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# Past, present, and future of global seawater intrusion research: A bibliometric analysis

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ABSTRACT

Seawater intrusion (SWI) is becoming one of the major environmental issues in more and more coastal areas around the world. Understanding the current SWI situation and forming research consensus are of great significance for further studies and coastal water resources management. In this study, we analyzed the SWI-associated literature available from the Science of Citation Index Expanded (SCIE) bibliographic database by using CiteSpace to further excavate existing research achievement. We explored a new method for identifying global geographic distributions of 501 coastal cities where SWI has been reported. It can be found that SWI is more likely to occur in well-recharged major basins (recharge rate 100–300 mm/a) or local shallow aquifers with high population density. According to current reports, about 32% of the coastal metropolitan cities (population > 1 million within 150 km from coastline) have been threatened. There was a 20-fold increase rate in the number of papers related to SWI compared to that in general science and technology. The United States of America, China, Australia were the top 3 contributors in SWI scope, contributed 46.4% of the total number of articles. More than 600 researches were supported by Chinese funds, which made China become the second contributor. But the number of citations per Chinese article was the lowest among the top 10 contributors. By co-citation analysis, we identified top 5% articles, and elaborated the background knowledge by taking Top 10 co-cited articles as example. A series of keywords with high co-occurrence were identified. Their meanings and relations were stated and graphically illustrated. As a keyword, SWI frequently appears in the following five research directions: analysis of the location or morphology of fresh and salt water interface, the prediction of groundwater quality, the geothermal circulation and tectonic activities, the coastal mangrove wetlands protection, and the management of water resources in coastal zones. We critically evaluated the bibliometric results and reviewed future opportunities and challenges for this field. With the development of new technology and the accumulation, the improvement of coastal environment will certainly benefit from the study of SWI.

## 1. Introduction

Coastal zone is a transitional zone between ocean and land, which plays a unique ecological role on linking marine and terrestrial hydrological ecosystems (Ferguson and Gleeson, 2012). About 40% of the world's population lives within 100 km from the coastline (UN, 2017). With the intensification of climate change and human activities, the water resource security has been an acute problem in coastal zones (Rahman et al., 2017). Seawater intrusion or saltwater intrusion (SWI) has become one of the main threats to the safety of freshwater supply in coastal zones (White et al., 2007). SWI currently threatens more than 100 countries and regions around the world, including the Nile Delta, the Mekong Delta, East and South Asia, the Mediterranean area, and North America (Barlow and Reichard, 2010; Abd-Elhamid et al., 2016; Han and Currell, 2018; Vu et al., 2018; Palacios et al., 2020).

SWI refers to the subsurface migration of seawater into fresh aquifers, which mainly caused by excessive groundwater exploitation and also involved in rising sea levels and changing climates (Werner et al., 2013). SWI can be distinguished by the significant high total dissolved solids (TDS), which caused by enrichment solutes in seawater, such as

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chloride or sodium (Seenipandi et al., 2019). As early as a century ago, classical Ghyben-Herzberg formula had been proposed to quantitatively study the relationship between brackish and fresh groundwater in coastal zones (Drabbe and Ghyben, 1889; Herzberg, 1901; Verruijt, 1968). It was widely used to determine the location of fresh-saline water interface controlled by the unconfined groundwater level. Then, Hubbert (1940) and Bear (1979) put forward a strict mathematical description for the limitations of this formula (Post et al., 2018). From then on, researchers have been trying to characterize the saltwater wedge shape and measure the degree of groundwater salinization. As a significant symbol of SWI researches, Bear et al. (1999) addressed the variable density and hydrodynamic dispersion problem. Nowadays, a complex SWI research system has formed and extended to many specific branches, such as coastal water management strategy, groundwater resource protection, submarine groundwater discharge (SGD), field monitoring technologies, hydrochemical and isotopic issues, and numerical simulation. The SWI process has also been increasingly recognized, especially the surface- and ground-water interaction and seawater induction are now considered to have significant effects on groundwater salinization (Ferguson and Gleeson, 2012; Cao et al., 2020). The research methods include but are not limited to field investigation, laboratory experiments, analytical solution, and numerical simulations. After years of geological survey and environmental monitoring, SWI researches accumulated massive information on a global scale and applied numerous new technology. A concern for researchers has come up that is to find hot topics and to distinguish potential breakthrough directions (Post, 2005; Mabrouk et al., 2013; Hussain et al., 2019).

Bibliometric is one of statistical methods for analyzing the impact of research outputs from literature. In recent years, many forms of software have been developed, which bring more and more bibliometric application in different research scopes (Leydesdorff and Bihui, 2005; Garfield, 2009). In the field of ecology and hydrology, bibliometric method has been used to investigate advance in various topics, such as global groundwater research (Niu et al., 2014), stable isotope of precipitation research (Wei et al., 2019), urban development and ecological safety research (Qing, 2015), and global research in sustainable development (Hassan et al., 2014). The analysis of research status and the prediction of research hotspots can play a guiding role on further research. Compared with the traditional methods of literature review, bibliometrics can allow scholars to quickly understand the target research field and identify the basic knowledge in the field. Knowledge of the discipline's history, which might have to take years of exploration in the past, is now relatively concise.

As a common tool in literature metrology, CiteSpace is a literature statistic and visualization software developed by Dr. Chaomei Chen from Drexel University based on Java platform (Chen, 2006). CiteSpace can be used to map knowledge of specific science and technology fields according to the citation information of the scientific literature, intuitively presenting the information panorama in the scientific field and identifying the key article, potential research hotspots and frontier directions (Chen, 2006). The co-citation analysis by the CiteSpace can generate and visualize the co-citation network from the set equal time interval slices, quantitatively and visually judge the key work and breakthrough progress in the research field through the pivotal points, turning points and other characteristics of the co-citation network (Chen, 2004). Highly co-cited papers can be regarded as a weathervane of academic development in a research field. Interdisciplinary researchers can conveniently establish coherence of ideas and constructs with other participants in a target discipline by strategically selecting high co-citation information (Trujillo and Long, 2018). Co-citation analysis transforms the cognitive process, which originally requires a lot of knowledge accumulation and rich field experience into the recognition and search of the structure, interaction, intersection, and evolution of the visual co-citation network, so as to accelerate the researchers' cognition of the field and promote the development of the field (Chen et al., 2015).

A large number of studies have verified the reliability of the convincing results of CiteSpace (Chen, 2006; Chen et al., 2010). Meanwhile, CiteSpace-based literature measurement is also limited by the ability of searching and statistics. The results obtained by semantic analysis are sometimes fragmented and need to be identified with professional knowledge. At present, there have been many outstanding reviews on the situation, identification, mechanism, and management of SWI (Mabrouk et al., 2013; Werner et al., 2013; Shi and Jiao, 2014; Ketabchi et al., 2016; Parizi et al., 2019). However, the vast amount of information still has the potential to be quantitatively exploited further.

This study aims to introduce the cognitive background and the opportunity of global SWI researches based on the bibliometric analyses. The objectives of this study are to (i) introduce a method to compile and map the distribution of reported SWI cities and analyze its relationship with aquifer recharge condition and local population, (ii) identify the development characteristic of SWI research and evaluate national research outputs, (iii) summarize the background knowledge, research trend and hot issues, and (iv) analyze research opportunities and challenges according to the keyword clustering.

## 2. Method and data sources

Science of Citation Index Expanded (SCIE) bibliographic database was used as a retrieval source. Although SCIE database is only a part of human innovation, it is highly reliable because all published articles have undergone rigorous peer review and almost all the bibliometric analysis will consider this database. Hence, the SCIE database has been a metric of scientific accomplishment in most fields of human creativity (Kostoff et al., 2000; Li et al., 2009). To ensure the retrieved data were as comprehensive and focus as possible, the terms "seawater intrusion" and "saltwater intrusion" were used. Any literature that contained these words in title, keyword lists, or abstracts was recorded. The retrieval period was 1970–2019. Recorded literature was exported with title, author, abstract, key words and references information to organize the local database. The literature data were last updated on January 2, 2020. The data retrieval method of annual total subjects' publication volume was the same, but the keyword retrieval can be changed to search by years of publication.

The co-occurrence analysis, including co-word (co-occurrence of keywords) and co-citation (co-occurrence of references and authors), was implemented by the CiteSpace 5.5 R2. The time slice was set as 3 years and data selection criteria was top 50%, which means only the top 50% of most cited or occurred items from each slice were selected for analysis.

The locations of existing study areas were obtained by matching the city names globally with the title or abstract database formed by 4,252 article. This process was conducted by JupyterLab based on Python. All world cities' names appearing in the title or abstract database were recorded. Then cities more than 150 km from the shoreline were excluded by using ArcGIS 10.2. Due to the complex composition of cities' names, it is still necessary to do manual screening for the remaining cities after the above mentioned processing (Fig. S1).

## 3. Results and discussion

### 3.1. Research outputs trend, related disciplines and study area identification

According to the citation analysis report from 1970 to 2019, more than 59,000,000 papers collected by Web of Science (WOS) core database. The general science and technology takes only 50 years to develop from publishing 342,773 articles (1970) a year to 2,852,866 articles (2019) (Fig. 1). In an age of information explosion, the study related to SWI is a little more than a speck at the foot of the knowledge mountain. For individuals, however, 4252 article in the target field, which have been cited 73,505 times, were still difficult to traverse. After de-

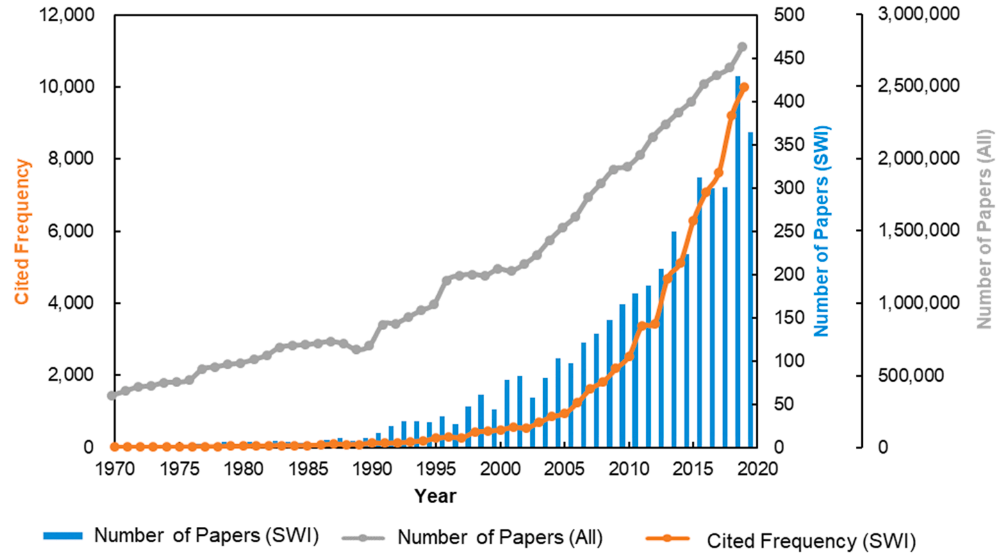


**Fig. 1.** Numbers of cited and published papers on all subjects and SWI scope.

duplicated by the CiteSpace, 4160 articles were obtained with 115,610 references in the retrieval period, from January 1970 to January 2020 (Fig. 1).

As can be seen from Fig. 1, the number of published papers and the citation frequency on SWI field have been dramatically increased in recent years. Since the early studies on SWI were sporadic, in the retrieval period, the number of the published papers in the recent 10 years (2010–2019) is 100 times that in 1970–1980. And the amount of published papers in the past10 years accounted for 65% in the past50 years. In contrast, the publication volume of general science and technology in the past 10 years is only 5 times that of 1970–1980. This rapid growth, which goes beyond general technological developments, is dominated by several factors. Firstly, on the demand side, with the rapidly economic development and population growth, more and more environmental problems (e.g. groundwater depletion, land subsidence, water pollution) appear in coastal areas (Konikow and Kendy, 2005; Ferguson and Gleeson, 2012). The increasing demand for freshwater resources has resulted in groundwater over-exploitation following by

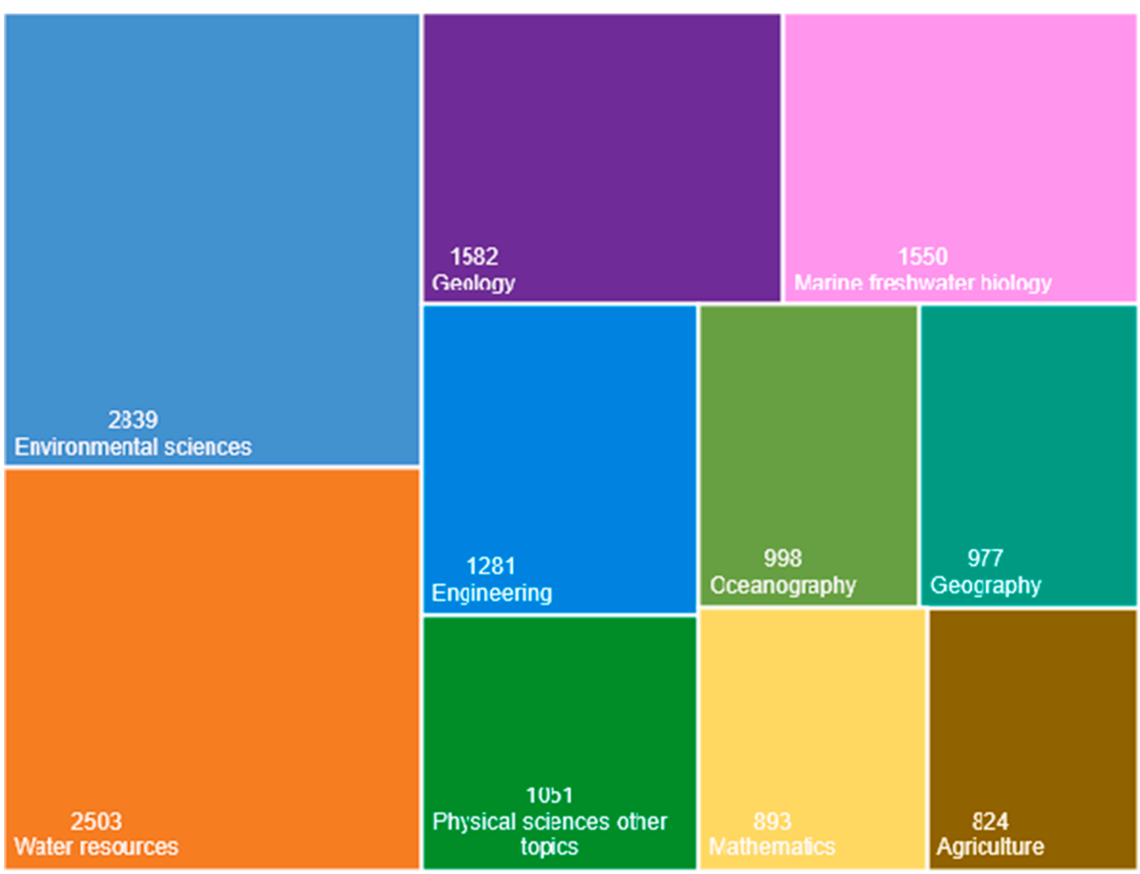


**Fig. 2.** Numbers and proportion of articles in related disciplines.

the occurrence of SWI. Secondly, the research on SWI has been further deepened. With the exploration of new technologies, especially the application of isotopic and geophysical methods, supplement of high-precision data on larger spatial and temporal scales, the SWI processes have been further understood (Beaujean et al., 2014; Xiong et al., 2018; Al-Rahbi et al., 2020).

SWI-related studies involve wide ranges of disciplines, which are often mutually contained and interrelated (Fig. 2). SWI can be affected by multiple factors, including vertical leaching caused by inundation, subsurface lateral intrusion, sea level rise (SLR), tidal fluctuation, geological structures, and human activities. Technically, SWI study requires coordination and application of different technical means, including the physical, chemical, and biological methods (Sylus and Ramesh, 2013). The wide range of disciplines brings both challenges and opportunities to the SWI study.

During the retrieval period, the earliest SWIrelated paper described the morphological distribution of the saltwater interface in the stratified aquifer, and provided the analytical solution under steady state (Öztürk, 1970; Collins and Gelhar, 1971). It exhibits the initial phase of SWI researches, which focused on solving the mathematical problems of location and morphology of fresh-salt water interface in specific conceptual models.

With the help of Web of Science built-in analysis tools, the most cited article (Svensen et al., 2004) in the whole download literatures reported that mantle-derived material intruded into carbon-rich deposits in the northeast Atlantic, resulting in the explosive release of methane, further led to extreme global warming that triggered the Eocene. Werner et al. (2013) reviewed the current situation and challenges of SWI problem, ranking second in the list of highly cited articles. The third list describes the impact of climate change on coastal areas and the impact of these factors on the seagrass growth and ecological effects (Short and Neckles, 1999). But these high citations are based on the global bibliographic library, not the specific field of SWI. These articles are widely accepted work related to SWI but should not be directly considered as the backbone of SWI or intensive discussed topics. The recognition of core literature on a specific scope depends on the co-citation of CiteSpace (White et al., 2004).

By the end of 2019, SWI had been reported in at least 501 cities worldwide (Fig. 3). It can be obtained by matching the global city database and the database composed by titles and abstracts of SWI related literature. Since researchers rarely mention other locations outside the target study area in the abstract and title, this result can be considered as the location of global SWI hazards. Compared with the traditional literature review method, this bibliometric method can greatly improve the accuracy and comprehensiveness of the research area distribution.

Based on the identified locations of SWI, we can explore the geographical characteristics of this hazard in more detail. Globally, about 30% cities with SWI crisis are distributed in local/shallow aquifers (Fig. 4). This is partly influenced by aquifer capacity, which tends to be low in local and shallow aquifers. On the other hand, about 28% cities with SWI crisis are distributed in major groundwater basins with relatively good recharge conditions (100–300 mm/a). Most of these cities are densely populated areas. It suggests that on a global scale, the large demand for fresh water in populated areas is one of the main inducements for SWI. Meanwhile, SWI remains a serious problem for metropolitan cities. Of the 501 cities that have reported SWI, 108 cities have population more than one million (occupied 22%). There are only 333 cities with a population of more than one million within 150 km from the shoreline, which means that at least 32% of the world's coastal metropolitan cities are suffering from SWI crisis (Fig. 5). However, the proportion is only 2% for cities with population less than 50,000. This difference further emphasizes the decisive influence of population and socio-economic development on SWI (Table S1).

### 3.2. Distribution and cooperation of research power

According to the collected literature, scholars interested in SWI were widely distributed in more than 100 countries and regions. The top 10 countries for total published articles are shown in Table 1.

Because an article may contain authors from different countries/regions, the records of published papers by country/region will exceed the

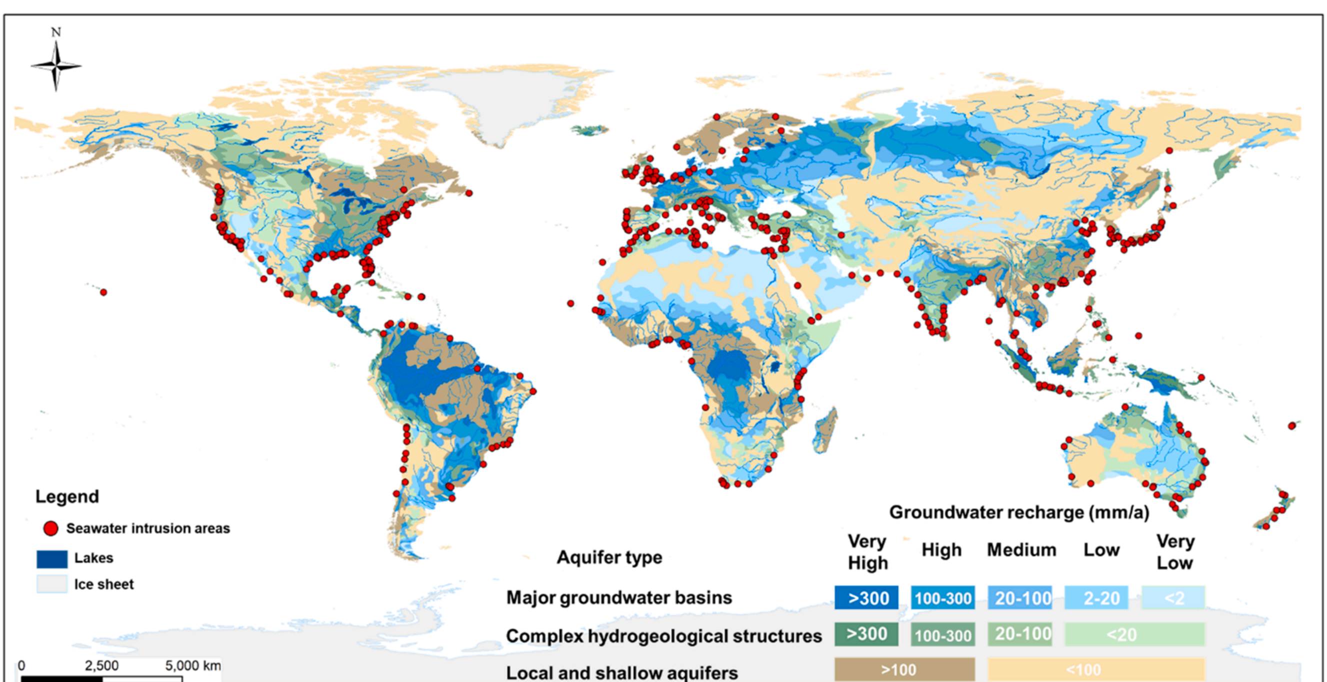


**Fig. 3.** Global geographic distribution of coastal cities with reported SWI crisis, identified according to the title and abstract of SWI related literature. Groundwater resources and recharge data are from German Federal Institute for Geosciences and Natural Resources (BGR) & United Nations Educational, Scientific and Cultural Organization (UNESCO), 2008; available at https://www.whymap.org.

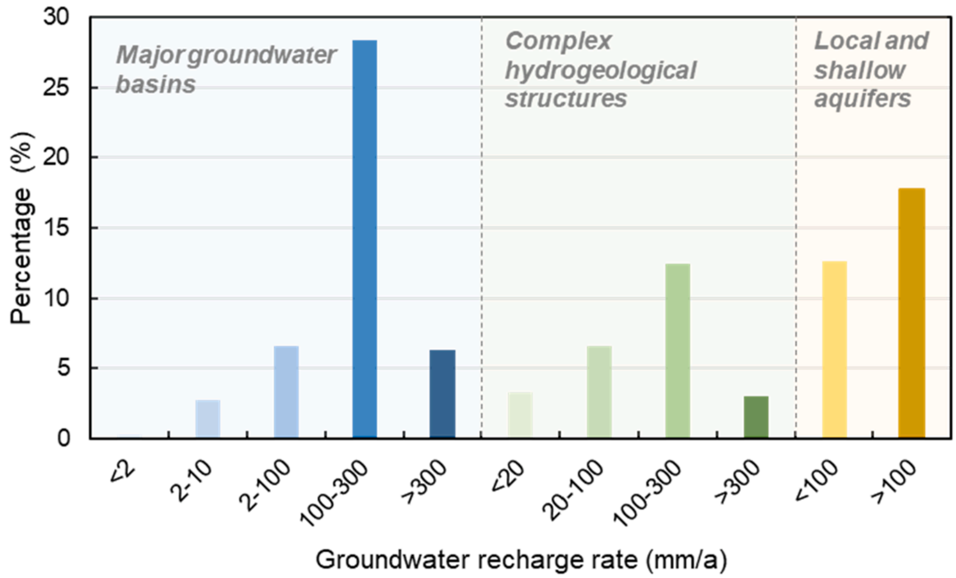


**Fig. 4.** Proportion of coastal cities with different aquifer properties and recharge rates. The percentage is expressed as ratios of city numbers of specific aquifer properties vs. total cities (501 cities) where have been reported SWI crisis. The types of aquifer properties are referenced from the Groundwater Resources of the World (BGR & UNESCO) (see Fig. 3).

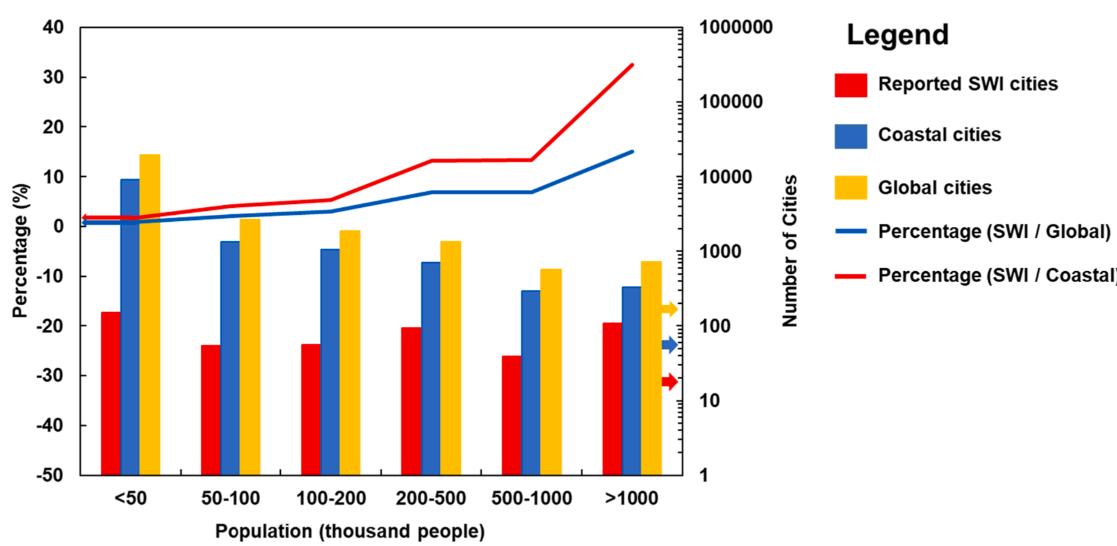


**Fig. 5.** The number of cities with different population and the percentage of coastal cities with SWI crisis among total coastal cities (<150 km from the coast) and global cities.

total number of published papers. The number of published papers can be regarded as a measure of a country's research strength. From 1970 to 2019, the United States published the most articles in the SWI scope, with a total of 1017 papers, accounting for 23.9% of the entire publications. China ranked second with 628 published articles, which account for 14.8% of the total number of publications. Australia was in third place, with 328 publications accounting for 7.7%. The following sequences are Italy, India, Germany, France, Spain, Japan, Canada, etc. (Table 1). These countries all have advanced scientific research competitiveness, and have important coastal cities or economic zones facing the SWI threat. In addition, a cooperation analysis between countries was also conducted. Fig. 6 shows the number of published papers and cooperation relationships between major research countries and regions. Cooperation is defined as the authors' addresses in two or more countries or regions appearing simultaneously in a single article. The close connection between each node indicates frequent exchanges and extensive sharing and cooperation between various countries in the world. The purple circle outside the country's name indicates that the country has a high centrality (Fig. 6). This exhibits that these countries are the core nodes of international cooperation. These countries (e.g. the United States and Australia) can be considered to play a leading role in international cooperation in the SWI field. Among the top 10 contributors, China, India, Japan and Canada are still relatively passive in international cooperation.

Fund is one of the basic supports for scientific researches. The National Natural Science Foundation of China ranked first as a single institution with outputs of 330 papers. It is followed by 139 studies funded by the U.S. national science foundation and 64 by the European Union. The fund-output relationship can reflect the current levels of investment and output situation in different countries. China's support is relatively concentrated and strong, which is closely related to China's complex water resources problems along 18,400 km continental coastline. It has an urgent need to assess potential water challenge at a national level in recent years.

 

**Table 1**
Top ten countries with the number of published papers.

| No. | Country | Records | Proportions (%) | h-index | Citations per papers | Total Cites |
|---|---|---|---|---|---|---|
| 1 | U.S.A | 1017 | 23.92 | 78 | 25.23 | 25,662 |
| 2 | China | 628 | 14.77 | 41 | 10.94 | 6869 |
| 3 | Australia | 328 | 7.71 | 51 | 29.08 | 9539 |
| 4 | Italy | 263 | 6.19 | 32 | 14.1 | 3709 |
| 5 | India | 241 | 5.67 | 33 | 15.65 | 3771 |
| 6 | Germany | 239 | 5.62 | 32 | 17.77 | 4246 |
| 7 | France | 226 | 5.32 | 31 | 17.29 | 3907 |
| 8 | Spain | 211 | 4.96 | 36 | 20.09 | 4240 |
| 9 | Japan | 184 | 4.33 | 27 | 16.4 | 3018 |
| 10 | Canada | 177 | 4.16 | 32 | 23.23 | 4111 |

Note: Records refer to the number of published papers by this country. Proportions refer to rate of Records to total amount of papers (4252). h-index is defined as *h* papers among the Records (*Np*) that has at least *h* citations. Citations per papers refer to the ratio of total citation frequency to Records, which was calculated in Web of Science database.

It's important to note that although the amount of Chinese articles is very large. The number of citations per papers for Chinese articles is the lowest among the top 10 contributors. And China is still not a dominant player in international cooperation. This emphasizes that Chinese scholars still need to enhance the influence of articles and international cooperation in the future. In addition, the h-index (defined as *h* papers among the country's publications (*Np*) that has at least *h* citations) of China is not very low (41, the third of top 10). This indicates that Chinese scholars also contributed quite a few of high-quality papers. However, some studies received relatively less attention, resulting in a low average citation rate. In addition to explore the comprehensive distribution of research power, the database can also be used to understand the research situation in any subfield of SWI. For example, what is the difference between SWI researches in carbonate aquifer and porous aquifer? Within the established retrieval range, it can be found that 2334 papers have mentioned "aquifer" in the title, keywords or abstract, while 407 and 341 have specifically mentioned "karst or carbonate aquifer" and "Quaternary or porous aquifer", respectively. The top three high *Np* countries about karst or carbonate aquifer aquifers refer to USA, Italy, and France. While the top three countries of studying Quaternary or porous medium aquifers refer to USA, China, and France, respectively. Although this is only a simple application for retrieving the scoped database. The retrieval results are qualitative rather than quantitative. Because quite a few scholars do not emphasize the aquifer type in the title, key words or abstract, but in the introduction of the study area. To some extent, this reflects the SWI situation in different regions. It also indicates that in the more specific subfields of SWI, the strength of national and regional research is somewhat redistributed based on local natural situation.

### 3.3. Core literature and basic knowledge

The number of citations is an important index to evaluate the influence of articles. However, citation frequency directly obtained from SCIE database refers to total citation times of the paper, but the cited paper does not necessarily belong to the target retrieval field (Chen, 2014). For example, the study of anomalous coastal methane emissions that triggered the early Eocene is not only revelatory in the study of SWI, but also widely mentioned in other environmental, ecological, and geological fields, resulting in a high number of citations. Therefore, highly cited literature may be associated with SWI problem but not necessary to be the basic and acknowledged information (Boyack and Klavans, 2010). To identify the core research of the SWI theme, citation network of a local database, which exports SWI-related literature information, was rebuilt by using the CiteSpace (Fig. 7). All 4160 deduplicated literatures were used for co-citation analysis. Top 10 co-citation literature and top 5% co-citation literature were shown in Table 2 and Table S2, respectively. According to the co-citation network (Fig. 7), the groups can be mainly divided into 9 clusters, with that clustering results less than 10 articles in clustering structure will be discard. The main clusters include SLR, SWI phenomena, surrogate model clustering, groundwater salinization, saline groundwater, viscosity-dependent flow, saltwater flushing, saltwater upconing, and conceptual model. These clustering tags are displayed according to the frequency of keywords. Therefore, these may represent features of the clusters. High cited papers focus on SLR, SWI phenomena and surrogate models. The topics of the most co-cited papers usually exhibit the hotspots of the core research fields, which has strong reference significance (Boyack and Klavans, 2010; Chang et al., 2015).

In the analysis of co-citation, one of the top ten influential papers belongs to the review category. Werner conducted a comprehensive review and outlook on SWI in 2013, introducing the main processes and influencing factors of SWI, common measurement methods, prediction

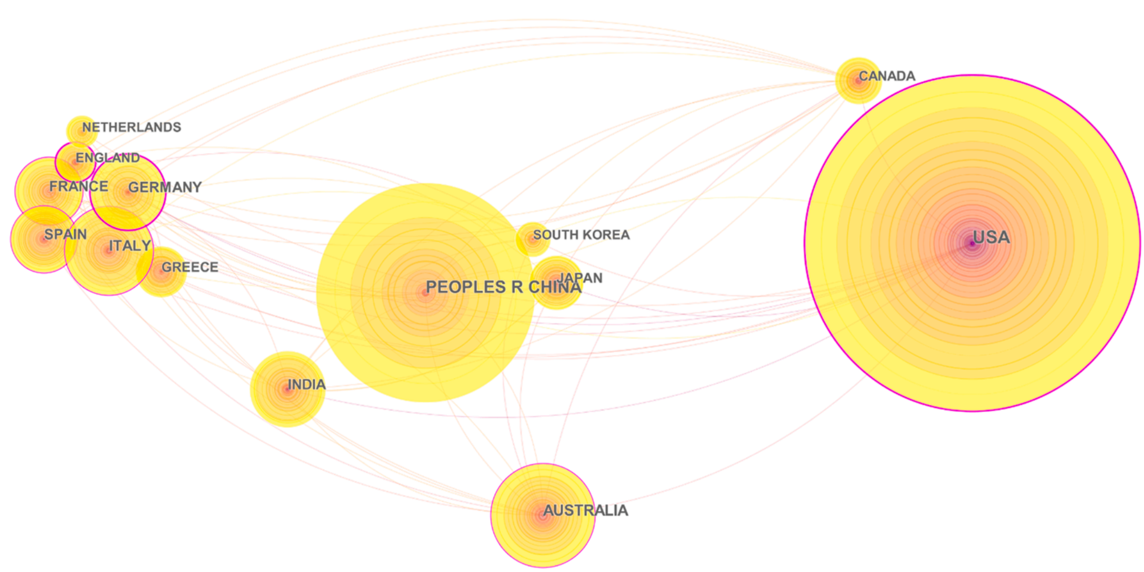


**Fig. 6.** Map of published papers and cooperation between countries or regions. The node size represents the countries' published volume, and the connection line between nodes represents cooperation. High centrality nodes are marked by purple circle, which means the country is facilitating communication between other countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

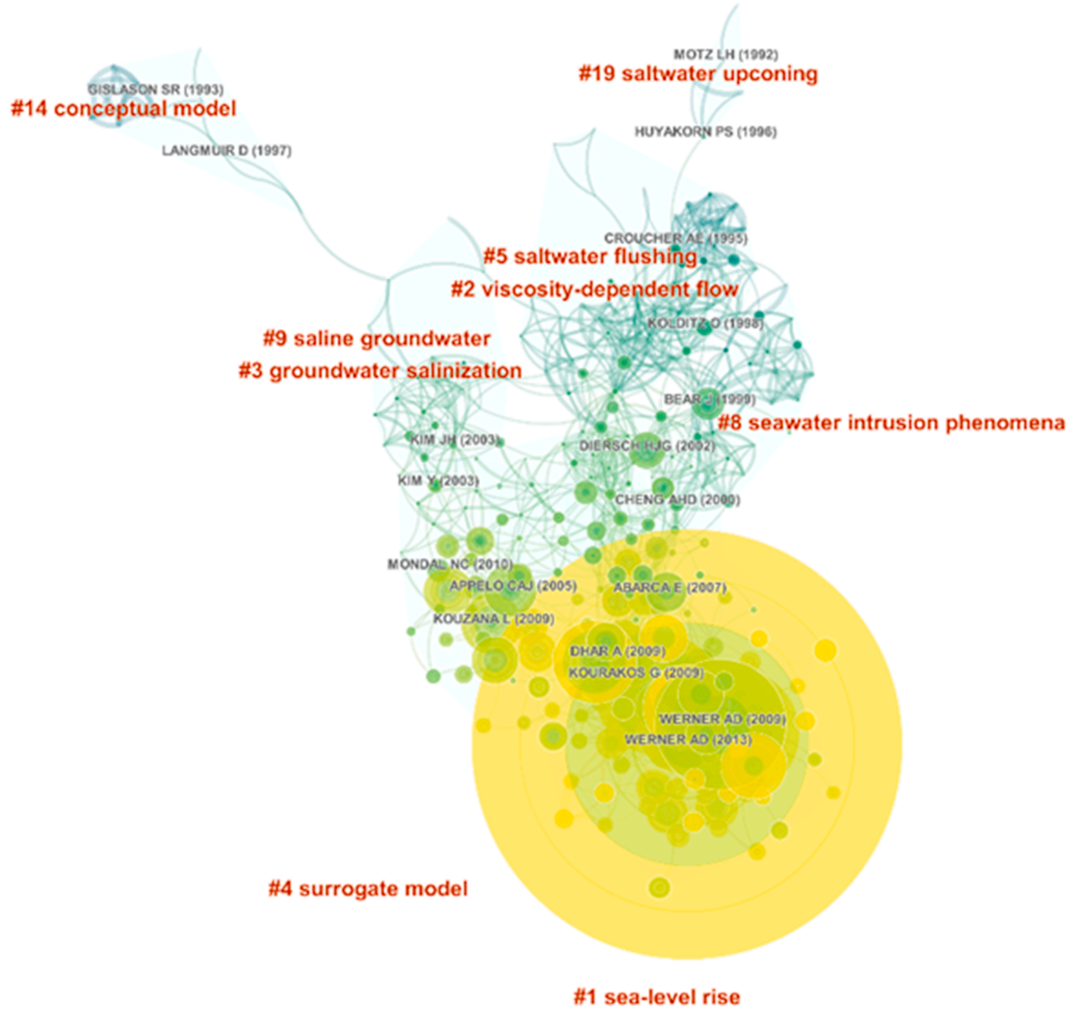


**Fig. 7.** Co-citation analysis map of SWI. The node size represents the co-citation frequency; the red character is the clustering label of the top large connected components cluster. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Co-citation analysis of SWI in SCIE.

| Freq | Year | Title | Journal |
|---|---|---|---|
| 304 | 2013 | Seawater intrusion processes, investigation and management: Recent advances and future challenges | Advances in Water Resource |
| 94 | 2009 | Impact of Sea-Level Rise on Sea Water Intrusion in Coastal Aquifers | Groundwater |
| 93 | 2012 | Vulnerability of coastal aquifers to groundwater use and climate change | Nature Climate Change |
| 90 | 2010 | Saltwater intrusion in coastal regions of North America | Hydrogeology Journal |
| 76 | 2011 | Does sea-level rise have an impact on saltwater intrusion? | Advances in Water Resources |
| 68 | 2012 | Vulnerability Indicators of Sea Water Intrusion | Groundwater |
| 63 | 2010 | Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands | Water Resources Research |
| 61 | 2010 | Coastal aquifers of Europe: an overview | Hydrogeology Journal |
| 48 | 2009 | Saltwater Intrusion Management of Coastal Aquifers. I: Linked Simulation-Optimization | Journal of Hydrological Engineering |
| 47 | 2016 | Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration | Journal of Hydrology |

Note: Freq refers to Frequency of co-citation in the local database. The higher the indicates, the more important it is in the field.

and management, and looking into the challenges facing this field (Werner et al., 2013). Some regional comprehensive reports also have high impact. The SWI status and processes in the European aquifers and islands were summarized by Custodio (2010). The mechanism and extent of SWI formation and following management measures were also summarized for North America (Barlow and Reichard, 2010). Due to high research competitiveness and early research time in these regions, these summary reports are very instructive.

As the most critical factor leading to a changing hydrodynamic environment in coastal zones, SLR related researches occupied half of the ten high co-cited literature. The impact of SLR on flux-controlled systems and head-controlled systems have been theoretically investigated (Werner and Simmons, 2009), showing that the flux system is more durable than the constant head cases at the same degree of SLR. The study highlights the role of inland boundary conditions. In order to address the question of whether SWI is more sensitive to human activity or more vulnerable to SLR, Ferguson and Gleeson compared the SWI extent caused by groundwater extraction with that induced by the SLR. The results show that human water use may be mainly responsible for the SWI occurrence. SLR may lead to relevant serious groundwater salinization when land-surface inundation happens in some areas with low hydraulic gradient. The long-term SLR seems will not lead to worse SWI situation under the condition of constant freshwater recharge, and the saltwater wedge might be pushed back to the original position through “lifting process” (Chang et al., 2011). Oude Essink et al. (2010) have established a three-dimensional solute transport model for coastal groundwater in Netherlands, taking climate change and human activities into account, including SLR, land subsidence, recharge changes, and other factors. It can provide a strong guidance for the establishment and display of numerical models in coastal areas. Ketabchi et al. (2016) evaluated and quantified the changes in the toe position of saltwater wedge under the influence of SLR through analytical and numerical models. It showed that land surface inundation resulted from SLR was an important factor controlling the aggravation of groundwater salinization. In two other influential papers, Werner et al. (2013) described the vulnerability of SWI to SLR, climate change, and changes in groundwater vulnerability under different boundary conditions. By combining numerical simulation model, meta-model, and the multiple objective optimization algorithm, Dhar and Datta (2009) developed a set of methodologies to generate initial solutions, which may significantly improve the efficiency of coastal water management. In general, SWI processes are closely affected by the boundary and discharge/recharge conditions of aquifers. Human activities also play important roles in modifying the SWI processes.

### 3.4. Research evolution and frontier

As the key summary of the academic papers, keywords are the core and essence of a paper. Changes in keywords are indicative of research hotspots (Li and Chen, 2016; Abbas et al., 2019). The principle of co-word analysis is that there must be a relationship between words or nominal phrases appearing in an article (He, 1999). Two keywords that appear in the one article form a keyword pair. By counting the keyword pairs occurrences frequent in the entire local database, a network of keyword pairs can be built (Radhakrishnan et al., 2017). Generally, the most co-occurrence frequent keywords are core knowledge of the focused research scope. The burst keyword refers to a rapid increase of cited frequent in a short time, which indicates the potential research hotspots, trends or frontier (Chen, 2006; He et al., 2019a; Zhang et al., 2020). The top 20 keywords and nominal phrases with high burst value were screened out and presented in Table 3.

By connecting multiple keywords, different hot topics can be classified. As the most discussed topic, SLR has the highest burst value, occurrence frequency, and a long discussion period (Fig. 8). SLR-relevant research stems from some concerns about climate change. It was initially thought that rising sea levels would inevitably lead to more serious SWI. However, further studies indicate that many other factors may be the dominant factors in SWI process, such as land-surface slope, recharge rate, surface inundation, aquifer thickness, and groundwater exploitation (Mahmoodzadeh et al., 2014; Ketabchi et al., 2016). Movement of fresh-salt water interface is dominated by regional hydraulic system, so the impact of a single factor is various in different places (Werner and Simmons, 2009).

Subsurface "solute transport" is the core problem of SWI, which focuses on the migration distance and reaction. Moreover, solute transport, adsorption, degradation, and mixing processes always accompany "variable density flow" problem (Werner et al., 2013). The variable density flow issue is usually considered in the application of numerical simulation and analytical solutions. Meanwhile, the differences of aquifer permeability and boundary conditions, which are caused by the formation structure and sedimentary characteristics, may be combined with the features of local groundwater salinization to form the variable density flow problem of a coastal aquifer system (Ketabchi et al., 2016). Hence, it needs to emphasize the accuracy of hydrogeological investigation on field scale. "Resistivity" can be detected by electrical resistance tomography (ERT) method, which is efficient and inexpensive to visualize the subsurface stratigraphic structure and salt distribution by recognizing the resistivity change (Martínez et al., 2009; Ogilvy et al., 2009; Palacios et al., 2020). As a cost-effective and large-scale available tool for field measurement, similar geophysical methods (e.g. airborne electromagnetics) have been applied on SWI investigation (Mills et al., 1988; Robinson et al., 2008; Pedersen et al., 2017). However, almost all geophysical methods need an "inversion" process to calibrate the received signals to other-sourced parameters of formation structure or salinity distribution (Beaujean et al., 2014; Steklova and Haber, 2017; Torres-Martinez et al., 2019). The challenge of this process is often caused by heterogeneity of aquifer systems (Nguyen et al., 2009). In addition, environmental "tracers" have been applied to investigate the subsurface hydrological and hydrochemical processes (Leibundgut et al., 2011). Combined with hydrochemical data, solute sources can be traced and the groundwater age can be estimated, which is helpful for describing groundwater flow system, constructing conceptual model, and inferring pollution migration processes (Bear et al., 1999; Bouchaou et al., 2008; Zuber et al., 2011; Han and Currell, 2018).

Another important research direction is the "vulnerability" evaluation of coastal areas. SWI is considered to be affected by both human activities and climate change, such as groundwater recharge, groundwater exploitation and aquifer characteristics. Hence, most of these researches use multiple index assessment, such as GALDIT, which is an acronym for six indicators including (G) groundwater occurrence (aquifer type), (A) aquifer hydraulic conductivity, (L) length of fresh water level above sea level, (D) distance from the shoreline, (I) impact of existing status, and (T) thickness of aquifer) (Lobo-Ferreira et al., 2005; Recinos et al., 2015; Parizi et al., 2019). Based on the above index analysis, regional assessment can be carried out. However, a change in one condition may have a chain reaction. It is also of great importance to establish hydrological/hydrogeological models for key areas. As for the word "plain", SWI is more common in coastal plain area, where the hydraulic gradient relatively low, the groundwater depression formed, and the threat of SLR, seawater is not only easy to intrude into the aquifer laterally, but also may inundate the low slope plain (Ferguson and Gleeson, 2012; Ketabchi et al., 2016; Yu et al., 2016).

"Circulation" and "discharge" are two keywords belong to SGD issue. Subsurface freshwater discharge may be an important source of nutrient for offshore region (Moore, 2010). Oceanic tide can change the hydrodynamic condition that constitutes a unique salinity cycle in coastal areas (Kuan et al., 2012; Yu et al., 2019). In a deep time frame, geothermal circulation in coastal areas is also an important problem in hydrogeology, which may be an important factor of climate change (Svensen et al., 2004).

"Optimization" refers to some optimization of SWI prevention and control measures, such as building estuary dams, underground dams, and redistributing extraction wells layout (Abarca et al., 2006). With the introduction of new optimization methods and the improvement of computing method, machine learning and meta-models (e.g. artificial neural network) have been more and more applied in this field (Dhar and Datta, 2009; Roy and Datta, 2018). In addition, "Growth" should refer to the population growth. With the increase of population, the demand for freshwater resources gradually increases, which brings potential water demand or pollution pressure to the sustainable

**Table 3**
Top burst value keywords.

| Keyword | Frequency | Burst | Keyword | Frequency | Burst |
|---|---|---|---|---|---|
| sea level rise | 226 | 24.14 | resistivity | 18 | 8.88 |
| impact | 190 | 16.18 | porous media | 62 | 8.78 |
| solute transport | 37 | 14.22 | hydrogeology | 15 | 8.55 |
| vulnerability | 64 | 14.12 | discharge | 40 | 8.49 |
| variable density flow | 54 | 12.90 | optimization | 72 | 8.21 |
| isotope | 21 | 11.05 | growth | 13 | 8.11 |
| zone | 37 | 11.00 | chemistry | 53 | 8.03 |
| inversion | 27 | 10.55 | pollution | 15 | 7.88 |
| seawater | 147 | 10.04 | circulation | 49 | 7.80 |
| plain | 22 | 9.79 | resource | 15 | 7.63 |

Note: Frequency refers to the keyword co-occurrence frequency. Burst is a quantitative measure of keywords from emergence to mass use in the local database. The more active a keyword is, the higher burst value it has. The burst detection in CiteSpace is based on Kleinberg's algorithm (Kleinberg, 2003).

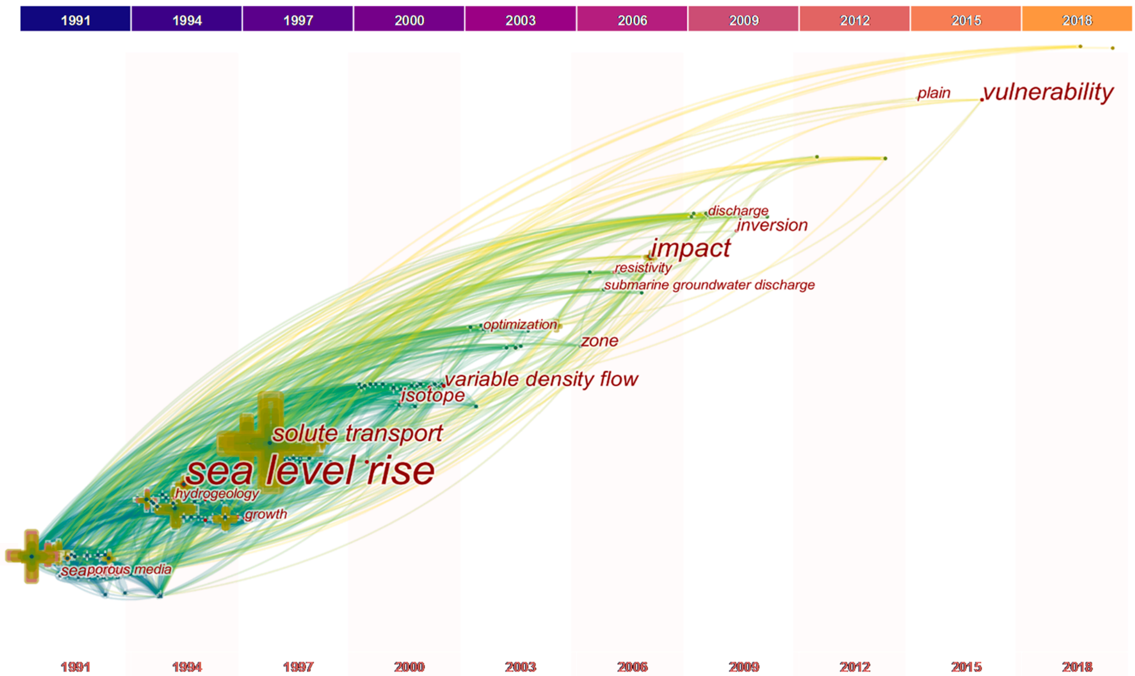


**Fig. 8.** Keywords' evolution map from 1990 to 2019. The node size represents the relative frequencies of keyword co-occurrence. The numbers at top boundary are the middle years of each time slice.

development of coastal areas (Barlow and Reichard, 2010; Ferguson and Gleeson, 2012; Shi and Jiao, 2014; Kalaoun et al., 2018). Fresh groundwater resources sustain the rapid increasing water demand in coastal zones, especially in semi-arid and arid coastal regions (Post et al., 2013; Mahlknecht et al., 2017; Alfarrah and Walraevens, 2018). "Growth" may also refer to a method to identify SWI events through the growth ring in the research on mangroves in coastal zones (Yanosky et al., 1995).

According to these above mentioned keywords, a schematic figure describing main problem and research directions can be proposed (Fig. 9).

Clustering can be formed according to the co-occurrence relationship

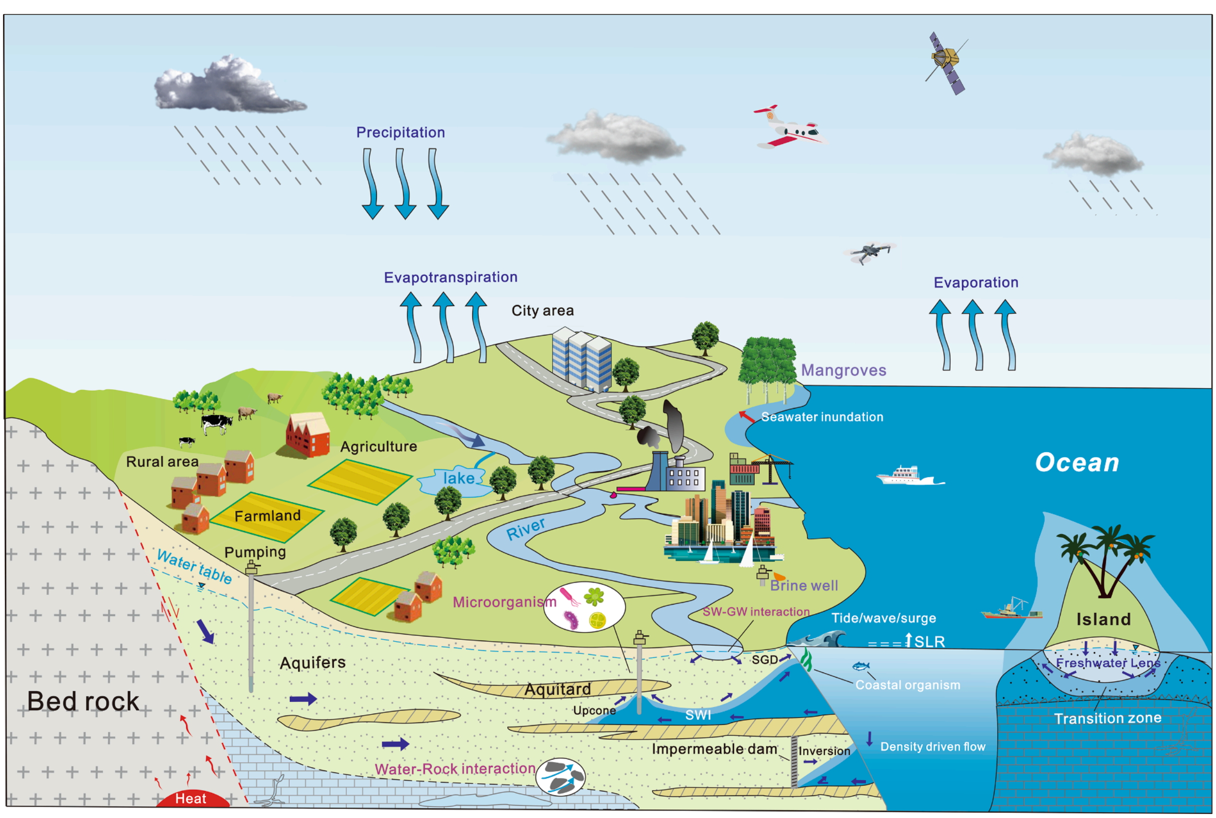


**Fig. 9.** Schematic conceptual model for showing main hydrological factors and SWI research directions in coastal area.

between keywords. The research directions, research methods and some typical research areas can be further understood (Table 4). The clustering results form 5 clustering labels, and the clustering names are: porous media, groundwater quality, hydrothermal circulation, recovery potential, and SWI. CiteSpace uses the silhouette as an index to measure the homogeneity of clusters (Chen, 2016). When the silhouette score is higher than 0.7, the relationship of keywords in cluster is highly close (Rousseeuw, 1987).

In this study, the silhouette scores of each cluster are 0.80, 0.68, 0.87, 0.90, and 0.78, respectively. As there are more than 30 keywords, only the first 15 keywords under each cluster are selected and shown in Table 4. Cluster ID 0 mainly points to analytical solution or numerical simulation study on determining the location and morphology of the interface of salt and fresh water in the porous media. It specifically targets the Henry problem, which is characterized by variable density and variable viscosity fluid. Tidal influence is another hot topic for the simulation study. Cluster ID 1 points to the problems related to groundwater quality in coastal areas, including prediction of water quality changes by numerical models, and identification of factors of water quality changes by isotope means. Cluster ID 2 indicates the related research on geothermal circulation and the material circulation in offshore areas. The tectonic movement that occurs in a particular stratigraphic structure can drive salt water to displace some of the original materials in the stratum, resulting in greenhouse gas emissions and other consequences, which may be an important factor in climate change. Cluster ID 3 is identified for showing the ecological influence of SWI, especially the impact of salinity changes on plants in coastal estuary or mangrove wetland. Cluster ID 4 refers to some relevant studies to explore different factors or water management policy from the degree of SWI. This kind of research aims at exploring reasonable management methods to realize sustainable utilization of groundwater resources in coastal areas.

It can be found that SWI appears with many different types of keywords. Especially among the above mentioned five directions, hydrothermal circulation and recovery potential are not usually included in the previous review. Inevitably, SWI start to be widely considered in the fields composed by those words. This is an extension of the SWI issue towards the geological and ecological scope. It is also a new opportunity that scholars concerned with SWI issues should seize.

**Table 4**
Keyword clustering results of SWI.

| Cluster ID | Silhouette | Label |
|---|---|---|
| **0** | **0.796** | **Porous media** (129.54); 3d density-dependent model (127.44); numerical model (89.61); viscosity-dependent flow (79.14); sea water intrusion (79.14); saline water (77.05); semi-analytical solution (74.96); reactive henry saltwater intrusion problem (74.96); numerical modelling (72.86); including tidal effect (72.86); unconfined aquifer (70.77); tidal effect (70.77); modeling groundwater (68.68); river interaction (68.68); groundwater age (66.59) |
| **1** | **0.677** | **Groundwater quality** (76.35); porous media (73.63); 3d density-dependent model (72.43); sea-level rise (65.68); Langat river (64.55); seawater intrusion (54.57); numerical model (50.78); viscosity-dependent flow (44.78); seawater intrusion (44.78); quantifying mixing (43.82); coastal watershed (43.82); alluvial plain (43.82); strontium isotope (43.82); south-eastern Tanzania (43.82); saline water (43.59) |
| **2** | **0.866** | **Hydrothermal circulation** (132.87); Guaymas Basin (77.64); basalt intrusion (77.64); conceptual model (69.81); low-temperature area (69.81); geothermal system (69.81); oxygen isotope (62); northern Samail ophiolite (62); thermal structure (54.19); anhydrite precipitation (54.19); ridge axe (54.19); tweed estuary (46.41); seasonal variability (46.41); equatorial Pacific (38.64); new production (38.64) |
| **3** | **0.903** | **Recovery potential** (83.82); salt pulses (83.82); oligohaline marsh macrophyte (83.82); taxodium distichum seedling (77.83); shoot responses (77.83); saltwater intrusion event (71.85); fresh-water marsh vegetation (71.85); soil flooding (65.9); pinus-taeda (65.9); salt-marsh grass (59.96); spartina paten (59.96); sublethal salinity stress (59.96); chloride concentration (54.04); saltwater-intruded estuary (54.04); growth ring (54.04) |
| **4** | **0.779** | **Seawater intrusion** (88.88); sea-level rise (83.12); general framework (77.9); cost-efficient management (77.9); brackish groundwater (77.9); saltwater intrusion area (74.03); pearl river delta (74.03); water resource (74.03); flux-controlled groundwater system (66.34); saltwater intrusion dynamics (66.34); sustainable groundwater management (62.52); stochastic forecast (62.52); Korba aquifer (62.52); global assessment (58.72); groundwater level fluctuation (58.31) |

Note: Silhouette is an index to measure the homogeneity of clusters. The higher the silhouette score, the more consistent of the cluster members are.

### 3.5. Limitations and prospects

An important point needs to be noted that CiteSpace is essentially a statistical and semantic analysis software. The representation of hot keywords is based on the frequency of a particular word or phrase appears in the entire local database (Li and Chen, 2016). It leads to the fact that keywords with high burst value and high frequency are the hottest topics and even controversial topics in this field. By this way, some of the default basic knowledge will not be expressed because there is less argument. For example, the decline in groundwater levels caused by unconscionable pumping is the direct driven factor controlling SWI in most coastal areas. However, due to the acquiescence to this conclusion, the keyword “pumping” does not appear in the ranks of high co-occurrence. It may result in ignoring some commonly held assumptions. This phenomenon reminds the importance of reading above mentioned highly co-cited references.

Although the analysis according to citation relations and semantic recognition in this paper is repeatable and verifiable, limitations still exist. For example, groundwater age plays an important role in understanding the mechanism of SWI. However, the groundwater ages are usually obtained by environmental tracers or numerical modelling. It can be emphasized by counting the co-occurrence frequency to show the importance of generic concepts (e.g. environmental tracers or modelling) and reduce the embodiment degree of specific concept (e.g. groundwater age) in semantic co-occurrence analysis. As the CiteSpace provides a platform to investigate new ideas (Chen, 2004), one should keep in mind that all the hot issues and methods are existing knowledge. The innovation may be originated from experiences but also controlled by intelligence. We can predict that existing branches of the knowledge path could be enriched in the future. But it cannot be expected to predict where or when the next breakthrough will occur.

To fix this problem, a prospect on SWI would be especially crucial. Generally, the narrow sense SWI researches toward the following field: the processes, measurement, prediction, and management of SWI (Werner et al., 2013). Due to the heterogeneity of complex stratum structure, there is a significant gap between laboratory experiment or mathematic solution and field-scale investigation on the SWI processes. For example, the shapes of saltwater distribution characterized by ERT method are usually quite different from that obtained from the sandbox analog models (Kazakis et al., 2016). It may be limited by the calibration of ERT method (Beaujean et al., 2014). But more complex conditions, such as the coastal rivers, wetland, land use change, abandoned wells, or even the biological activities have more or less impact on SWI processes (Carabin and Dassargues, 1999; Han et al., 2015; Yuan et al., 2016; Mastrocicco et al., 2019; Cao et al., 2020). More laboratory model scenarios, empirical summaries, and improvements in the accuracy of field observations are still needed to reduce the gap between theoretical and practical studies. On the other hand, it should be noted that the SGD and

SWI are complementary processes. Their interactions and joint responses to other factors (e.g. tides and climate change) need to be further understood (Prieto, 2005; Taniguchi et al., 2006; Fang et al., 2021). With the understanding of SGD, the control of SWI is no longer limited to protect terrestrial fresh water resources, but focuses on the coastal solute cycle. The critical role of SGD in nearshore waters requires a strategic balance when considering disaster mitigation from SWI (Swarzenski et al., 2001; Moosdorf and Oehler, 2017; Utsunomiya et al., 2017; Montiel et al., 2019; Zhou et al., 2019). An ideal situation is to maintain stable coastal ecosystems without contaminating freshwater by seawater or impeding proper nutrient excrement (Moore, 2010). A large number of studies have preliminarily elucidated the hydrodynamic variations and global solute flux of SGD (Li and Wang, 2015; Moosdorf et al., 2015; Santos et al., 2021). However, some processes based on long-term monitoring remain to be reported, such as the seasonal changes in SGD-driven fluxes and river-driven fluxes, the behavior of nutrients and emerging pollutants in coastal environment, and the role of SGD in ecosystem services (Sugimoto et al., 2016; Utsunomiya et al., 2017; McKenzie et al., 2020; Szymczycha et al., 2020).

In terms of SWI measurement, it is no longer unrealistic to comprehensively obtain information, such as salinity distribution, groundwater residence time, solute transport path, and salt source, by combining water level monitoring, hydrochemistry, environmental tracers, and hydrogeological conditions (Guo and Huang, 2003; Saravanan et al., 2019; Zeynolabedin and Ghiassi, 2019; Cao et al., 2020). However, one problem that cannot be ignored is that a large length of the global coastline is poorly monitored (Werner et al., 2013). Convenient and economical underground information sensing method is almost indispensable for the future SWI research. At present, the airborne geophysical method has been explored in large-scale long-term monitoring of SWI in many places, including Denmark, the Netherlands, the USA, and China (Jørgensen et al., 2012; Delsman et al., 2018; Goebel et al., 2019; He et al., 2019b).

Different numerical models based on variable density flow have been developed to predict SWI. One of the main problems of numerical models is that the initial and boundary conditions sometimes have to be simplified, such as the ocean boundary is set as a fixed head (Werner and Simmons, 2009; Watson et al., 2010; Webb and Howard, 2011). This does not mean that the current models are disconnected from reality, but that we are learning from them. Meanwhile, there are more directions to be considered in organizing regional water management strategies through models. In addition, there is still no quantitative method to judge whether a simplified conceptual model is reasonable or not for simulation. For example, differences in the impact of SLR have been demonstrated in head-controlled systems and flux-controlled systems (Werner and Simmons, 2009), but how to define land boundaries is usually data based or completely subjective (Carrera et al., 2010). In particular, it is a challenge to simulate the development of SWI taking into account geological heterogeneity and transient conditions.

Another question related to SWI prediction is whether the SWI evolution will differ on different timescales, especially under the long time processes' effects, such as water–rock interaction (Liu et al., 2008; Park et al., 2012). And what are the characteristics and linkages of SWI on the day, month, and year scales under the changes of tidal, precipitation, population, economic activities, and climate? As a global environmental issue, the impact of climate change and human activities on SWI is an essential issue to be well monitored and further investigated (Sherif and Singh, 1999; Jayathunga et al., 2020; Sithara et al., 2020). Although SWI control is no longer an unsolvable problem in engineering, the reversal process may take a very long time (Oude Essink, 2001; Berger and Gientke, 2020; Wu et al., 2020). Some areas have adapted their water management practices to meet local resource, economic and environmental requirements (Javadi et al., 2015; Walther et al., 2020; Han et al., 2021; Yang et al., 2021). Optimizing coastal zone management strategies to ensure long-term water security will also be an important issue.

Multidisciplinary cooperation plays an indispensable role in the SWI study. SWI is not only a hydrological problem, but also a problem related to social and economic development (Giordana and Montginoul, 2006). SWI research offers basic information for more comprehensive researches, such as pollution control and ecosystem maintain (Herbert et al., 2018; Ma et al., 2020; McKenzie et al., 2020). Meanwhile, the further understanding of SWI process also depends on the progress of technology and methods in other basic subjects. The combination of any discipline (e.g. geology, oceanography, engineering, and economics) with SWI problems is not surprising and often leads to exciting results. For example, the diversity of the microbial community in the salt-freshwater transition zone was high (Chen et al., 2019). This not only improves the understanding of coastal microorganisms, but also confirms that bacteria can be regarded as a potential indicator of SWI. Solving the SWI problem also requires a deep geographical interpretation. How does SWI affect human society and coastal ecosystem? How the human society and ecosystem generate feedback? These problems can't be solved without the intersection of social science and economics.

The solution to the SWI problem depends on a variety of data to form a complete chain of evidences. Although numerous institutions and local governments have reported a large amount of data and analysis results, there is still no proper platform to verify and summarize these data systematically. This situation limits the utilization of the existing data, making it difficult to analyze the SWI process on a large spatial scale or dynamically track the salinity change. An appropriate international data platform is within reach and will be beneficial.

## 4. Conclusions

A bibliometric analysis of global SWI research during 1970–2019 was conducted by using CiteSpace. The research outputs trend, related disciplines and global study areas were identified. The contributions of difference countries in SWI issue were critically evaluated. Co-citation and keywords co-occurrence were used to clarify the core literature, background knowledge and research branches. The opportunities and challenges were summarized.

501 coastal cities have reported SWI crisis around the world. About 58% of these cities locate at well-recharged major basins (recharge rate 100–300 mm/a) or local/shallow aquifers. Population density is one of the controlling factors that leads to SWI, and SWI tends to occur in coastal cities with large populations. About 32% of coastal metropolitan cities are threatened by SWI crisis, while this proportion is only 2% for coastal cities with population less than 50,000.

The increase rate of SWI-related papers is 20 times greater than that of general science and technology. The United States of America, China, and Australia contributed 46.4% of the total number of SWI-related articles. Although the second largest number of researches with has been financially supported by China, some papers still failed to attract appropriate academic attention, resulting in a relatively low average citation. By contrast, China's influence in this research field needs to be further improved.

Combined the top 5% of core literature and top 10 core literature, the basic directions and methods have been reviewed. The measurement, simulation, predication, and management of SWI form the main branch of SWI research, which relay on the hydrodynamic, chemical, isotopic analysis and numerical simulation. With the increasingly concerning about climate change in scientific community, the impact of SLR is the most widely discussed topic. Meanwhile, SWI is frequently mentioned in the aspect of coastal mangrove wetlands protection and geothermal circulation. This highlights the extension of SWI research into geological and ecological directions, which bring both the challenges and opportunities for scholars.

Ultimately, SWI is a hydrological problem driven by the development of human society and economy. Coastal counties around the world are likely to suffer its hazard. The global SWI crisis may be even more challenging when coupled with climate change. Despite more than 50 years of research, the current worldwide SWI have not been well monitored and some fundamental problem still exists. It is expected that the global research efforts can be well collaborated to understand better coastal groundwater flow and solute transport processes, to avoid environmental degradation of coastal systems, and to enhance the global coastal water security.

### 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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2021.126844.

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