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MANAGEMENT OF SEAWATER INTRUSION IN COASTAL AQUIFERS: PRESENT AND FUTURE CHALLENGES

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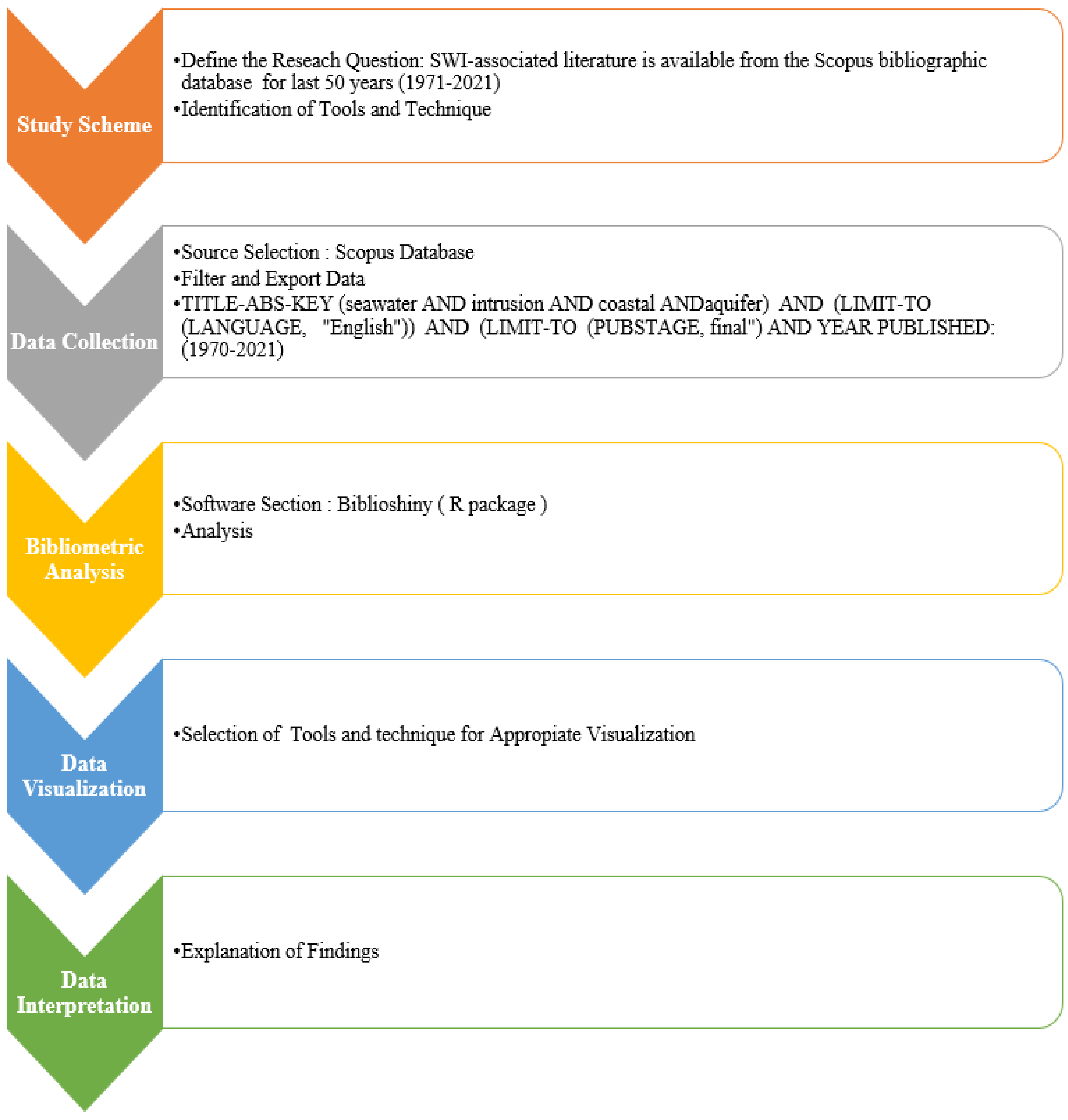
Background:

- Groundwater is considered the main source of water in many coastal areas. The increase of water demands increases the abstraction from aquifers which has resulted in lowering water tables and caused saltwater intrusion(SWI).
- Saltwater intrusion is one of the main causes of groundwater quality degradation and a major challenge in the management of groundwater resources in coastal regions.
- Understanding the current SWI situation and forming research consensus are of great significance for further studies and coastal water resources management .

Objectives :

- This study conducted a bibliometric analysis to evaluate the SWI-associated literature is available from the Scopus bibliographic database for last 50 years (1970-2020).
- Statistical and scientific mapping analysis by using Bioblioshiny excavate existing research achievements further.

Standard Bibliometric Analysis Process



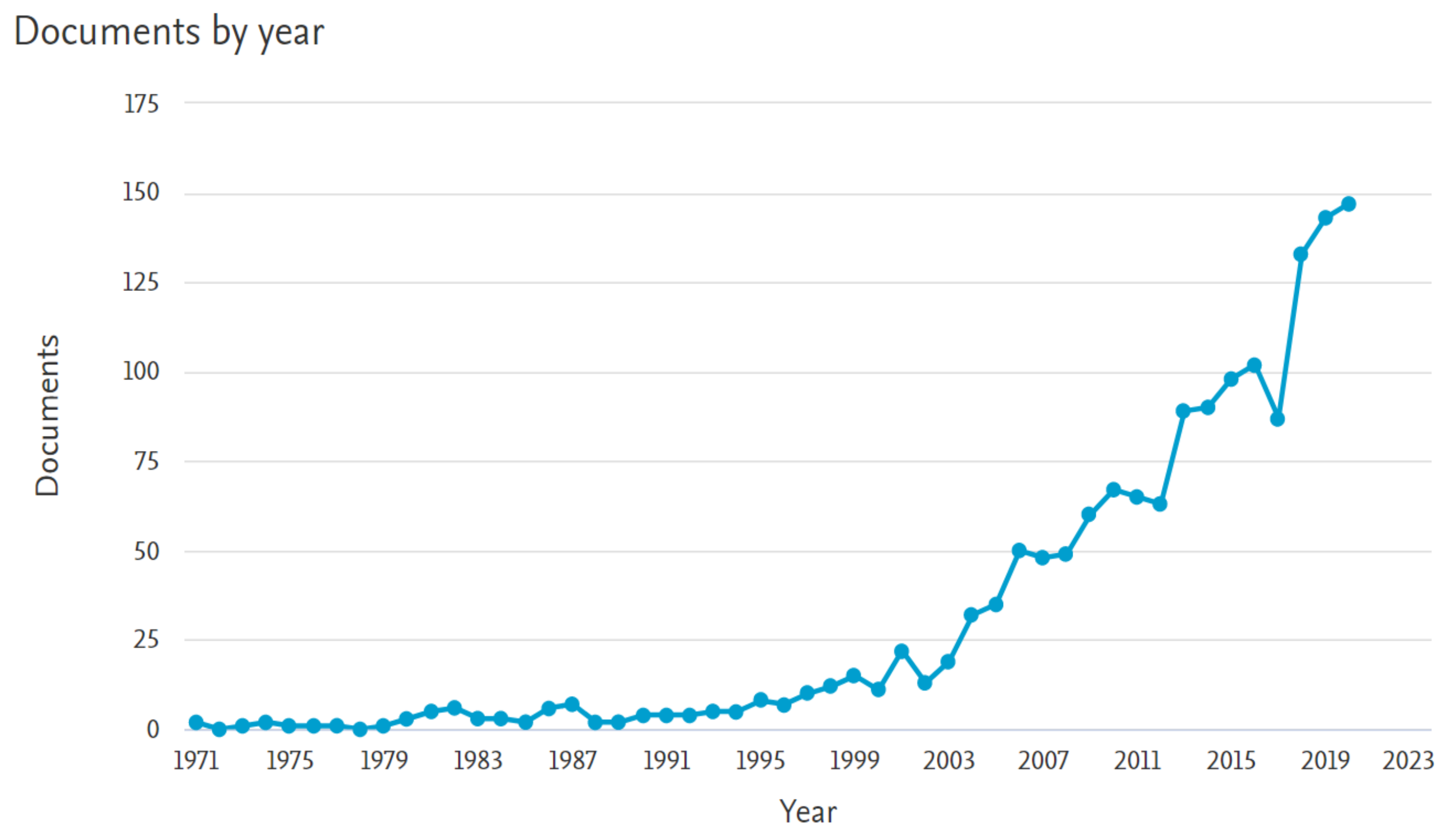
Study Scheme
- Define the Reseach Question: SWI-associated literature is available from the Scopus bibliographic database for last 50 years (1971-2021)
- Identification of Tools and Technique

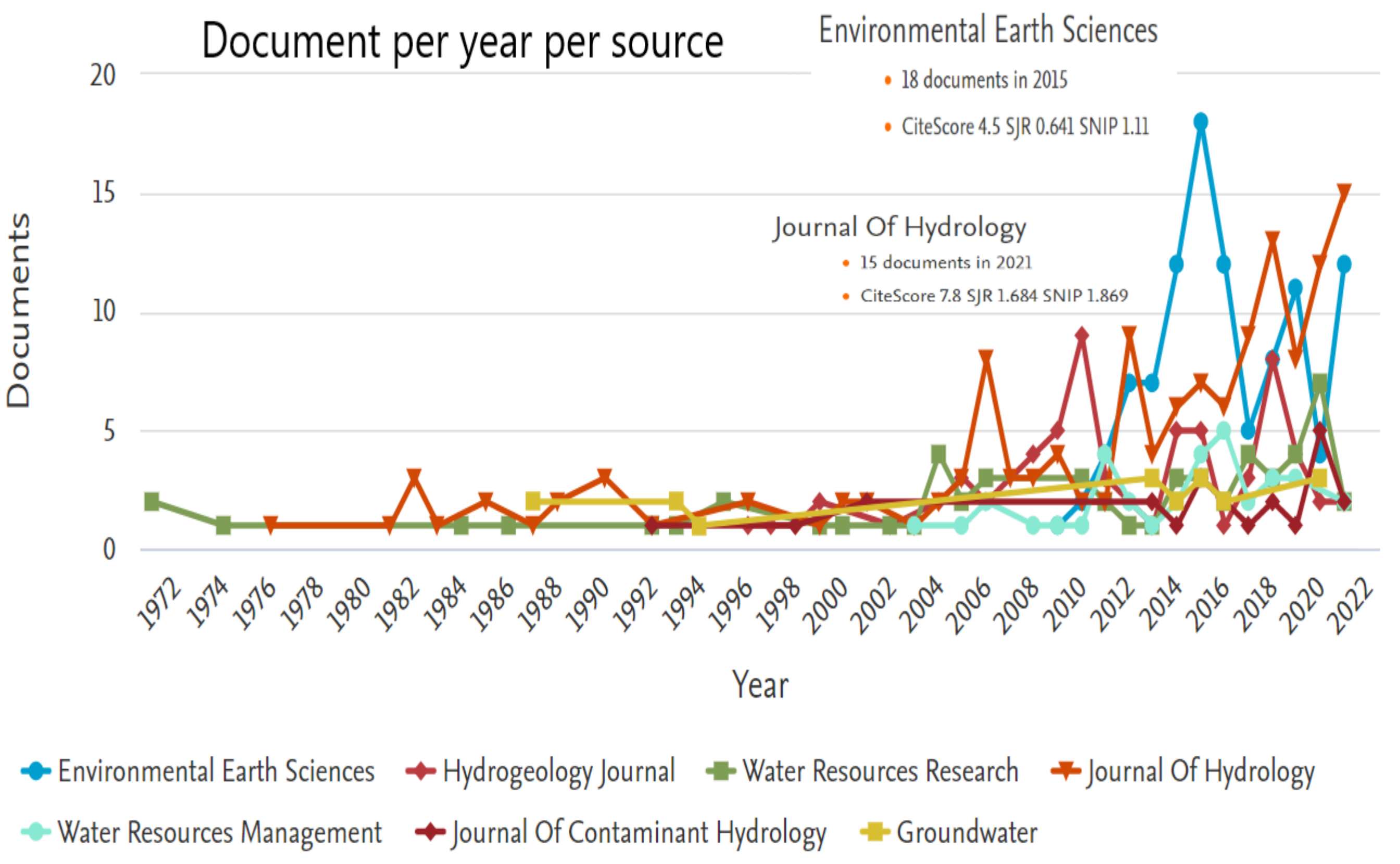
Data Collection
- Source Selection : Scopus Database
- Filter and Export Data
- TITLE-ABS-KEY (seawater AND intrusion AND coastal ANDaquifer) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, final") AND YEAR PUBLISHED: (1970-2021)

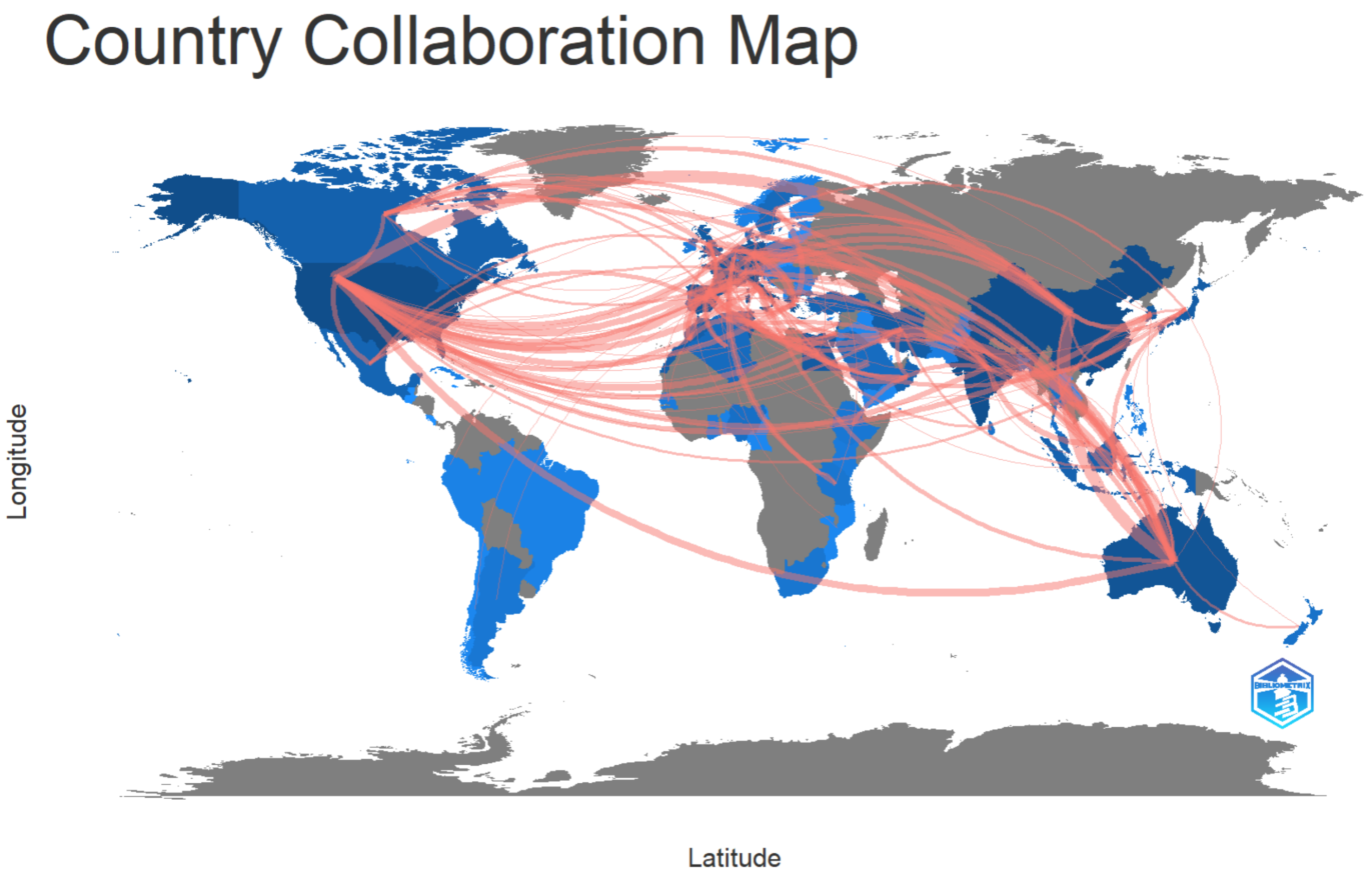
Bibliometric Analysis
- Software Section : Biblioshiny (R package)
- Analysis

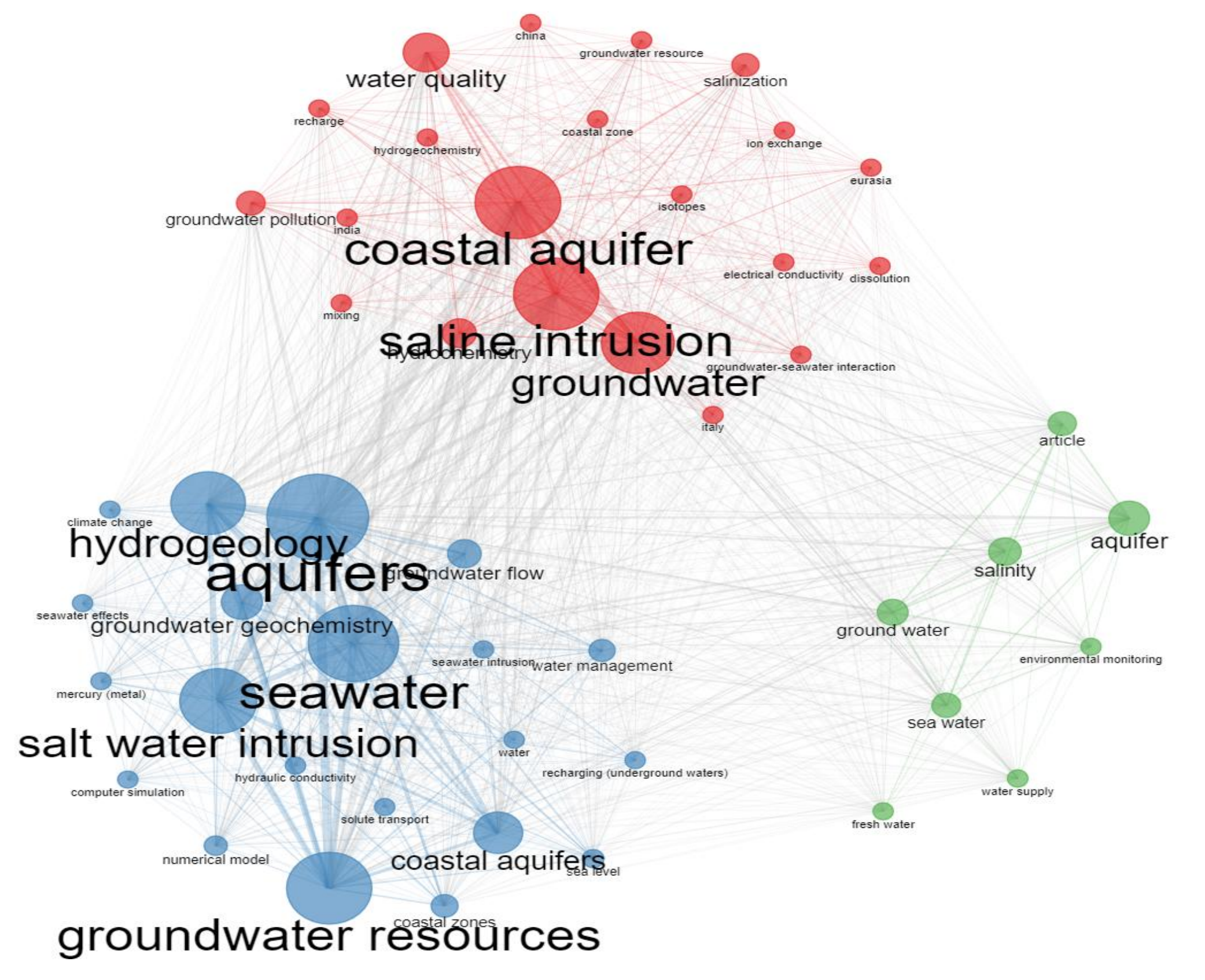
Data Visualization
- Selection of Tools and technique for Appropiate Visualization

Data Interpretation
- Explanation of Findings









Observation:

- From 1971 to 2021, RTI research productivity gradually grew after that initial publication.
- More document was published in Environmental Earth Science in that Journal of Hydrology, but Citation score was more Journal Of hydrology than others.
- Therefore, the greater the CiteScore, the more critical the journal is considered. depict the most common keywords listed by authors in SWI research publications originating in the WORLD MAP.
- The circle size and colors denote keyword occurrence levels and different coupling clusters, respectively; keywords listed four or more times were included; 33 keywords met this criterion.
- The most common keywords in seawater intrusion of coastal aquifer publications were seawater (1067 occurrences), aquifer (1027 occurrences), and coastal aquifer (939 occurrences). Terms such as saline, climate change, etc., are least expected.

Conclusion:

- Implementing SWI knowledge, such as processes, investigative methodologies, and managerial approaches is perhaps the most critical scientific problem in SWI research. Strategies are required to close the gaps between SWI knowledge and management practice.
- To illustrate the benefits of SWI research methodologies and knowledge, more studies that retrospectively and critically analyze the effectiveness of management practices, particularly initiatives deriving from SWI research findings, are needed to illustrate the benefits of SWI research methodologies and knowledge.
- Subsurface intakes were not considered a mitigating strategy for seawater intrusion into costal aquifers in the available literature and experiments.

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Management of Seawater Intrusion in Coastal Aquifers: Present and Future Challenges[156]

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Keywords Seawater Intrusion, Coastal aquifer, Groundwater, Management, Bibliometric

Abstract

Due to population growth and rapid industrialization, massive withdrawals of groundwater resources have resulted in seawater intrusion into coastal aquifers worldwide. This problem is common in arid and semi-arid regions (40% of the world's population.) The effects of seawater intrusion on the local community's health and economic and socio-cultural developments in coastal areas have prompted a wide range of research. The current study's goal is to provide a comprehensive review of the processes that control seawater intrusion into coastal aquifers over the last 50 years and the necessary mitigation measures. The SWI-associated literature is available from the Scopus bibliographic database and statistical and scientific mapping analysis by using Bioblioshiny to excavate existing research achievements further. This intends to examine the reputation and trends of seawater intrusion in coastal aquifer research from 1970 to 2021 to assist other researchers in comprehending the global scope of study and predicting the dynamic directions of seawater intrusion in coastal aquifer research. Implementing SWI knowledge, such as processes, investigative methodologies, and managerial approaches is perhaps the most critical scientific problem in SWI research. Strategies are required to close the gaps between SWI knowledge and management practice. To illustrate the benefits of SWI research methodologies and knowledge, more studies that retrospectively and critically analyze the effectiveness of management practices, particularly initiatives deriving from SWI research findings, are needed to illustrate the benefits of SWI research methodologies and knowledge. The following are the goal: a) Examine the patterns of seawater intrusion in journal publications about coastal aquifers, and b) Comprehensive review of the processes that control seawater intrusion into coastal aquifers and the new proposed methodology are then explained in detail.

MANAGEMENT OF SEAWATER INTRUSION IN COASTAL AQUIFERS: PRESENT AND FUTURE CHALLENGES

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KEYWORDS

SEAWATER INTRUSION, COASTAL AQUIFER, HYDROGEOLOGY, GROUNDWATER, SALINE, WATER MANAGEMENT

ABSTRACT

Due to population growth and rapid industrialization, massive withdrawals of groundwater resources have resulted in seawater intrusion into coastal aquifers worldwide. This problem is common in arid and semi-arid regions (40% of the world's population.) The effects of seawater intrusion on the health of the local community and economic and socio-cultural developments in coastal areas have prompted a wide range of research. The current study's goal is to provide a comprehensive review of the processes that control seawater intrusion into coastal aquifers over the last 50 years, as well as the necessary mitigation measures. Various investigation methods and the new proposed methodology are then explained in detail.

1 INTRODUCTION

For domestic, industrial, and agricultural needs, most of these coastal regions rely on groundwater as their primary source of freshwater. As the population continues to rise at an alarming rate, increased demand for freshwater supplies is met by extensive pumping of fresh groundwater, resulting in a lowering of the water table or piezometric head, which leads to saltwater intrusion (SWI) and emphasizes the importance of groundwater monitoring, management, and conservation(Bear, 1999). Around the world, more than 100 countries and regions around the world are threatened by seawater intrusions such as the Nile Delta, the Mekong Delta, East, and South Asia, the Mediterranean region, the Wadi Ham delta, and North America(H. Abd-Elhamid et al., 2016; Barlow & Reichard, 2010; Han & Currell, 2018; M. Sherif & Kacimov, 2007; Vu et al., 2018).

SWI is the subterranean migration of seawater into fresh aquifers, primarily driven by unsustainable groundwater exploitation and linked to rising sea levels and climate change (Werner et al., 2013). The significant increase in total dissolved solids (TDS) induced by enrichment solutes in seawater, such as chloride or sodium, distinguishes SWI(Seenipandi et al., 2019). The famous Ghyben-Herzberg formula was proposed over a century ago to statistically examine the interaction between brackish and fresh groundwater in coastal zones (Alexander Herzberg, 1901; Drabbe & Ghijben, 1889; Todorovic & Verruijt, 1968). It was commonly employed to locate the fresh-saline water interface, governed by the unconfined groundwater level. The limitations of this formula were then described mathematically by (Bear 1985; Hubbert, 1940). Researchers have been attempting to quantify the form of the saltwater wedge and measure the degree of groundwater salinization since then (Post, 2018). (Bear, 1999) addressed the variable density and hydrodynamic dispersion problem as a significant symbol of SWI research. Coastal water management strategy, groundwater resource protection, submarine groundwater discharge (SGD), field monitoring methods, hydrochemical and isotopic concerns, and numerical simulation have evolved into a complex SWI research system. The SWI process is becoming more widely known, particularly the interplay between surface and groundwater, and seawater induction is now thought to significantly affect groundwater salinization(Cao et al., 2020; Ferguson & Gleeson, 2012). Field study, laboratory experimentation, analytical solution, and numerical simulations are some research approaches. SWI researchers gathered massive data on a global scale and applied several innovative technologies after years of geological survey and environmental monitoring. Finding hot subjects and distinguishing potential breakthrough directions has become a worry for scholars(Javadi et al., 2015; Mabrouk et al., 2018; Post, 2005).

Many types of software have been developed in recent years, allowing for increased bibliometric use in various research areas (Garfield, 2009; Leydesdorff & Bihui, 2005). The bibliometric method has been used in the field of ecology and hydrology to investigate advances in a variety of topics, including global groundwater research (Niu et al., 2014), stable isotope of precipitation research (Wei et al., 2019), urban development, and ecological safety research, and global research in sustainable development (Qin, 2015). Scopus is the only database that includes a comprehensive, curated abstract and citation database and enriched data and linked scholarly content (Hassan et al., 2014). Find relevant and trustworthy research quickly, identify experts, and get reliable data, metrics, and analytical tools to support confident research plan decisions - all from a single database and subscription.

The bibliometric R-package software was used in this work, open-source software that provides a set of tools for undertaking quantitative research in bibliometrics. Biblioshiny created the R-package, written in the R programming language(Aria & Cuccurullo, 2017). It contains the most important algorithms for statistical and scientific mapping analysis. The web interface app (Biblioshiny) was introduced in recent versions of the bibliometrix R-package (i.e., 2.0 upwards) to assist users without coding abilities in conducting bibliometric analysis. Data can be imported in BibTex, CSV, or Plain Text format from databases via the Biblioshiny interface. Biblioshiny also allows you to filter data. Our research took advantage of the features of biblioshiny for bibliometrix to import data from Scopus in BibTex format. In the results section, the study analysis is presented. This review work intends to examine the reputation and trends of seawater intrusion in coastal aquifer research from 1970 to 2021 to assist other researchers in comprehending the global scope of research and predicting the dynamic directions of seawater intrusion in coastal aquifer research. Implementing SI knowledge, such as processes, investigative methodologies, and managerial approaches, into practice is perhaps the most critical scientific problem in SI research. Strategies are required to close the significant gaps between SI knowledge and management practice. To illustrate the benefits of SI research methodologies and knowledge, more studies that retrospectively and critically analyze the effectiveness of management practices, particularly initiatives deriving from SI research findings, are needed to illustrate the benefits of SI research methodologies and knowledge. The following are the goal:

i. Examine the patterns of seawater intrusion in journal publications about coastal aquifers.
ii. Comprehensive review of the processes that control seawater intrusion into coastal aquifers and its advantages and disadvantages.
iii. New proposed method to control SWI.

2. BIBILIOMETRIC ANALYSIS

A bibliometric analysis study differs from a review paper in that it focuses on current trends, difficulties, and future directions for a specific subject. Scopus' built-in tool (for extracting the database) and Bioblioshiny (mapping and visualization) software were used for this bibliometric investigation. Tracing publications using the SCOPUS database is a systematic approach to bibliometric study. The issue was searched in SCOPUS utilizing the search phrase "Seawater Intrusion Coastal Aquifer." Only articles or ongoing papers were included in the final results. The SCOPUS database yielded 1,683 accurate document records, according to the findings. The year of publication is limited in this study, and it ranges from the earliest, in 1970, to the most recent, in 2021. TITLE-ABS-KEY (seawater AND intrusion AND coastal AND aquifer) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final") AND YEAR PUBLISHED: (1970-2021) were the search parameters. As a result, 1,683 documents were shown. In addition, the majority of the document kinds were articles. Later these documents are exported to Bibtex file format. The findings were reviewed based on the year, source, author, affiliation, nation, study area, document types, languages, and the critical topic's search. Bibliometric indicators like total publications, top institutions, leading authors, and h-index were utilized to rank the papers. The data was analyzed using Biblioshiny, a combination of spreadsheet and bibliometric analysis tools (R Package). Biblioshiny was used to perform the author keyword analysis and bibliographic coupling. Biblioshiny was used to generate global collaboration, subject trends, three-component analysis, word clouds, and treemap analysis. The first publication on seawater intrusion in coastal aquifer research was in 1970, and it was mentioned 19 times.

From 1971 to 2021, RTI research productivity gradually grew after that initial publication. Figure 1 shows the articles and cumulative publications records from 1970 to 2021, indicating a substantial increase in overall accumulated publications. If this is the case, the annual publication will continue to rise. Figure 1 represents several journal Documents per source Journal. There is gradual flocculation occurring between the Environmental Earth Science and Journal of Hydrology from 1971 to 2021. More document was published in Environmental Earth Science in that Journal of Hydrology, but Citation score was more Journal Of hydrology than others. Therefore, the greater the CiteScore, the more critical the journal is considered.

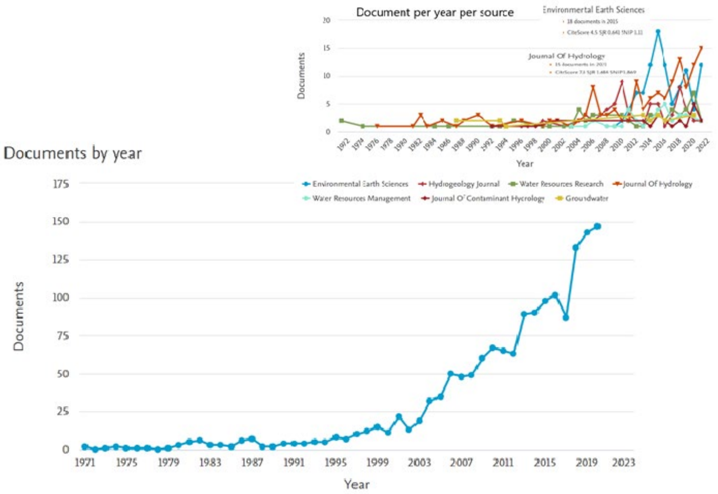
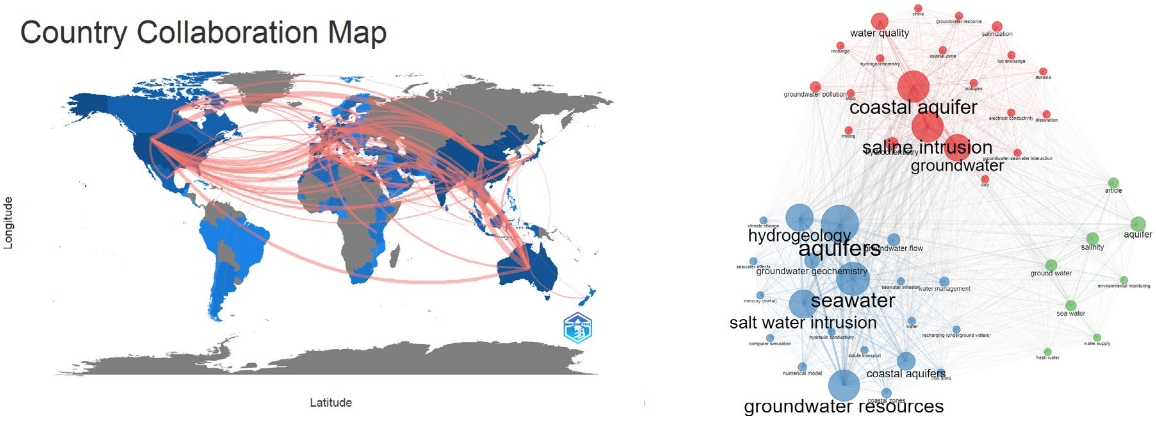


Figure 1: Number of Journal Publication from 1971-2021 and Document Number per year per source.



(a) (b)

Figure 2: Country Collaboration Map and common keywords listed in SWI research

Figure 2 (b) depict the most common keywords listed by authors in SWI research publications originating in the WORLD MAP. The circle size and colors denote keyword occurrence levels and different coupling clusters, respectively; keywords listed four or more times were included; 33 keywords met this criterion. The most common keywords in seawater intrusion of coastal aquifer publications were seawater (1067 occurrences), aquifer (1027 occurrences), and coastal aquifer (939occurrences). Terms such as saline, climate change, etc., are least expected.

3. SALTWATER AND FRESHWATER INTERACTION MECHANISM

Saltwater intrusion is one of the world's most significant environmental problems, threatening the quality and availability of freshwater in coastal aquifers, especially in arid and semi-arid regions. In natural conditions, SWI refers to replacing freshwater in coastal aquifers with seawater due to density-dependent landward migration of a salty water body SWI is defined by (M. Sherif & Singh, 2002) as a mechanism in which dense seawater displaces deep inland freshwater and moves along the bed's floor. As a result, it is regarded as the final result of density-dependent interaction. Between freshwater and saltwater, it is responsible for groundwater movement dynamic equilibrium. Although the hydraulic gradient of flow into the sea is relatively small, the slight density gradient between seawater (density of 1025 kg/m3) and freshwater (density of 1000 kg/m3) plays a significant role in the natural progression SWI. The displaced freshwater with lower density shifts to upper regions and leaves the aquifer as submarine groundwater discharges in a cyclic pattern to maintain dynamic equilibrium in the system. As a result, the flow pattern in the system along the coast is cyclic (even under steady-state conditions), with some saline water entrained within the overlying freshwater and returned to the sea, causing further seawater intrusion(Barlow, 2003; M. Sherif & Singh, 2002).

Furthermore, the spreading of the solute and the mixing phase is regulated by hydrodynamic dispersion, combining mechanical and Physico-chemical distribution (molecular diffusion). This process creates a mixing zone (or transition zone) between the two fluids, where the water density changes from freshwater to saltwater (Bear, J. & Zhou, 2007; Bear, J. J. & Cheng, 1999; Sherif, M. M. & Al-Rashed, 2001)In coastal systems, this region still occurs between freshwater and salty water. It is thought to be the main flow route for the available cyclic movement of saltwater receding to the sea (Bear, 1985). The saltwater/freshwater interface is the boundary between the bodies of these two fluids. They formed a distinct zone of salty water in the freshwater body is known as the regional saltwater wedge. As a result, the saltwater wedge is designed to be a source of pollution that degrades aquifer water quality and quantity (Figure 3). As shown in, any coastal aquifer with this issue should have three distinct zones: saltwater zone, mixing/transition zone, and freshwater zone.

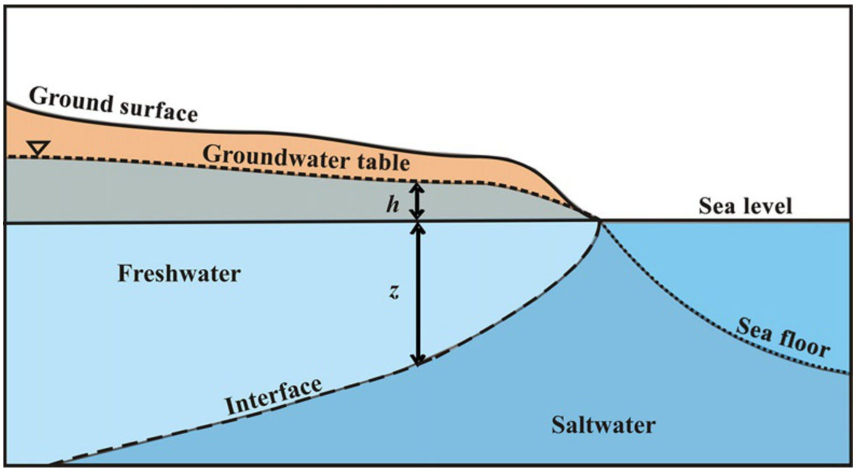


Figure 3: Saltwater and Freshwater Interaction(Vandenbohede et al., 2009)

4. FACTORS INFLUENCING SALTWATER INTRUSION

The common factor influencing saltwater intrusion is natural and anthropogenic factors. The most common factors that are worsening the Saltwater intrusion (SWI) issue by disrupting the natural hydraulic equilibrium condition in coastal aquifer systems due to natural and human activities are summarized by (Oude Essink, 2001; Patel & Shah, 2008) in Figure 7. The overall effect of these factors is to increase total aquifer salinization, which has significant implications for the quality of groundwater supplies and the natural environment. Some of these variables have short-term effects (for example, tidal), others have intermittent effects (for example, seasonal variations in natural groundwater flow), and others have long-term consequences (for example, climate change and the majority of human activities).

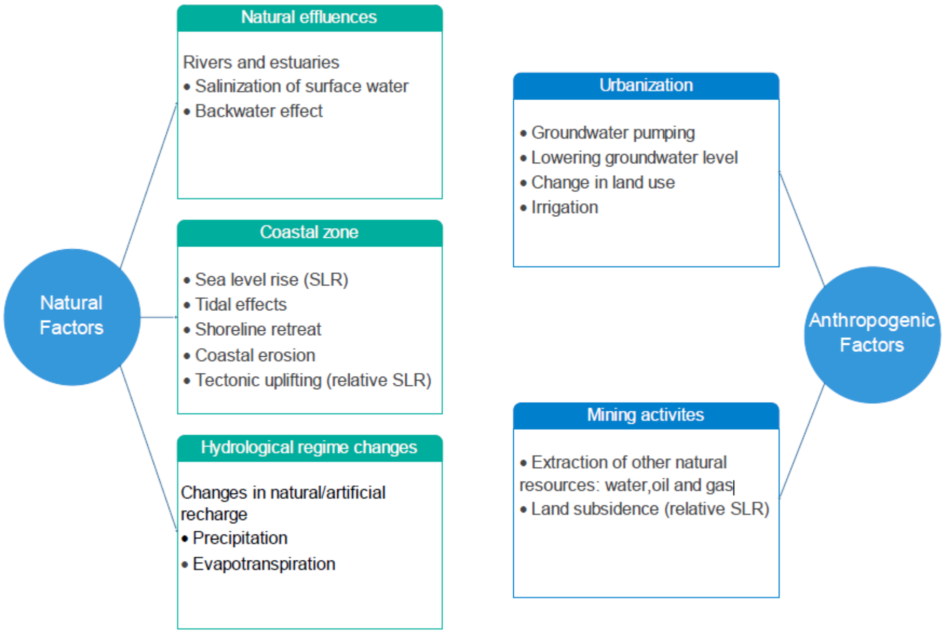


Figure 4: Natural and anthropogenic factors influencing the saltwater intrusion (Hussain, 2015)

5. METHOD USED FOR CONTROLLING THE SALTWATER INTRUSION

Groundwater is a vital resource for supporting the societies and economies of coastal regions, which are among the world's most heavily populated areas. One-third of the world's freshwater demand is met by groundwater (Bear, 1999). (Howard, 1987)addressed the degrading effects of SWI caused by excessive groundwater abstraction. The initial loss of freshwater can be offset by natural replenishment of storage at regulated groundwater withdrawal rates. However, the problem (SWI) only occurs when there is an inappropriate and unplanned use of fresh groundwater combined with a substantial decline in recharge, resulting in public health, socioeconomic, and environmental issues. As a result, remediation steps must be implemented to prevent further deterioration in water quality in coastal aquifers. However, groundwater remediation may be very expensive and time-consuming, depending on the source and degree of salinity. As a result, various arrangements and prices of external sources/sinks of water will promote sustainable water resource management in coastal areas. Determining a suitable ultimate landward extent of saline water and the calculation of the sufficient freshwater discharge needed to preserve the interface of the saltwater wedge in the seacoast location are both parts of the management of coastal aquifers.

A seaward hydraulic gradient should be maintained to regulate saline intrusion, and a portion of the freshwater should be allowed to flow into the sea. This hydraulic gradient to the seaward acts as a hydraulic barrier towards the SWI (Todd, D. K. & Mays, 2005; Tsanis & Song, 2001; van Dam, 1999). Different methodologies to regulate SWI have been attempted by (Bruington, 1972; Pool & Carrera, 2010; Richter, 1953; Sharma & Sanghi, 2013; M. M. Sherif & Hamza, 2001; Todd, 2015; van Dam, 1999). Seawater intrusion can be controlled by several methods using biological, chemical, and physical techniques. It is an expensive process and can take a long time, depending on the source of intrusion and level of salinization. Different measures have been presented to control SWI in coastal aquifers. (Todd, 1980) presented various methods of preventing saltwater from contaminating groundwater sources, and later it was revised by (Todd, D. K. & Mays, 2005) to control seawater intrusion.

The method used to control saltwater intrusion in coastal aquifers:

- Changing the pumping pattern (reduction of pumping rates and relocation of pumping wells)
- Use of physical surface/subsurface barriers,
- Natural/ artificial recharge (pressure or positive barriers),
- Pumping of saline water along with the seacoast (abstraction or negative barriers) a
- Combination techniques (mixed barriers).

With high rates of saline water pumping, some of these methods require the disposal of abstracted salts to reduce environmental problems (Bruington, 1972).

Each method has advantages and weaknesses when compared to the others. One method might be suitable for one specific location, while another location might not. With the several methods mentioned above to control the seawater intrusion, the economy plays a significant role. Reducing pumping and rearranging pumping wells are cost-effective but not practicable. The abstraction of seawater and a subsurface barrier are expensive methods. Hence they are generally not considered. Increasing groundwater recharge by percolation ponds is economically feasible and quickly adopted(Purnama & Marfai, 2012).

5.1 REDUCTION OF PUMPING RATES

Reduced abstraction from pumping wells could be the most straightforward and cost-effective way to maintain aquifer groundwater balance and monitor SWI. However, the options for reducing abstraction may be limited in certain areas due to water demand requirements. A backup source of water must be given to compensate for the forced reduction in the pumping schedule (Bruington, 1972)**.** Increasing public understanding of the importance of minimizing water losses in water use and supply network systems in various residential, agricultural, and industrial sectors, as well as encouraging them to use renewable or recycling services (e.g., recycled treated wastewater and desalinated water), will significantly contribute to the scenario's success. However, the cost of providing good quality water from these resources and making it accessible in vulnerable areas is another problem that limits this approach to a temporary solution for aquifer protection. This is especially true in areas experiencing rapid population growth and, as a result, rising demand patterns that are unable to achieve the desired results (Abd-Elhamid, H. & Javadi, 2008; Vandenbohede et al., 2009) suggested that the actual conditions of the SWI problem be regulated by integrating this temporary management strategy with other control steps. (Reichard & Johnson, 2005) demonstrated that using this approach could help reduce the amount (and cost) of in-lieu delivery of surface water for general consumption by residents and feed the aquifer against SWI. (Bear, 1999) demonstrated that redistribution of pumping plans, such as minimizing or turning off wellfields that are less vulnerable to intrusion, can help reduce SWI in the Nile delta aquifer.

5.2 RELOCATION OF PUMPING WELLS

Pumping wells are usually moved further inland away from the coast in this method to provide a stronger seaward hydraulic gradient by holding groundwater levels above sea level and reducing the excessive outflow of fresh groundwater (Todd, D. K. & Mays, 2005; van Dam, 1999)**.** This approach may be restricted in some cases due to land scarcity or conflicts with other public-sector or private-sector strategic initiatives, both of which would put an end to the process. The size (length) of the aquifer to accommodate new positions of wells far from the intruded saltwater wedge is another barrier to managing SWI in some cases and under high levels of pollution. Furthermore, the expense of transporting and in-lieu delivering water from new pumping wells (far enough from the coast) to pre-developed areas near the seashore (susceptible zones) may be a constraint in this strategy. As a result, this technique is also a temporary solution and does not prevent saline water intrusion into the aquifer (Abd-Elhamid, 2010)**.** (Sherif, M. M. & Al-Rashed, 2001)suggested planning pumping in the center of the Nile delta aquifer (simulated in 2D aerial using SUTRA) to ensure potential sustainability. (Maimone, M. & Fitzgerald, 2001) emphasized the management strategy for a coastal aquifer by installing a new well system away from the coastal region as a more reliable technique than another solution that assumed a more profound drilling plan for the old-existing well fields along the coast. The system's old wells extracted brackish water, which was then used for domestic purposes after desalination

5.3. USE OF PHYSICAL SURFACE / SUBSURFACE BARRIERS,

Concrete, grout, bentonite, slurry walls, and sheet piles are widely used in physical subsurface barriers in front of seawater along the shore (M. S. Hussain et al., 2019).

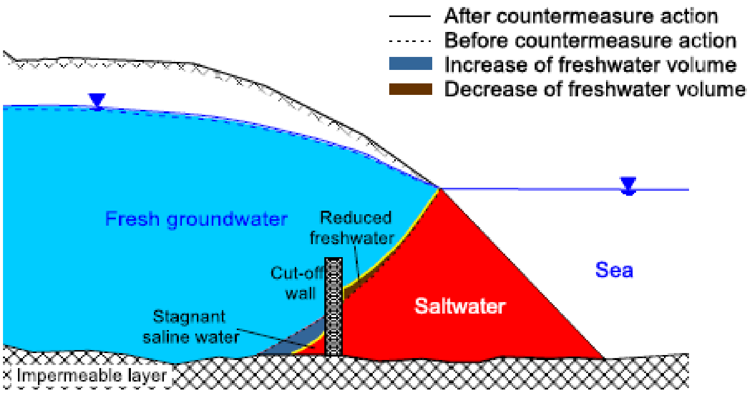


Figure 5 : Physical surface/subsurface barriers(Hussain et al., 2019)

The physical barrier demonstrated its great defensive ability when placed at greater depths and closer to the shore in the absence of abstraction. Under this pumping action, and in aquifer systems where the inland boundary is defined with a lower inflow velocity than the intruded velocity of saline water and high anisotropy, physical barrier control design is highly beneficial in protecting the aquifer. In general, installing a physical subsurface barrier is costly in deep aquifers (Oude Essink, 2001). Another problem has been the stagnant state of the intruding saltwater that has remained behind the barrier since its construction (Figure 5). However, under heavy pumping and a low hydraulic gradient of the flow system, the reverse diffusion of seawater through the barrier and underneath its foundation, and thus mixing with this plume of stagnant saltwater, may cause a process deficiency. (James et al., 2001) introduced a biological barrier against SWI in a completely different and novel technique. The technique relied on the injection of bacteria and nutrient solutions to lower the hydraulic conductivity of subsurface layers and thus the risk of SWI .

5.4 ARTIFICIAL RECHARGE

SWI may occur in any geological state of a confined or unconfined aquifer with a single or multiple layers (Figure). The aquifer is artificially recharged by high-quality water (e.g., surface water, rainwater, pumped groundwater, treated wastewater, or desalinated water) within the positive or pressure barriers to preserve the system's seaward gradient by raising the inland piezometric heads (M. S. Hussain et al., 2019). In general, artificial water recharge aims to reduce flood flows, store water in aquifers, increase groundwater levels, relieve over-pumping, and eventually improve water quality and suppress saltwater (Lahr, 1982). The approach is one of the most recommended and evaluated strategies in the literature. However, in the case of intensive pumping, the use of artificial recharge can be unsuccessful (K. A. Narayan et al., 2007).

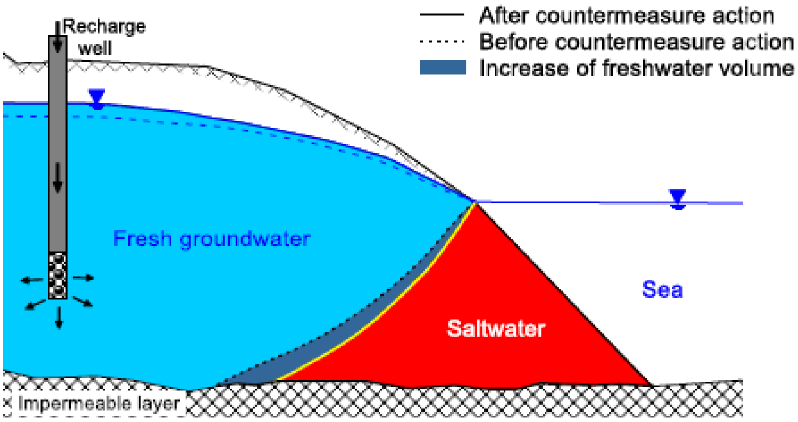


Figure 6: Artifical Rechage (Hussain et al., 2019)

(Luyun et al., 2011) investigated the positive potential of the deep recharge barrier in SWI repulsion using experimental, computational, and numerical modeling. Surface reservoirs, dams, canals, and other spreading recharge basins can also be used as recharge systems to feed unconfined aquifer systems by collected water infiltration. One of the key constraints to the recharge barriers is the expense of supplying high-quality water (e.g., desalinated water) and its delivery for recharging purposes. Furthermore, the lack of such water locally, especially during dry years or in water-stressed areas, maybe a significant constraint (H. F. Abd-Elhamid & Javadi, 2011). As a result, in recent years, a greater focus has been put on sustainable water sources, such as treated wastewater, as a means of recharge against seawater intrusion (e.g (Hussain, 2015; Javadi et al., 2015; Kourakos & Mantoglou, 2011; Koussis et al., 2010; Reichard & Johnson, 2005; Shammas & Thunvik, 2009). The use of recycled water in common utility sectors and artificial storage in subsurface layers will help to meet a portion of the water demand, resist flooding and drought, and protect the system from SWI.

5.5 COMBINED BARRIER

Combining both above techniques will help improve control of saltwater intrusion by combining the advantages of the individual strategies. For example, a combination of pumping rate reduction and recharge barrier (Johnson et al., 2001) and pumping rate control with artificial recharge The mixture of positive and negative obstacles is referred to as a mixed or hybrid barrier (Figure 8). The technique is concerned with the specification of both extraction and recharge. This mixed barrier (the primary focus of this section) employs the principles of a) repeated cycles of recharge and abstraction via the same well system and b) injection of freshwater while abstracting saline water. Several studies have indicated that variants of the above scheme are the most successful approach among other forms of barriers (Abd-Elhamid, 2010; Kourakos & Mantoglou, 2013; Koussis et al., 2010; Rastogi et al., 2004; S. Troisi, 1994; Tsanis & Song, 2001)

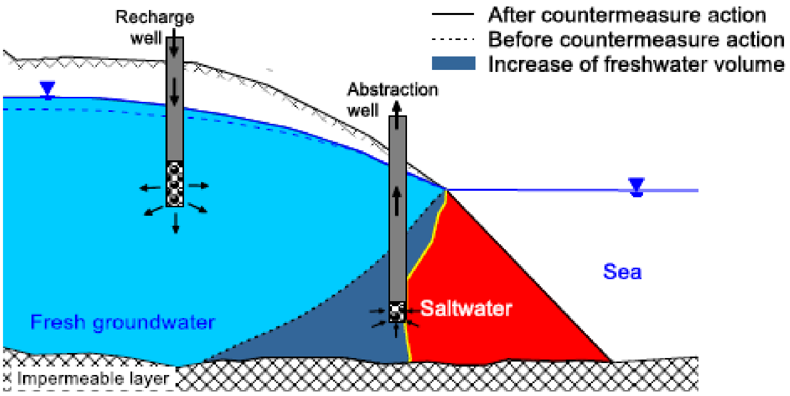


Figure 7 : Combined Barrier (Hussain et al., 2019)

5.5.1 AQUIFER STORAGE AND RECOVERY (ASR)

Aquifer Storage and Recovery (ASR) is a technique introduced by (Cederstrom, 1947) and has been widely used in developed countries for the management of water resources as an alternative to surface storage of water such as dams and reservoirs (Hussain et al., 2019). The methodology involves persistent storage of excess water by deep injection through recharge wells into a deep aquifer or other water-bearing formations when water is available or during the year's wet and low-demand season (Figure 8).

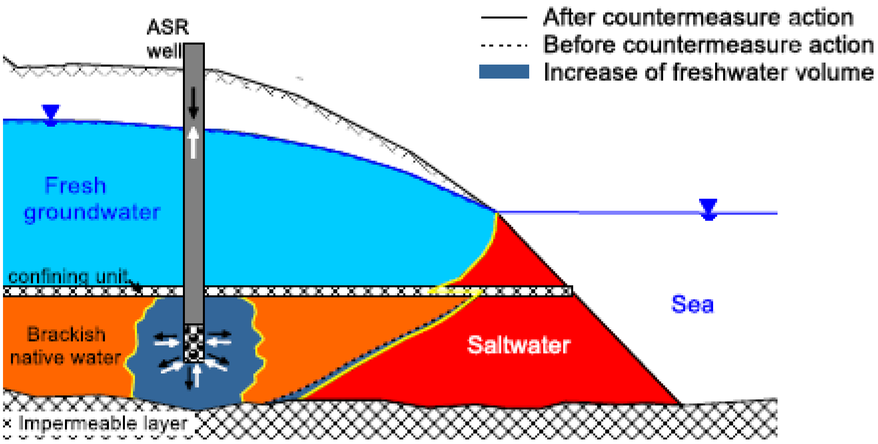


Figure 8 : Aquifer Storage and Recovery (Hussain et al., 2019)

The stored water is then recovered when needed using the same wells to meet the community's water demand and during the next dry or high-demand season of the year (Pyne, 1995). Depending on the quality and level of contamination of the native groundwater in the aquifer and the recharge water quality, the recovered water may be required to pass a short treatment process. The ASR process is repeated continuously over the years depending on the levels of water scarcity. The recovery efficiency in the ASR process is defined as the total volume of recovered water as a percentage of the volume stored in each operating cycle while satisfying a target water quality criterion in the abstracted water (Pyne, 1995). Like any other deep management strategy, ASR has some economic cost and quality limitations, and its implementation needs further attention. For instance, the high rates of mixing of injected water with a poor-quality native groundwater tend to reduce the total recoverable volume of freshwater (recovery efficiency). In addition to this water-water interaction, the quality of the injected water can also be threatened by water-rock hydrochemical interaction(Hussain, 2015).

5.5.2 ABSTRACTION, DESALINATION AND RECHARGE (ADR)

An innovative and cost-effective methodology called the Abstraction, Desalination, and Recharge (ADR) is used to control saltwater intrusion in coastal aquifers (H. F. Abd-Elhamid & Javadi, 2011). This methodology aims to overcome all or at least most of the limitations of the previous models figure 9.

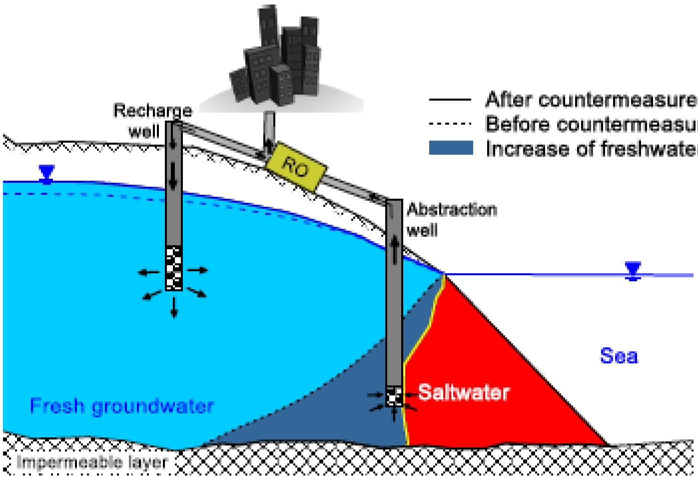


Figure 9 : Abstraction, Desalination, and Recharge (ADR) Methodology(Hussain et al., 2019)

Abstraction, Desalination, and Recharge (ADR) consists of three components:

- Abstraction (A) of brackish water from the saline zone using abstraction wells.
- Desalination (D) of abstracted brackish water using reverse osmosis process, and
- Recharge(R) of the treated water into the aquifers using recharge wells.

They demonstrated that this approach is both efficient and cost-effective in controlling SWI. This methodology's significant advantages in controlling SWI have been lower energy consumption, lower cost, and lower environmental impact. Desalination of the harvested saline water resulted in an improvement in overall usable freshwater due to the technique. It will be impossible to use desalinated water to restore the aquifer in arid or semi-arid regions where the combined amount of desalinated water and abstracted freshwater does not meet demand. On the other hand, desalinated water is a relatively large water source generated by an energy-intensive process. The ADR methodology is not effective when the mixing zone/ interface is close to the sea. Desalination may involve water with very high salinity, which could increase desalination costs. In this case, the abstraction of saline water and disposal to the sea could be more cost-effective. Also, if a sufficient freshwater source is available in the area, freshwater recharge could be more efficient. Low-cost effluents reclaimed from urban wastewater treatment plants can recharge the aquifer to solve this issue.

5.5.3 ABSTRACTION, DESALINATION, AND RECHARGE BY TREATED WASTEWATER (ADRTWW))

This methodology uses the more cost-effective water sources such as chemically treated wastewater (TWW), collected rainwater, and the transfer of good-quality water from nearby rivers, canals, reservoirs, and ponds. In developed urban areas, treated wastewater (TWW) will provide a reliable, long-term water source. The availability of other outlets, on the other hand, is determined by the coastal site's pre-existing hydrological features and hydro-environmental formations. As a result, TWW is the main target of the proposed process, ADRTWW (abstraction, desalination, and recharge by TWW), which is shown schematically in Figure 10.

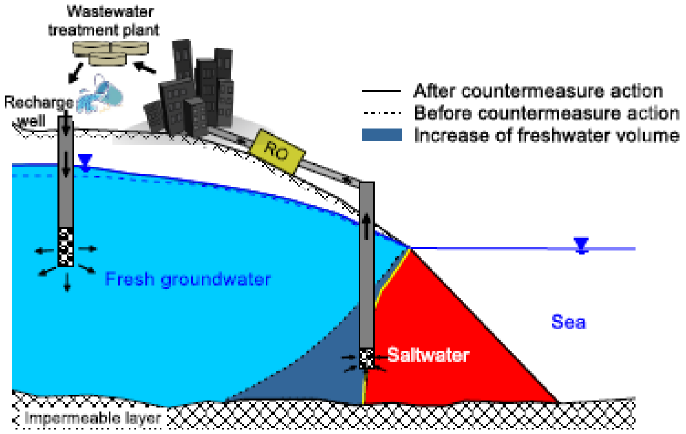


Figure 10 : Abstraction, Desalination, and Recharge with treated wastewater (ADRTWW) Methodology (Hussain et al., 2019)

The ADRTWW has a greater potential for monitoring SWI than ADR and traditional barriers because of its low economic and environmental costs (isolated or combined).

Three stages comprise the ADRTWW methodology:

- Using deep negative barriers (abstraction wells) to remove brackish water from the saline wedge;
- Desalination of the collected brackish water using a small-scale reverse osmosis (RO) plant and use of the desalinated water as a replacement for the urban water supply system; and
- Recharging the aquifer using an external source of TWW (Hussain, 2015).

The main differences between the ADRTWW and ADR methodologies:

i. In ADR, the excess desalinated water is used to recharge the aquifer, while in ADRTWW, the entire desalinated water is used for public use. In ADRTWW, high-quality recycled water is used for recharge instead of desalinated water, which has a lower economic cost.
ii. In the ADR method, the aquifer is recharged by deep injection wells. In the ADRTWW approach, unconfined aquifers may also be recharged by surface infiltration basins (with lower energy consumption).

6. DISCUSSIONS

Seawater intrusion is a natural process that develops over time because of overexploitation of coastal aquifers and direct hydraulic contact between freshwater and saltwater bodies of water. Coastal groundwater systems that have not been altered are less susceptible to this occurrence. Pumping techniques accelerate the process of Seawater Intrusion. Seawater intrusion into coastal aquifers can be controlled in a variety of ways including pumping control, artificial recharge, re-location of pumping and well fields, management of landuse, use of scavenger wells. The critical component in reducing seawater intrusion is maintaining an appropriate balance of abstraction and recharge in the catchment area and its surroundings. In general, a seaward hydraulic gradient should be maintained, while allowing a portion of natural freshwater recharge to flow into the sea. The required groundwater flux to the sea can be maintained by properly managing coastal aquifers and limiting the seawater's ultimate landward reach. The optimum discharge of freshwater to the sea can be determined in order to maintain the interface (dispersion zone) in that position. Numerous studies examined the application of pumping control methods (Ahlfeld & Heidari, 1994; Gorelick, 1983; M. Sherif & Kacimov, 2007). While the alternatives outlined above may be practical for preventing seawater intrusion, they may not be economically or environmentally viable due to natural environmental circumstances. Numerous approaches examined in earlier research for preventing and managing seawater intrusion in the study area were excluded from consideration, including the proposed technique. Pumping brackish water is a proposed technique for restoring the balance between freshwater and saline water in coastal aquifers in order to reduce the problem of seawater intrusion. Brackish water can be pumped from the dispersion zone at a specified discharge rate for a specified period of time and used for desalination or to irrigate crops with a higher salt tolerance. This type of abstraction is expected to prevent saline water intrusion, which can result in the dispersion zone being pushed closer to the coast. This process will be repeated until a state of dynamic equilibrium with regard to the salinity distribution is achieved. Pumping brackish groundwater from coastal aquifers would decrease seawater migration deep into the aquifer and contribute to improving groundwater quality (M. M. Sherif & Hamza, 2001). (Rastogi et al., 2004) reported that by combining freshwater injection with saline water extraction, the volume of seawater can be reduced while the volume of freshwater increased. The authors constructed a series of three-dimensional numerical simulations utilizing multidimensional hydrodynamic dispersion models. (Park et al., 2012). They explored a range of seawater extraction systems for mitigating seawater intrusion caused by groundwater pumping in their study. This approach of pumping brackish water to prevent seawater intrusion is not well known at the moment due to a knowledge gap about the needed discharge rates at optimal pumping locations and time duration analyses (M. M. Sherif & Hamza, 2001). To our knowledge, few studies have been undertaken to determine the efficacy of pumping brackish water to minimize seawater intrusion. The studies undertaken thus far have emphasized its potential as a means of mitigating seawater intrusion but have not conducted a complete examination of its effectiveness in light of many criteria such as pumping site, abstraction rates and intensity, length required, and cost analysis. The optimal pumping position required to reduce or shift the saline water toward the shore in order to eventually maintain or push the dispersion zone toward the coast has not been specified in any of these investigations. According to (M. M. Sherif & Hamza, 2001), brackish groundwater pumping can be used to regulate the interface between fresh and subsurface saline water bodies. A well-designed brackish water abstraction system located some distance from the shore would provide a stagnant interface. Thus, as long as the balance between recharge and discharge is maintained, more freshwater can be pumped.(van Dam, 1999) discussed this type of brackish/fresh pumping combination in coastal aquifers. He also commented on the usage of scavenger wells as a mechanism for local and regional scale control of the interface's position and movement. (Sowe et al., 2019) would use pumping brackish water techniques to enhance groundwater quality and may theoretically be used pumping brackish water to neighbouring desalination plants.

7. CONCLUSION AND RECOMMENDATION

This research provided a thorough review of the most common approaches for controlling and mitigating SWI in coastal aquifers. The approaches given include some conventional practice that can be used as temporary solutions before the main control scheme is implemented. Another way of control is to install surface and subsurface physical barriers in front of the intruding seawater body. Hydraulic barriers, on the other hand, have grown in popularity as a result of the high costs of equipment, materials, and large-scale installation of physical barriers. Different combinations of these control strategies can be implemented reduce the risk of seawater intrusion and its impact on the quality of groundwater in the coastal aquifer. The implementation seawater intrusion knowledge, such as processes, investigative methodologies, and managerial approaches, into practice is perhaps the most critical scientific problem in seawater intrusion research. To close the significant gaps between seawater intrusion knowledge and management practice, strategies are required. To illustrate the benefits of seawater intrusion research methodologies and knowledge, more studies that retrospectively and critically analyze the effectiveness of management practices, in particular initiatives deriving from SWI research findings, are needed

An environmental impact assessment should be conducted during the planning stage to highlight the environmental impacts of various control measures. The benefits and drawbacks of each methodology are discussed in this study. Controlling SWI in a cost-effective and efficient manner should be a priority for every groundwater exploration project in coastal areas. Furthermore, limitations in terms of economic cost and water demands of increasing population in coastal areas should be considered. While the alternatives outlined above may be practical for preventing seawater intrusion, they may not be economically or environmentally viable due to natural environmental circumstances. Numerous approaches examined in earlier research for preventing and managing seawater intrusion in the study area were excluded from consideration, including the proposed technique. Pumping brackish water is a proposed technique for restoring the balance between freshwater and saline water in coastal aquifers in order to reduce the problem of seawater intrusion research on the most appropriate desalination technology for the location which could improve the water quality and reduce both the economic cost and environmental impact especially on marine environment. Subsurface intakes were not considered a mitigating strategy for seawater intrusion into costal aquifers in the available literature and experiments.

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