao et al. (2021). The literature review identified several studies focusing on SWI in different regions. Cao et al. (2021) highlighted the challenges associated with SWI in coastal aquifers, emphasizing the importance of including density information, addressing data problems, and considering aquifer bottom topography and initial conditions. Werner, (2010) developed classical and mathematical models for SWI management in Australia, while Han et al. (2011) investigated GW salinization methods in the Laizhou Bay, China. Other studies examined SWI in regions such as the delta basin of Andhra Pradesh, India (Gurunadha Rao et al., 2011), the coastal aquifer of Wadi Ham in the UAE by Sherif et al. (2012) and a bedrock aquifer on the west coast of Korea by Park et al. (2012). More recently, Ding et al. (2020), Hasan et al. (2021), and Basheer and Salama, (2022).

The reviewed studies provide valuable insights into SWI management and control approaches. They cover a range of techniques, including physical, geochemical, and geophysical investigations, numerical simulation modelling, hydrogeological analysis, and optimisation techniques. These studies address issues such as excessive groundwater extraction, seawater-freshwater interface, and vulnerability assessment of coastal aquifers. The findings emphasize the need for comprehensive monitoring, modelling, and management strategies to mitigate the impacts of SWI. This bibliometric review provides a comprehensive overview of SWI research, highlighting its global significance and the increasing attention it has received. The review demonstrates the applicability of bibliometric analysis and visualization techniques in understanding the conceptual impact of literature outcomes. The studies reviewed offer valuable insights into SWI management approaches, contributing to the development of effective strategies for addressing this environmental challenge. Appendix A shows another summary of SWI literature, in which we conducted a review from 2010 to 2022 on the engagements of different approaches towards SWI across the globe.

3. Concept, theoretical aspect, approaches, and methodology

SWI is the subsurface movement (lateral and vertical) of seawater landward into coastal freshwater aquifers (Werner et al., 2013). This process causes an increase in the salinity concentration of freshwater in coastal aquifers, thereby degrading the quality of GW resources. Global warming is an essential central control of sea-level rise and river discharge. On the other hand, human activities (agriculture, industry, and urbanisation) control the decline in GW levels in coastal aquifers. The driving forces of such phenomena are sea level rise, decreased river discharge, and unsustainable GW pumping from coastal aquifers. Under natural conditions of freshwater and seawater interactions in coastal areas, the seaward movement of freshwater acts as a barrier to prevent seawater from encroaching on coastal aquifers, and the freshwater-seawater interface remains near the coast or far beneath Earth's surface. However, the natural condition has been disrupted, and landward movement of the interface has occurred globally in major cities (Fig. 3). This has occurred as a result of the over-pumping of GW from coastal aquifers to satisfy the increase in water demand for the coastal communities, due to the rise in population, urbanisation, and industrial and agricultural development (Fig. 4). Therefore, seawater intrudes into coastal aquifers and contaminates freshwater, thus decreasing its availability to the coastal communities.

An assessment of the impact of SWI on freshwater resources in coastal regions is crucial for developing effective management strategies. Various techniques have been employed to assess the influence of SWI on freshwater resources, including hydrogeological and hydrogeochemical methods, isotopic signatures, statistical analysis, numerical modelling, and hydrogeophysics (Alhumimidi, 2020; Balasubramanian et al., 2022) (Fig. 5). This review examines the distribution and utilization of these techniques in SWI studies. However, the unavailability of monitoring wells or the scarce dis-

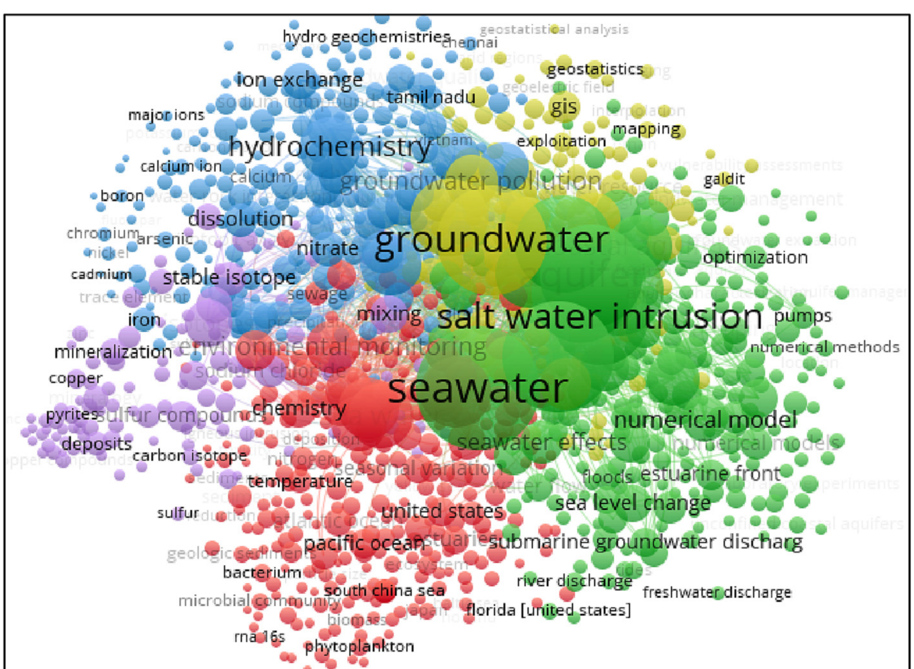

Fig. 2. Keyword probability of occurrences map, showing the bibliometric network of SWI from the Scopus database (1970–2022).

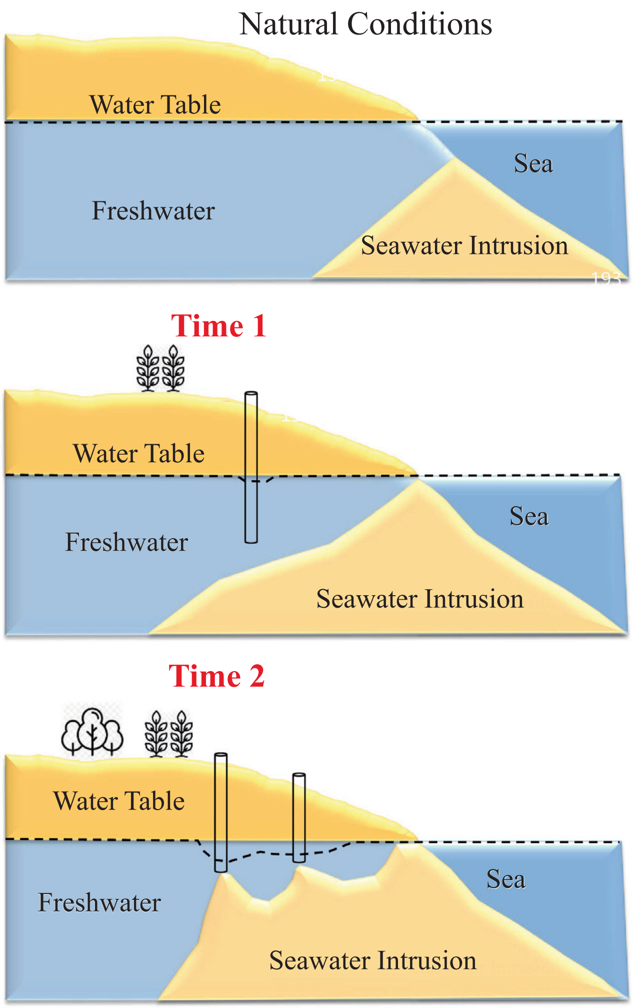

Fig. 3. Diagram illustrating the freshwater-seawater interface landward movement through time.

tribution has resulted in cost-effective techniques to delineate SWI (Bear & Dagan, 1964; Weinstein et al., 2021). The SWI identification and delineation techniques published from 1970 to 2022 were reviewed, and the percentage of each established technique is shown in Fig. 6a. The isotope approach accounts for 3.7% of the studies, while hydrochemistry constitutes 8.1%. Geophysics, as an advanced technique, is employed in 9.2% of the studies, while hydrogeology forms 7.2%. Modelling and simulation techniques are widely used, representing 49.4% and 22.3% of the literature, respectively.

Hydrochemical analysis involves examining the ion composition of groundwater (GW) and assessing changes in its chemistry (Amiri et al., 2016). Salinity, measured by electrical conductivity (EC), is a primary chemical indicator of SWI occurrence. Anions such as chloride (Cl^-) and bromide (Br^-) are commonly used to trace SWI to the aquifer system due to their distinct origins. Various ionic ratios, including Cl^- /Br^-, Mg^{2+}/Ca^{2+}, Na^+/Cl^-, K^+/Cl^-, SO_4^{2-}/Cl^-, and $Ca2^+/(HCO_3^- + SO_4^{2-})$, are reported as leading indicators for SWI identification (Alfarrah & Walraevens, 2018; Nair et al., 2013). Multivariate statistical analysis is also employed to analyze patterns and trends in hydrogeochemical data affected by SWI (Balasubramanian et al., 2022). The isotopic approach, often combined with hydrogeochemical data, is utilized to study SWI in coastal GW systems (Balasubramanian et al., 2022; Sankoh et al., 2022). Stable isotopes such as $\delta^{18}O$ and δ^2H are widely used, accounting for approximately 65% of the studies (1970–2022) (Fig. 6b). Other isotopes, including $\delta^{87}Sr$, $\delta^{34}S$, $\delta^{14}C$, δ^3H, $\delta^{13}C$, and $\delta^{11}B$, are employed to a lesser extent (11% – 4%) (Mahlknecht et al., 2017).

As reported in the literature, the main geophysical methods used to identify and map SWI are electrical resistivity and electromagnetic techniques (Fitrianto, 2021). Surface geoelectrical resistivity surveys, integrated with vertical electrical sounding (VES) and electrical resistivity tomography (ERT), delineate the lateral extent of SWI (Niculescu & Andrei, 2021). Electromagnetic techniques such as transient electromagnetic soundings (TEM), frequency-domain electromagnetic (FDEM), and time-domain electromagnetic (TDEM) methods complement electrical resistivity methods (Alhumimidi, 2020). Integrated geophysical approaches, combining different methods, contribute to accurate estimation

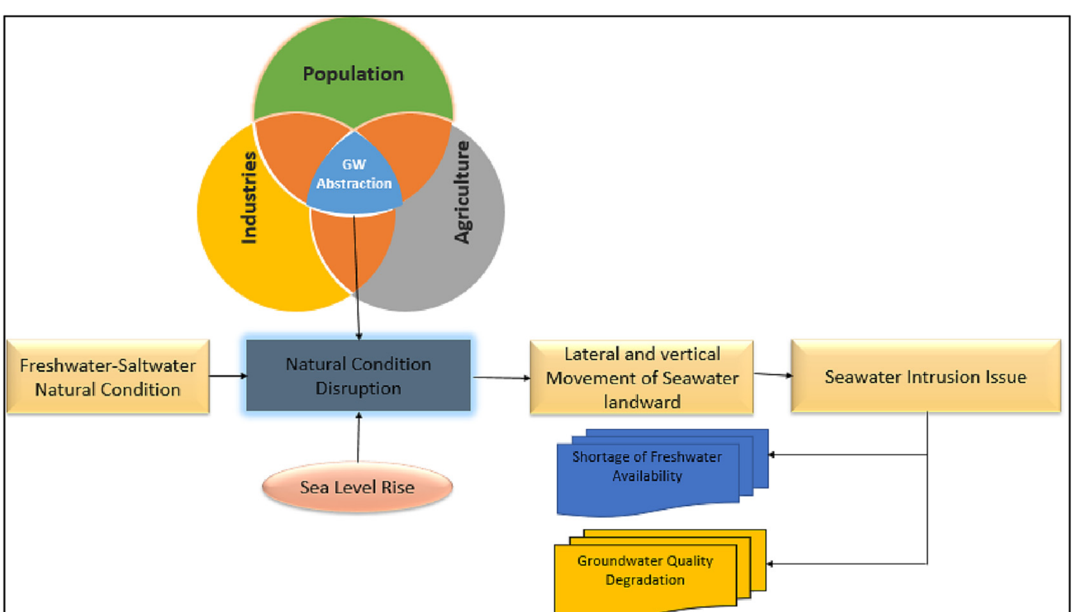

Fig. 4. Diagram summarising the cause and impacts of SWI on freshwater resources in coastal communities.

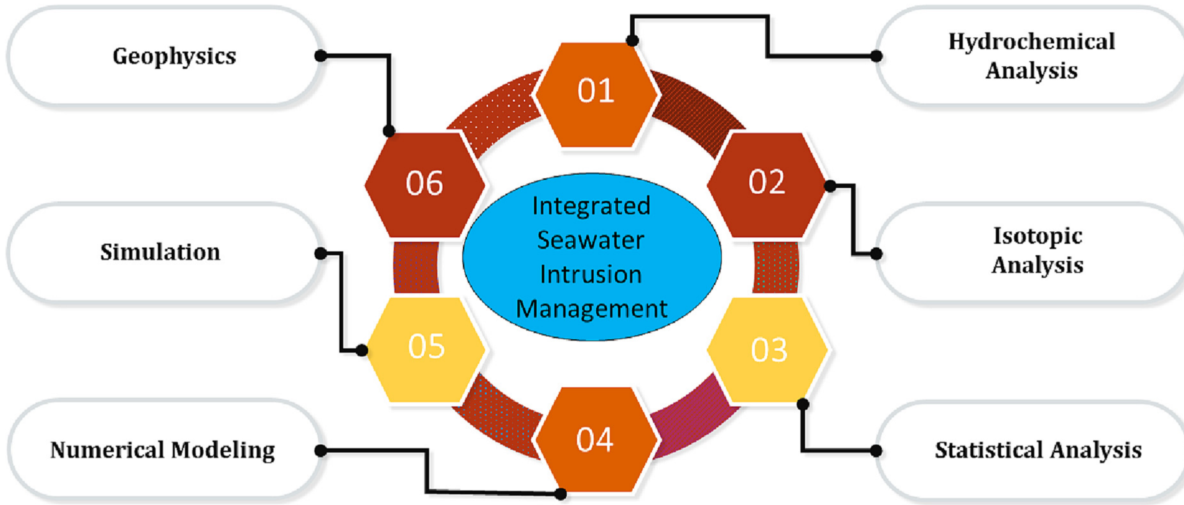

Fig. 5. Diagram showing the integrated approach for SWI research.

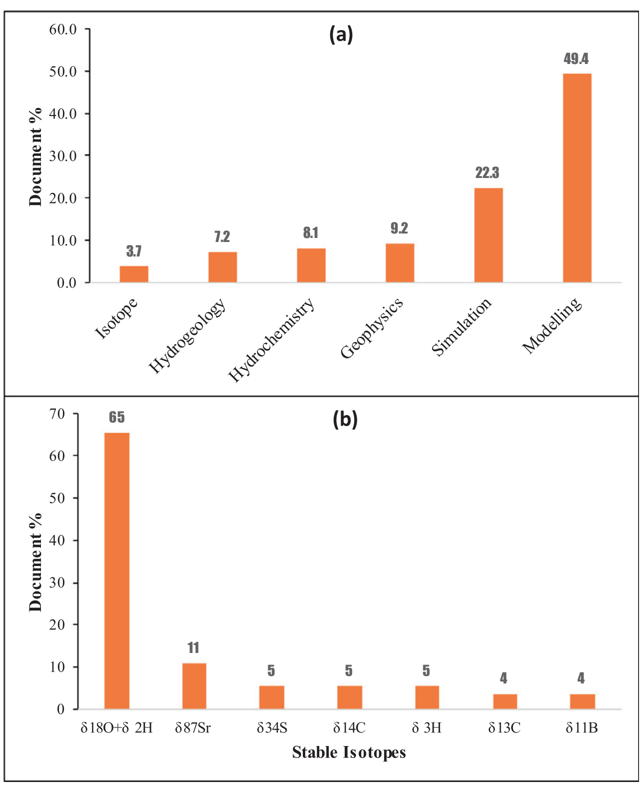

Fig. 6. (a) The percentage of publications for each technique of SWI. b) the percentage of publications for each type of stable isotope used for SWI.

and modeling of SWI extent, freshwater-seawater interface, and mixing zones. Two physics-based modeling approaches, the sharp-interface method, and the variable-density approach, are used to simulate SWI. Analytical solutions based on the hydrostatic approximation are employed in the sharp-interface approach. Notably, the SEAWAT code, coupled with MODFLOW for groundwater flow and heat transfer simulations, is widely used for modeling SWI. To effectively manage the threats posed by SWI to freshwater resources in coastal regions, it is essential to assess its impact. Hydrogeological and hydrogeochemical methods, isotopic signatures, statistical analysis, numerical modeling, and geophysical techniques all play vital roles.

3.1. SWI management

SWI management practices were applied to ensure a sustainable water resource supply in coastal areas. Conventional methods include reducing groundwater (GW) abstraction, relocating wells, and constructing physical and hydraulic barriers. Reducing freshwater extraction from coastal aquifers is a direct approach to controlling SWI, especially when supplemented with alternative water sources like treated municipal wastewater (Qadir et al., 2020). The potential of using treated wastewater for agriculture could serve as a substitute for GW. Varying approaches to SWI management have been reported, including upstream pumping increase and downstream reduction (Rejani et al., 2008). Subsurface physical barriers, such as concrete and grout, has been used to control SWI, but their construction is costly and may result in trapped saline water (Sugio et al., 1987). Surface physical barriers, created by extending the coastline, can help delay SWI progression and protect groundwater (Nawa and Miyazaki, 2009). However, constructing large-scale surface barriers remains limited due to high costs. Land reclamation studies in coastal areas have shown a reduction in ion concentration as an indicator of SWI retardation (Chen and Jiao, 2007).

Hydraulic barriers, including recharge, abstraction, and their combination, have gained prominence in SWI prevention. Artificial recharge through injection wells using high-quality water, such as desalinated seawater, treated wastewater, and desalinated brackish water, is a popular method, particularly in arid regions (Abdalla and Al-Rawahi, 2013). This technique is more suitable for confined and deep aquifers. Shallow and unconfined coastal aquifers can be protected by recharge through surface basins, reservoirs, and lakes, as well as surface recharge canals. Recharging coastal aquifers through dams has proven effective in mitigating SWI, as observed in the Sultanate of Oman (Abdalla and Al-Rawahi, 2013). Another management technique involves pumping brackish and saline water from coastal aquifers to create a hydraulic barrier (Kacimov et al., 2009). This water can be utilized for desalination plants, industrial purposes, and irrigation (Van Dam, 1999; Schwartz, 2003; Sherif & Hamza, 2001; Wright & Missimer, 1997). The combination of recharge and abstraction, known as a mixing wall, involves injecting freshwater during saline water extraction. The hydraulic barrier method has received increased attention due to its effectiveness, lower cost, and the availability of alternative water sources like reclaimed water and dam water. Consequently, multidisciplinary research on SWI man-

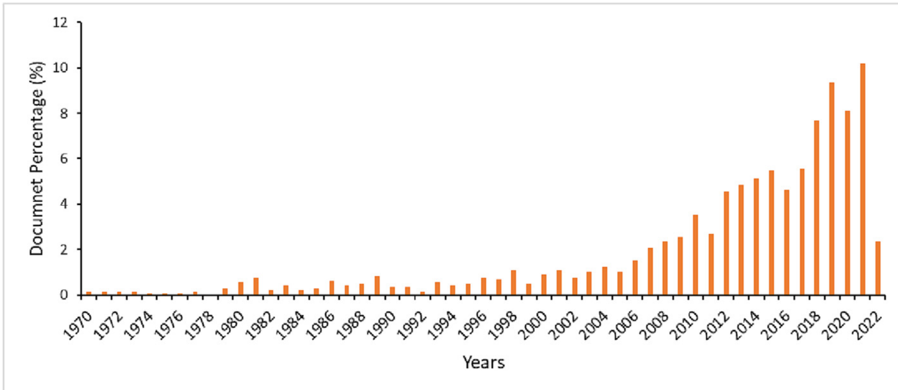

Fig. 7. Documents percentage and the increasing trend per year.

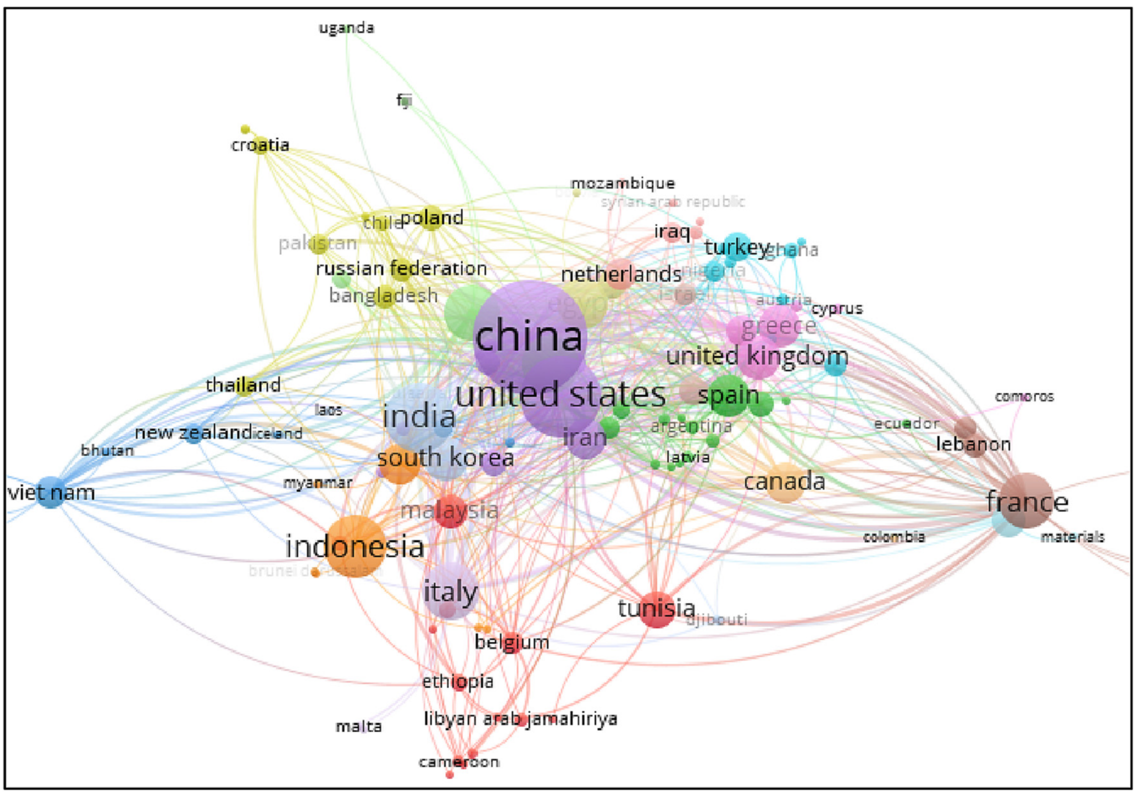

Fig. 8. Global trends based on countries' strength-network in SWI research.

agement continues to be encouraged (Kayode et al., 2017; Yang et al., 2021).

4. Survey and assessment of SWI

4.1. Global trends for SWI

This section provides a global overview of previous research on SWI from 1970 to March 2022, based on an extensive research database. The analysis reveals a projected increase of 97% in SWI publications, primarily originating from technical literature. Fig. 7 illustrates that 74% of the total documents were published between 2010 and March 2022, while 12% were published from 1970 to 2000. Comparing the number of published documents from 2000 to March 2022, there has been an average increase of 88%, consistent with findings reported by (Cao et al., 2021).The exponential growth of SWI research can be attributed to factors such as population growth, technological advancements, economic development, and ecological considerations. Before the emergence of isotope and geophysical investigations, traditional methods were employed to understand the spatiotemporal patterns of SWI. However, incorporating a wide range of disciplines such as geology, marine science, environmental science, engineering, water resources, mathematics, and oceanography is crucial to comprehensively address the challenges and opportunities associated with SWI. Indicators affecting SWI include anthropogenic activities, subsurface lateral intrusion, geological structures, and sea level rise, as highlighted by literature.

During the 1970s and early 1980s, mathematical and conceptual modelling approaches were employed to solve seawater interface issues, considering the morphological spatiotemporal

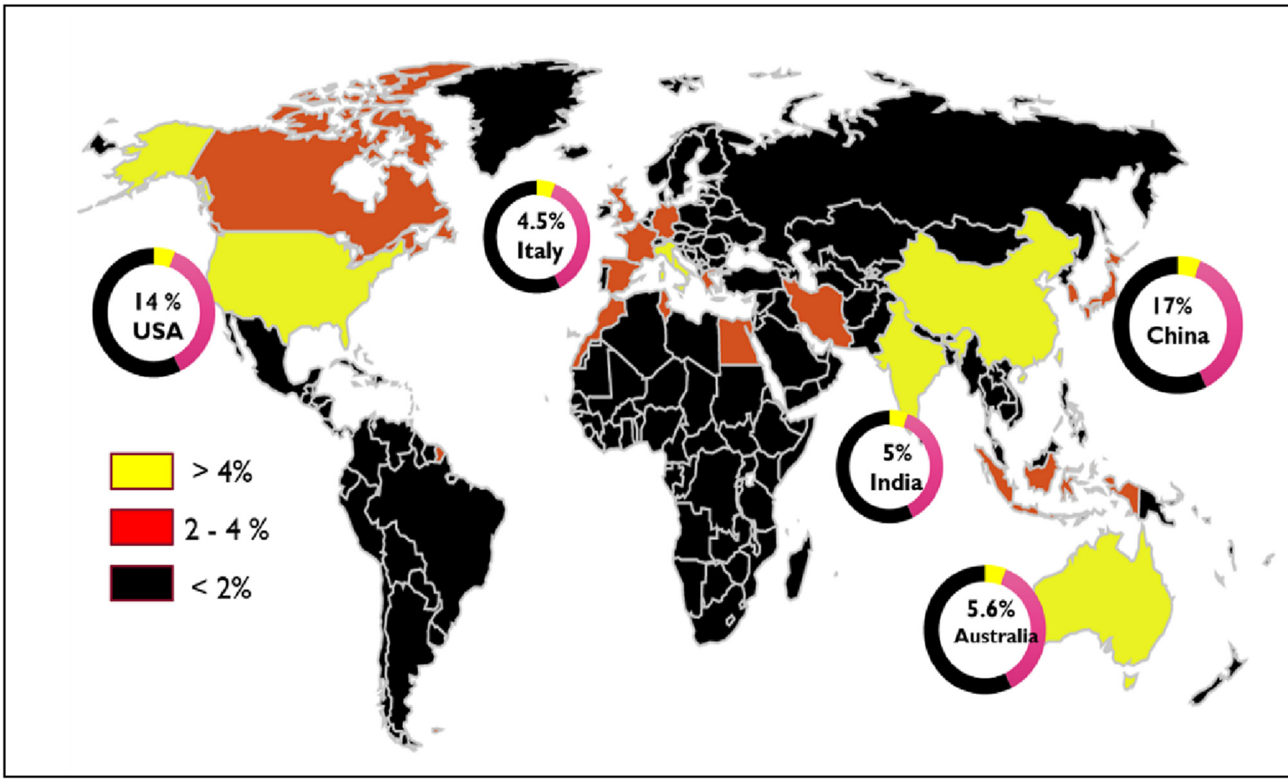

Fig. 9. Global trends in terms of geographic distribution of countries with reported maximum SWI documents (1970–2022).

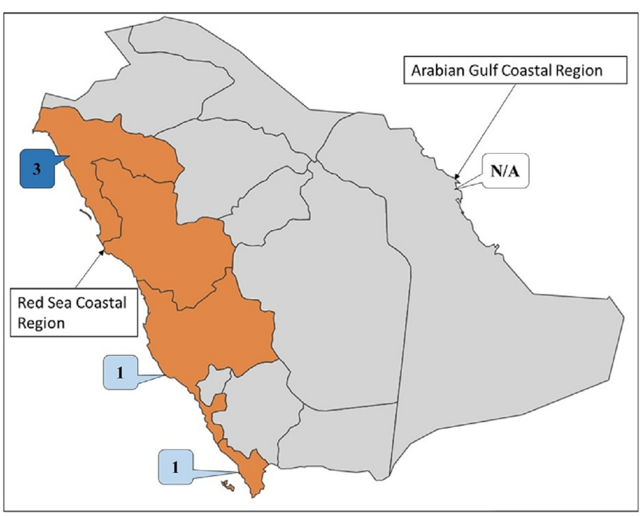

Fig. 10. Map showing SWI studies conducted on coastal regions of Saudi Arabia.

distribution of aquifers. However, the advent of Industrial Internet of Things (IoT) 4.0 and soft computing techniques has led to new technological advancements in SWI research. Singh, (2014) emphasizes the urgent need for a new strategy to assess and control groundwater (GW) pumping to safeguard against SWI. This study proposes and reviews a comprehensive computational programming tool for SWI management. SWI has been recognized as an agent of environmental footprint and global warming, impacting the well-being of flora and fauna. The literature underscores the evident influence of climate change on GW, aquifers, and coastal areas. Shallow and local aquifers have contributed to approximately 30% of cities experiencing SWI crises, with around 28% of affected cities located in primary GW basins.

The strength of research in the field of SWI is reflected in the wide interest and number of documents produced by each country. The analysis of bibliographic data reveals organizational co-authorship relationships and extensive networking among researchers based on region and county, as depicted in Fig. 8. The countries with the highest research strength are then connected. Surprisingly, China emerges as the most productive country in SWI research as of 2022, contrary to previous findings suggesting the United States held the highest strength from 1970 to 2019. This shift is attributed to the National Natural Science Foundation of China, which ranked first among single institutions with 330 published papers, followed by the U.S. National Science Foundation and the European Union. The demand for domestic water in densely populated coastal areas facing seawater challenges serves as a major driving force for SWI research. In terms of population and industrial contributions, China, the United States, Australia, India, and Italy have the highest involvement in the field of SWI. Fig. 9 highlights these five countries as the most cited and contributing nations to SWI research worldwide. The analysis identifies over 501 cities facing SWI issues, with China, the United States, Australia, India, and Italy accounting for 17%, 14%, 5.6%, 5%, and 4.5% of these cities, respectively.

4.2. Status of SWI in Saudi Arabia

Saudi Arabia, a semi-arid region with low precipitation and high evaporation rates, relies heavily on groundwater (GW) resources to meet its growing water demand. However, the coastal aquifers in Saudi Arabia are susceptible to salinization due to SWI, particularly in densely populated coastal cities. This section provides a comprehensive review of SWI studies conducted in Saudi Arabia, focusing on the different regions and the number of publications (Abdalla, 2016; Alfaifi et al., 2019; Alshehri et al., 2021; Batayneh et al., 2014; Alhumimidi, 2020). SWI studies in Saudi Arabia are reviewed in detail (Appendix B), and the study regions are mapped with the number of publications (Fig. 10).

In the western coastal region along the Red Sea, several studies have investigated SWI in shallow coastal aquifers. Alshehri et al. (2021) examined the GW quality in the Al Qunfudhah coastal region, using water quality indices and multivariate statistical analysis to assess the impact of SWI on water quality. They identified total dissolved solids (TDS) and chloride ion concentrations as key indicators of SWI. Similarly, Batayneh et al. (2014) employed a hydrochemical approach in the Aqaba Gulf coastal aquifer, using ionic ratios and factor analysis to cluster GW, brackish water, and saline water. They found high salinity levels and concluded that SWI significantly affects GW quality in the area. In the Red Sea coastal area, Salem Alhumimidi (2020) utilized geophysical techniques to map GW geophysical characteristics in the Duba region. While no hydrochemical analysis was performed, the study focused on lithological subsurface mapping. Waheidi et al. (2021) used hydrogeophysical methods to characterize a coastal shallow aquifer in the Aqaba Gulf, primarily focused on delineating brackish water zones rather than identifying SWI.

One study conducted in the Darb region along the Red Sea coast, by Alfaifi et al. (2019), integrated hydrochemical and hydrogeophysical approaches to study SWI in a coastal aquifer. Their findings indicated the impact of SWI on GW quality, with TDS as the primary chemical indicator. The electrical resistivity profiles and tomography results confirmed the presence of SWI in the aquifer. Abdalla, (2016) investigated the Jazan coastal aquifer and the Red Sea coastal area using hydrochemical analysis. He used electrical conductivity (EC) and ionic ratios as chemical indicators for SWI identification, finding higher EC values seaward, correlating with Na^{+}, Cl^{-}, and SO_4^{2-}. The study concluded that SWI was the potential source of saline GW in the Jazan coastal aquifer. However, SWI studies in Saudi Arabia have primarily focused on the western coastal regions along the Red Sea. These studies have employed a combination of geophysical and hydrochemical techniques to understand SWI dynamics and its impact on GW quality. However, isotopic approaches have not been utilized, and the eastern coastal aquifers remain unassessed. Further research is needed to address SWI management in Saudi Arabia's coastal regions and explore the potential of isotopic methods in understanding SWI processes.

5. Research gaps and future direction

Conventional studies on seawater intrusion (SWI) in coastal aquifers have primarily relied on hydrochemical data to identify the source of salinization in groundwater (GW) bodies. Indicators such as total dissolved solids (TDS), ion concentrations (e.g., chloride and sodium), and ionic ratios have been used to determine the salinity source from SWI (Amiri et al., 2016). However, there is a need for an integrated approach that combines geological, hydrogeological, hydrogeophysical, and hydrochemical data to reduce uncertainties in SWI identification. Geophysical methods have been predominantly used to determine the extent of SWI along coastal regions, and there has been an increase in geophysics-based studies in recent years. The integration of these advanced techniques with hydrological, hydrochemical, and isotopic studies is considered a promising direction for future SWI research. Isotopic signatures of GW in coastal aquifers are being explored to assess SWI, and a multi-isotope approach has shown potential in evaluating the impact of SWI on freshwater bodies (Hasan et al., 2020; Wang et al., 2022).

In Saudi Arabia, SWI assessment and its impact on GW resources in coastal regions have received limited attention. Previous research has focused on some parts of the western coastal area, while the eastern coastal region remains unexplored (Abdalla, 2016; Alfaifi et al., 2019). Comprehensive and integrated investigations encompassing hydrochemical, geological, hydrogeological, isotopic, and hydrogeophysical aspects are necessary to assess the extent and impact of SWI in Saudi Arabia's coastal aquifers. This research will provide a foundation for sustainable water resource management in coastal areas. There is a gap in SWI management studies, particularly regarding hydraulic barriers and the utilization of alternative water sources like reclaimed or desalinated water. While no published work on SWI mitigation in the coastal regions of Saudi Arabia has been found, studies conducted in other Gulf Cooperation Council countries, such as Oman and the United Arab Emirates, offer insights into SWI management strategies (Abdalla & Al-Rawahi, 2013; Zekri, 2008). Future research should prioritize filling the gaps in SWI assessment, management, and the utilization of alternative water sources to ensure the sustainable management of water resources in Saudi Arabia's coastal areas.

6. Conclusions and recommendations

This comprehensive review paper examines the progress in SWI research from 1970 to 2022, with a focus on conceptual advancements, identification techniques, protection, and mitigation measures. The study highlights the use of interdisciplinary approaches and advanced technologies, such as hydrogeology, hydrochemistry, isotopes, and geophysics, for accurate mapping of SWI extent and distribution. Hydrochemical and hydrogeophysical methods are commonly used, with geoelectrical and electromagnetic methods also prevalent in geophysical surveys. The hydraulic barrier is identified as an effective management technique for SWI. The research identifies the United States and China as leading contributors to SWI studies, emphasizing the importance of a global perspective. Reclaimed water and treated wastewater within permissible limits are proposed as potential solutions for groundwater recharge to mitigate SWI. Modelling and simulation are recommended as reliable monitoring strategies, particularly for complex systems like SWI. Integration of computational techniques, industrial IoT, and advanced monitoring systems is suggested to enhance real-time data delivery and decision-making processes. In the context of Saudi Arabia, SWI assessment and management have received limited attention, with no studies addressing SWI management found in the literature review. Future research should focus on integrated approaches, including hydrological, hydrochemical, isotopic, and hydrogeophysical techniques, to accurately identify and delineate SWI in coastal aquifers. It is essential to cover all coastal areas at risk of SWI and consider both shallow and deep aquifers. Establishing an advanced monitoring system with multi-screen wells and multi-aquifer tapping is crucial for early detection and warning of SWI. Further studies on SWI management are necessary to guide decision-makers in safeguarding and monitoring freshwater resources in coastal cities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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