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Risk to pollution of aquifers associated with productive activities and environmental management of water resources: bibliometric analysis and trends

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ABSTRACT

Its analyzed the evolution and trends of the concept, and studies the models used to know the vulnerability and risk of aquifers and strategies for their management. The methodological process starts from questions guiding the knowledge of research trends, authors among others to proceed to carry out the analyses from the databases of Scopus, Web of Science and Dimensions. VOSviewer and Bibliometric (Rstudio) software were used. Among the most representative results, it was found that most of the research to determine the risk of aquifer contamination is focused on different models such as improved flux prototypes for NO2 emission from agriculture (IPNOA), pollutant origin surcharge hydraulically (POSH), intrinsic vulnerability methods ground water occurrence, overall aquifer class, depth to groundwater (GOD), depth recharge, aquifer, soil, topography, impact, hydraulic conductivity (DRASTIC), substance, infiltration, not saturated, type of coverage, topographic surface, conductivity (SINTACS) and chlorofluorocarbons (CFC) among others. Different models have been used that integrate both hydrological and hydro-geological aspects as well as social aspects including fundamental rights, other models such as the diffuse model, which has had better results in its application, the gaps in the research, are especially focused on conducting holistic research when assessing the risk of these dynamical systems.

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1. INTRODUCTION

Water has become one of the main sources of development of countries, while it has become one of the most important concerns for the twentieth century, given the increase in production systems and unsustainable practices which have become a serious threat to both human health and ecosystems. In the vast majority of countries of the world agriculture has been the main cause of water pollution, especially in groundwater, nitrates have been the main source of such pollution. After the green revolution, the consumption of agrochemicals has been increased both for fertilization and for the Phyto-sanitary control of crops, generating infiltration into the soil and runoff from them, turning aquifers into highly vulnerable ecosystems, the term vulnerability to aquifer pollution is used to represent the intrinsic characteristics that determine the sensitivity of the aquifer to be adversely affected by a load imposed pollutant [1], to measure this vulnerability different methods can be taken into account, including simulation models of spatial, statistical or process-based or hybrid indices.

In Latin America, researches have been limited in relation to the amount of groundwater and therefore, the degree of contamination of the same is unknown, however, these ones have served as complementary or alternative sources for the use of surface water, while they have been affected, not only by agricultural production systems as mentioned in previous lines, but also, by other systems such as the construction of tunnels, roads, mining systems, among others [2], which confirms the need to carry out research both on the supply of water resources and its state and vulnerability.

This article takes a tour around the different subjects that from 2012 to 2021 have been carried out around the risk of aquifer pollution, as well as reviewing research trends and knowledge gaps from the creation of networks using VOSviewer and R software to identify the correlations and forms of behavior of the literature related to the topic. This analysis will allow the academic and scientific community to identify the main publications and topics associated with the risk of groundwater contamination, in addition to identifying the research gaps to be explored, main authors and research institutes that are addressing the topics, the countries that are developing this research to a higher extent, as well as the cooperation between different researchers to solve the research gaps in a global problem as important as pollution of aquifers.

This document proposes some models used for the analysis of the risk of aquifer pollution and its management processes, among the most outstanding were found: the depth recharge, aquifer, soil, topography, impact, hydraulic conductivity (DRASTIC) model, which considers water depth, net recharge, aquifer lithology, soil type, topography, nature of the unsaturated zone and hydraulic conductivity. The substance, infiltration, not saturated, type of coverage, topographic surface, conductivity (SINTACS) model) where it is taken into account-water table-infiltration, self-purification effect of the unsaturated zone, typology of the cover soils, aquifer lithology, hydraulic conductivity and slope of the topographic surface, this model is a derivative of the DRASTIC, both, evaluate the vulnerability of the aquifer dividing it into cells or polygons, for which, they calculate a vulnerability index from a system by weighted ranges. The improved flux prototypes for NO2 emission from agriculture (IPNOA) model is one of the best-known methods used to assess nitrate content. The autoregressive, moving average (ARIMA) model is used to find patterns that are repeated over time to make future estimates which are based on historical data and not on independent variables. Remote sensing and GIS models, where satellite images and terrain elevation models have been used to take it to a process of mapping and spatializing the risk of contamination of aquifers. modular finite-difference groundwater flow (MODFLOW) model and multi-species transport in 3-dimensions (MT3D) model, is used in hydrogeology to simulate the underground flow of any aquifer and finally, one of the most used in Latin America is the pollutant origin surcharge hydraulically (POSH), which allows to identify the potential of pollutant loads to which the aquifer is exposed.

2. METHODOLOGY

Initially a keyword search was done to configure the search equation, for the processing of the information the following sequence was carried out. In Figure 1, the procedure carried out for the analysis of investigative processes that have been consolidated for the analysis of aquifers worldwide is shown. This procedure consists of four main phases. Firstly, the most important topics are defined, followed by a clear definition of the consolidated problem in some research questions. Then, the search equation is defined, and finally, the process and analysis of the information are conducted.

Subsequently, the construction of the guiding questions was made, which are listed below: “What are the thematic areas and countries conducting the most current researches on the risk of water pollution in aquifers?”. What are the key descriptors related to the risk of water pollution in aquifers?”. “What are the relevant research trends of studies regarding the risk of water pollution in aquifers?”. “What is the relationship among countries, authors and journals on the issue of the risk of water pollution in aquifers?”. How has the process of managing the risk of aquifer contamination been? What are the main gaps in the research conducted of the risk of contamination of aquifers?”.

Based on the approach of the previous questions, a quantitative analysis was carried out, using the web of science, Scopus and Dimensions databases, obtaining a better result by number of publications in the Scopus database. Initially, a keyword search had been carried out also using Google scholar database in order to identify the main descriptors considering some keywords such as pollution, pollution management, aquifers, in order to find an approximation to the search equation. It was based on the methodology carried out by [3], where a bibliometric was made to know about the IoT in wetlands. In Table 1, the different search equations used for the analysis of information are shown, along with the results for each equation in terms of the number of documents found in the last 10 years for each equation. We constructed five search equations which are related in Table 1.

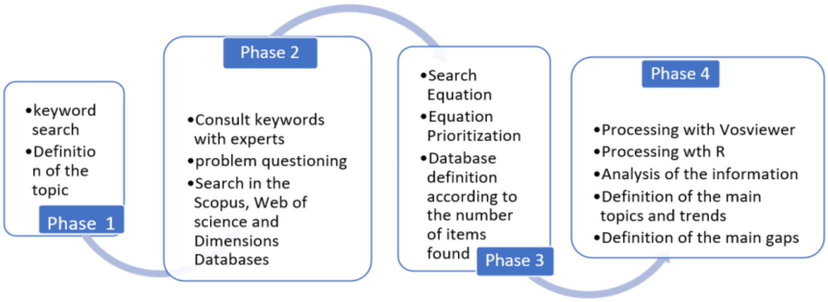

Figure 1. Methodological process

Table 1. Search equations

Equation	Search Equation	Results
Equation 1	(Aquifer and contamination and environmental and management)	A total of 881 documents were obtained. For the last 10 years: 483 documents were obtained.
Equation 2	(Underground and aquifers and contamination and environmental and management)	A total of 109 documents were obtained. For the last 10 years: 53 documents were obtained.
Equation 3	(Risk and of and water and contamination and environmental and management)	A total of 3688 documents were obtained. For the last 10 years: 1260 documents were obtained.
Equation 4	(Contamination and of and aquifers and productive and activities)	In total: 18 documents were obtained.
Equation 5	(Contamination and of and aquifers and agricultural and activities)	A total of 522 documents were obtained. For the last 10 years: 314 documents were obtained.

To achieve a better result in the information acquired, some search criteria were determined, as follows: keywords in English, different documents including articles and secondary documents, likewise, we worked with information from 2012 to 2021, the year 2022 was not included since it is the year that is in progress that would alter the statistics. For the processing of the information, the VOSviewer software was executed to establish the analysis of co-occurrence of the publications made among different countries, it was taken into account that at least five documents have been published in the subject.

Additionally, bibliometric networks were generated by combining the keywords with the co-occurrence, to finally decide to analyze those declared by the author to have a higher visualization of the relationships. Subsequently, we proceeded to analyze the citations by documents considering a minimum of 10 citations, it was also taken into account the citations registered in the journals considering a minimum of five documents per journal. In the R software, other aspects were reviewed, such as the index of publication collaboration between authors, number of documents published per author, dynamics of annual publications, as well as annual citations, as well as three-phase graphic analyses were carried out, considering journals, affiliations and authors who have published against the risk of aquifer contamination and its management.

3. RESULTS

It was decided to work with the search equation No 1 where 483 documents were found for the years analyzed, the criterion for its selection is because the publications found within the database had a higher relationship with the subject of study. In the bibliometric analysis it was found that there are 483 documents in the period studied, of which 83.1% corresponds to research articles, 5% to book chapters, 5% to Review, 4.8% to conference paper, 0.6% to books and the rest in other documents, likewise it is found that the area where the largest number of documents are published is in Environmental, followed by Earth Sciences and Agricultural Sciences, it is remarkable that there are also publications on the subject of study in the area of social sciences, this is because the problems of water pollution become social problems, if there are no good water health conditions, this will affect health and increase the social crisis. Figure 2 displays the knowledge domains where scientific papers related to the subject of this research are most frequently published. Figure 3 depicts the countries at the forefront of hydrological research, focusing on studies related to aquifer pollution and management processes. The primary contributors to scientific production in this field are the United States, China, and India, as illustrated in Figure 3.

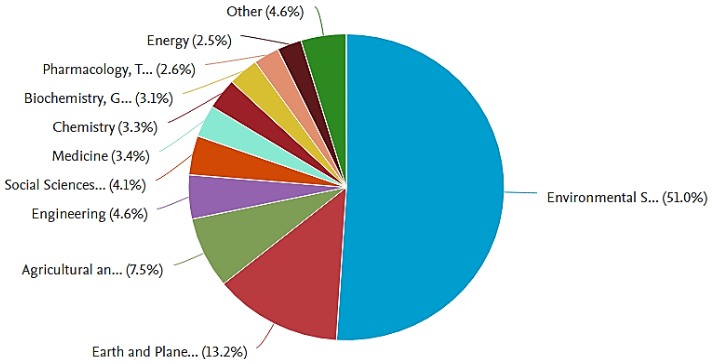

Figure 2. Documents by thematic area

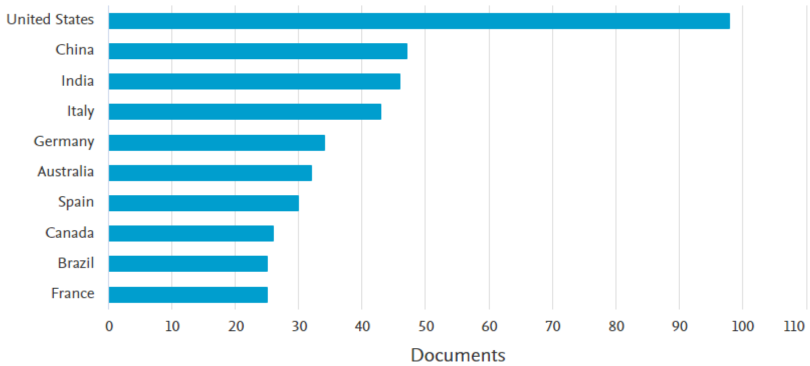

Figure 3. Countries that have publications related to aquifer pollution and their management

According to the analysis, a total of 78 countries have contributed to publications regarding aquifer contamination and management processes. Among these countries, 32 have met the criterion of publishing at least five documents in the last 10 years. Notably, the United States leads with 98 publications, followed by China with 47 and India with 46 publications. These countries not only have the highest publication output but also exhibit substantial collaboration in terms of joint publications. Figure 4 demonstrates the collaborative relationships, with Germany and Canada displaying strong publication ties with the United States.

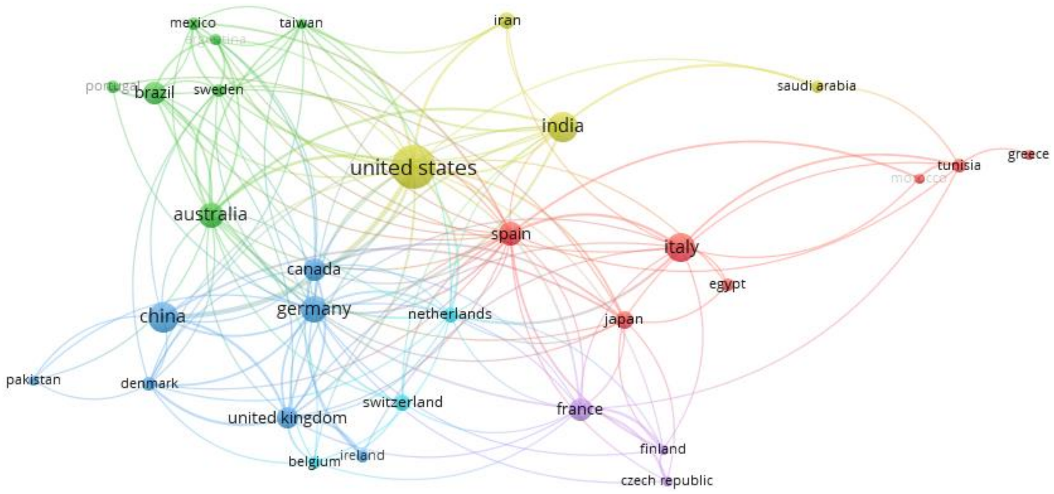

Figure 4. Collaboration of scientific production between countries

The results of the bibliometric networks against the co-occurrence of the key descriptors, allow us to identify that the trends related to the contamination of aquifers and their management are intertwined with citations related to groundwater, aquifers, quality, water quality, in addition to others such as Hydrochemistry, nitrates and aquifer pollution. A total of 5865 words were identified, considering a minimum keyword co-occurrence threshold of 10. This resulted in a selection of 298 words, which are presented in Figure 5.

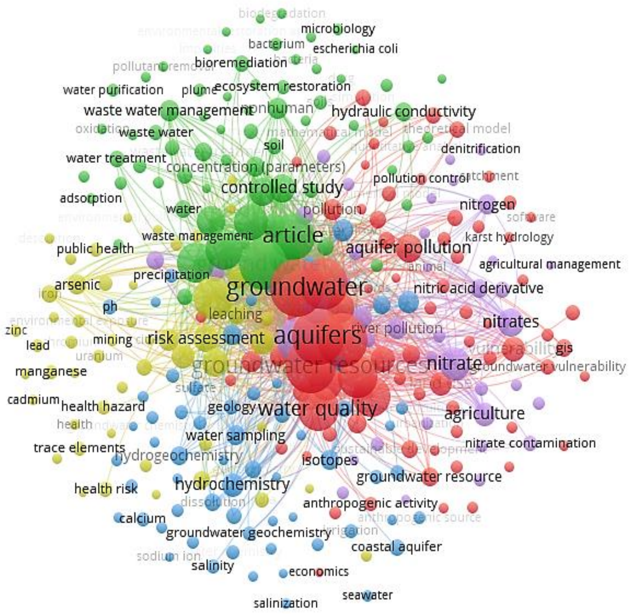

Figure 5. Key descriptors related to the risk of aquifer contamination

3.1. Research trends towards the factors that generate risk to the contamination of aquifers and the main models used

Faced with the analysis of the citations, it was observed that of 484 documents, 220 fulfill the function of having been cited at least 10 times, among which we find [4], who carried out the work called "Mapping the groundwater vulnerability for pollution at the pan African scale", where the DRASTIC method was used for the construction of a map at 1:60,000,000 scale which revealed that groundwater in Central and West Africa is highly vulnerable since the water table is very low, likewise, agricultural activities are quite influential in the contamination of the same ones, since they are shallow, in addition a sensitivity analysis was carried out that showed that the depth of the groundwater, the hydraulic conductivity and the net recharge generate significant changes in vulnerability and in the risk of contamination.

Another work of great importance is related to [5] in which an assessment of the risk of nitrates in groundwater was made using intrinsic vulnerability methods: a comparative study of the environmental impact of intensive agriculture in the Mediterranean region of Sicily, Italy, where it is stated that in recent years in Italy, the consumption of agrochemicals and manure has increased which has generated a higher contribution of nitrates, which has increased the contamination of both, surface and underground sources, for the study the method of parametric models IPNOA was used in addition it was combined with the method of intrinsic vulnerability of the aquifer (SINTACS and DRASTIC) to later take them to a geographic information system (GIS) process, where it was concluded that the SINTACS method is the most appropriate to build a relevant risk map. Other relevant research is Groundwater Residence Times and Nitrate Transport in Coastal Aquifer Systems: Daweijia Area, Northeast China, where CFC method were applied to make a relationship between the distribution of the average residence time of groundwater and nitrate transport, concluding that nitrates without denitrification process can accumulate for many years in water sources increasing pollution in a considerable way [6].

In the study entitled groundwater vulnerability assessment using DRASTIC and pesticide DRASTIC models in an area of intense agriculture in the Ganges Plains, India, seven parameters were considered: depth at water level, net recharge, aquifer material, soil material, topography, vadose zone impact and hydraulic conductivity, additionally we worked with the DRASTIC for which, land use was added, from a linear regression analysis it could be established that to measure the vulnerability of groundwater the best model is the DRASTIC Pesticide, and it was found that the most vulnerable areas are those whose land use is dedicated to the intensive cultivation of vegetables with intermediate urban areas [7].

In Colombia, the Technological University of Pereira-UTP conducted research in the municipality of Pereira based on the methodological approach to process-based risk management, taking strategic prospective planning as a complement. The risk was assessed based on the interaction between the intrinsic vulnerability of the aquifer, determined by the modified DRASTIC method (DRASTIC); and the anthropic threats assessed from six key aspects: Management of Groundwater sites, solid waste, wastewater, pollution by receiving surface sources, hydrocarbons and hazardous substances and agricultural production. The results showed that the highest values of pollution risk are associated with the spill of hydrocarbons (42.9%) and the inadequate disposal of wastewaters (38.2%). The development of the strategies was based on the management of water quality, within the results of threat and risk, being these ones, the aspects that can be intervened as they are not typical of the nature of the aquifer, but of anthropic actions [8].

Through a graduate thesis from the University of La Salle in the city of Bogotá, DRASTIC was implemented in order to define the areas of vulnerability of the it Guadalupe aquifer (Tenjo, Cundinamarca) particularly to pollution, developing a useful and reliable tool for an integral management of the resource that can be the basis in future land management plans [9]. For the aquifers of Funza, in the province of Cundinamarca, the degree of intrinsic vulnerability of the aquifer systems of the study area and the potential danger represented by anthropic activities that may affect the sustainability of groundwater were established, under the GOD and DRASTIC methodologies, the latter included the assessment by pesticides [10] The University of Sucre, jointly with the regional autonomous corporation of sucre (CARSUCRE), it elaborated the maps of intrinsic and specific vulnerability to pesticides of the Morroa aquifer through the DRASTIC parametric system where the geometry of the system was defined based on the variables of the method, through the Arcgis 9.2 software. The results are part of the basis of environmental management and a starting point for research aimed at protecting the aquifer against contamination by pesticides and other substances of special environmental care [11]. In a graduate thesis from the Catholic University of Colombia, a methodology based on the DRASTIC method was proposed, in order to evaluate the potential for groundwater contamination. Relevant adjustments were made for the hydro-geological characteristics of a country such as Colombia [12].

As it has been evidenced, there are different methods to assess the risk of pollution of aquifers, in the case of Costa Rica, a pollutant load map was developed in the northern sector of the Barva aquifer from the pollutant origin surcharge hydraulically (POSH) method, to later generate the pollution risk map. This method has been widely used in Spain, Brazil, Mexico and Argentina [13]. The threat of the aquifer by contamination is known from the identification and characterization of potentially polluting sources, of which the class, concentration, volume, mode of soil disposition and time of application of the pollutant load must be known, according to [14] in [13]. The land was divided into cells of 250* 250m, which were assigned the maximum value of pollutant load potential, distributed in high, moderate, reduced and null. The pollutant load is contributed by the human activities that are generated and that are exacerbated due to an inadequate urban, industrial and agricultural planning although there are guidelines and policies for land use planning [13], which is a constant in other countries.

Another concern of groundwater is the intrusion of seawater and nitrates, especially in those places where water is used for consumption. In places such as Tunisia (Africa), a study was developed to evaluate the presence of nitrates using hydro-geochemical tools, the electrical conductivity was also analyzed in order to identify the location of the main columns of intrusion of seawater and thus be able to delimit the groundwater for consumption. It is also stated that it is necessary to carry out the risk assessment of pollution in similar scenarios to carry out management processes [15].

Land use change and especially deforestation has brought with it significant impacts to aquifers, in the study conducted for the detection and prediction of the impact of land-use changes on groundwater quality, a case study in northern Kelantan, Malaysia, nitrate concentrations were used as an indicator to determine changes in land use and quality of groundwater, in addition, a geospatial modeling was carried out with which it was demonstrated that these concentrations increase significantly in agricultural wells over time, likewise, the self-regressive integrated moving average model (ARIMA) was used, in order to make the future projection of the behavior of nitrate pollution [16].

In Bangladesh, a concern is presented for the safety of drinking water for which an investigation was conducted in order to detect the quality of groundwater through physicochemical analyses and social surveys to determine the social perception against water for consumption, it resulted in an intrusion of salt water in the analyses, therefore, a potential influence of the salinization of groundwater, 100% of the samples showed that water is not suitable for drinking, complemented by the perception of the community against different diseases that have been generated by water pollution, making this study an input to generate sustainable water policies [17].

In Bangladesh, groundwater is commonly extracted through wells and is used for human consumption in arid and humid rural areas due to its availability. That is why it was necessary to develop a study that would allow to know the quality of the water from a number of considerable samples in different wells dug in the area, where specifically, nitrogen concentrations were measured, recognized for generating a risk to the health of the population, without neglecting that in Bangladesh a large number of victims are reported, due to arsenic contamination in groundwater [18].

One of the aspects that has generated the most contamination of aquifers has been drilling for exploration and exploitation of hydrocarbons, in this sense, a study entitled “A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States” was carried out. In which, from different case studies, four potential risks are identified: contamination of shallow aquifers by gas leaks, contamination by disposal of improperly treated shale gas wastewater, accumulation of toxic gases or sediments and excessive use of water for hydraulic fracturing [19], being this, the very document with the highest number of citations among those studied in this article with a total of 966 citations.

Another aspect that has generated water pollution has been Arsenic, present especially in countries with volcanic influence, such as those of Latin America, which is present in young rocks and it is generated by the oxidation of sulfated minerals that make the water have a high pH and generate imbalance in the quality of water for consumption, the study entitled: One Century of Arsenic Exposure in Latin America: A review of history reveals the risk of aquifer contamination by the presence of this mineral [20].

Another country concerned about the presence of arsenic has been India, where an investigation was made conducting geospatial interpolation of pollutants to identify poor sanitary practices in waste management, agricultural activities, industrial pollution, for such an evaluation the heavy metal contamination index was used, which was considered the best one to determine the risk to people’s health, likewise, it was identified that shallower waters had less heavy metals than more surface waters [21].

Organic compounds have become another main source of groundwater pollution, in the research entitled: “Synthetic organic compounds and their transformation products in groundwater: Occurrence, fate and mitigation”, it was made a compilation of different studies of the influence of organic compounds on groundwater, especially by pesticides, pharmaceutical products, industrial chemicals, organophosphates, likewise, the main challenges of managed groundwater, the injection and infiltration of recovered water and the filtration of the banks, in relation to the natural attenuation of organic micro-pollutants, are analyzed, and information is provided on the future chemical quality of groundwater [22].

In the Guanzhong river basin in China, an investigation was carried out to analyze the hydro-geochemical characteristics, hydro-chemical facies of groundwater and their formation mechanisms, assess the quality of groundwater for domestic use using the water quality indicator (WQI) and assess the non-carcinogenic risks of water consumption and forms of contact with the skin of men, women and children through the human health risk assessment model (HHRA) established by the united states environmental protection agency (USEPA). This study yielded essential information for the protection and management of local groundwater, which contributed to the sustainable development of drinking water in the area, generating a harmonious relationship between society and the environment. It was possible to determine the activities that were contributing pollutants to groundwater and the largest contributors of nitrogen and fluoride concentrations by the use of fertilizers [23].

In rural areas of Argentina, due to agricultural and livestock activities, nitrogen inputs to groundwater are also generated. In this case, the characteristics of groundwater quality in an unconfined aquifer in Argentina were studied, determining pollution by nitrogen concentrations, NO3 transformation processes and their relationship with different types of land uses, based on isotopic analysis and multivariate statistical analysis. This information was compared with the urban area, showing that in this one, pollution is more considerable than in the rural area, especially by the disposal of waste from sludge systems and animal pens [24]. A similar study was conducted in China, which included groundwater quality monitoring, isotope analysis, and the Markov chain monte Carlo (MCMC) model to determine the outflow amounts of riverine NO3 from four potential sources such as atmospheric deposition (AD), chemical nitrogen fertilizers (NF), soil nitrogen (SN) and manure and sludge [25].

In Sao Paulo – Brazil, an investigation has also been carried out on the state of aquifers, in which three indicators are proposed: (1) dependence on groundwater, (2) availability and (3) quality. The results showed that the dependence of the population on groundwater is high, specifically to the north, center and west of São Paulo since there is a great demand for the resource for different activities. As for availability, in some places there is overexploitation of the resource and in others, due to the population present, low availability for its distribution. Finally, groundwater quality is affected due to natural concentrations of chloride and fluoride and human activities in urban areas. However, quality is categorized as very good in a large portion of the territory [26].

In Argentina, specifically for intermediate cities, a Hazard Indicator (HI) was developed to identify the sources of groundwater contamination that need to be monitored and controlled frequently and to recognize the public supply wells that need to be treated. This was applied in Mar del Plata, south-east of the Province of Buenos Aires, Argentina. The proposed HI includes three variables: potential pollution discharge (PCL), effluent disposal mode (ED) and the distance between pollution sources and wastewater supply wells or well protection areas (WP) and three classes: low (10-18-green), moderate (9-30-yellow) and tall (31-50-red). As a result, underground fuel tanks and mines and quarries showed a high HI, as well as 2% of industries and 90% of industries and landfills presented the lowest Risk Indicator. The recommendations based on the results were based on two strategies: mitigation or prevention. Mitigation consists of reducing HI (passing from red to yellow) and preventing the migration of HI (from yellow to red and from green to yellow) [27].

In Tunisia, in the Souassi aquifer, groundwater risk was assessed using intrinsic vulnerability and threat maps and the DRASTIC indicator of the United States environmental protection agency (USEPA), which determines vulnerability through different variables such as groundwater depth (D), recharge I, saturated zone lithology (A), soil type (S), topography (T), impact of the vadose zone (I) and hydraulic conductivity (C). Additionally, the socioeconomic value of groundwater and indicators of weakness/resistance to the threat of pollution, such as age, the state of facilities and their interaction with population growth, were considered in the research. It was concluded that maps are an appropriate spatial tool for decision-making at a local scale and are the most appropriate to guide risk management and analysis [28].

In Yucatán Mexico, a study was also conducted to analyze the risk of groundwater contamination from the interaction between surface pollutant loads and the vulnerability of the aquifer due to its high permeability. For the risk analysis, an inventory of the polluting sources was carried out and with the help of geographic information systems (GIS) and the method called European cooperation in science and technology (COST) action 620 Group, the danger rates were calculated. This method yielded adequate results for the research and allowed easy and low-cost mapping and risk assessment. The vulnerability was modeled with the depth, recharge, soil, topography, Impact, land use (DRSTIL) index which is a modification of the DRASTIC index, mentioned in an earlier case. For this study, D is the depth of the water, R the recharge, S the soil, T the topography, I the impact of the vadose zone and L the land use. The vulnerability classification coincided with land use, slope, soil type, topography, and depth of the water table, as well as with urban activities, which drastically affect dangerousness [29].

In the Ecuadorian Amazon basin, a study was carried out to evaluate the risk of aquifer contamination from the overlapping of vulnerability maps using the GOD method [1] and pollutant loads applying the POSH method, to prioritize water resource protection zones. Pollutant loads are identified according to the origin of the pollutant and the increase of natural water to the aquifer [30]. In the GODS method, G corresponds to the degree of hydraulic confinement, O is the attenuation capacity of the contaminant due to the substrate, depending on the soil parameters, D is related to the depth of the groundwater or aquifer top for the confined and S indicates the form of attenuation of the pollutant and its removal according to the amount of organic matter [1]. Vulnerability was categorized as null, negligible, low, medium, high, and extreme [30].

As it can be seen from this international count, different methods and instruments have been used depending on the need and purpose of the study. In these cases, samplings have been used to determine groundwater quality according to its physicochemical parameters, the pollutant loads, and their potential are identified from the POSH method and the vulnerability of aquifers to pollution by the GOD method and its variations, geographic information systems, among others. All the studies seek to generate valuable information to facilitate the decision-making of the involved participants in the territories aimed at the conservation of the underground water resource, which supplies communities in urban and rural areas.

3.2. Research trends in the management of risk to aquifer pollution

Water pollution management is limited given the scarce economic resources that are used for this purpose, therefore there are some simple alternatives to assess the threat of groundwater, in the work of [31], a tool of five different models representing common geological environments, polluting routes and transport processes is proposed, this is done in order to prioritize sites that require more immediate intervention. The tool is based on semi-analytical stationary state models that simulate different pollutant transport scenarios.

In the Mediterranean, groundwater is analyzed for management and protection, especially in coastal ecosystems dependent on groundwater. A study was made from a trans-disciplinary approach among hydrology, hydrogeology, social sciences, and the fundamental right to understand the socio-economic and environmental complexity of ecosystems dependent on groundwater, it is proposed that collective management is necessary to promote the efficient use of water and reduce its conflicts [32].

Aquifer management has been approached from the perspective of sustainability, this is how the study entitled: "Towards sustainable groundwater use: setting long-term goals, back casting, and managing adaptively" , three approaches are proposed: multigenerational, back casting, and managing adaptively, the first one refers to long-term management, the second one to immediate action from public policies and the third one refers to the capacity of resilience to meet long-term objectives, This research proposes that these approaches can achieve the sustainability of aquifers while generating resilience in adjacent ecosystems [33].

Other experiences with the management of water resources have been carried out through models, such as the study for hydro-environmental management of water resources: a diffuse-based multi-objective commitment approach, where a diffuse model for the sustainability of groundwater was designed, based on

MODFLOW and MT3D models that are qualitative and quantitative simulation models and whose objective was to formulate socio-optimal and sustainable policies for hydro-environmental management, as well as the analysis of the uncertainties of conflicts around groundwater quality, finally, the best management method is the fuzzy social choice (FSC) which is used to consider a commitment of everybody for all solutions [34]. Another trend for groundwater management is in the collaborative models or models of participation of water resources used in different scenarios for decision-making [35].

Biodegradation is one of the most sustainable methods used for aquifer management and decontamination, the study entitled “Biodegradation: Updating the Concepts of Control for Microbial Cleanup in Contaminated Aquifers” presents an important review of classical concepts such as redox thermodynamic zoning or the use of stationary state transport scenarios to assess rates of biodegradation, This study proposes some perspectives for biodegradation, some of these solutions are based on the control of the plume fringe and transport times [36].

Another bio-remediation work was entitled “Assessment of groundwater quality and remediation in karst aquifers: a review”, where bio- remediation models were determined combined with remote sensing tools for the analysis of different ways of approaching of aquifer pollution ,it presents an overview of hydro-geological processes and concepts related to groundwater flow, transport of pollutants in karst systems, followed by a brief discussion on the interaction of surface and groundwater to propose the aquifer pollution management process [37].

In a semi-arid basin of Brazil, a study was carried out to prioritize the areas that required actions to mitigate and monitor pollution by decision makers and involved participants, who develop public policies for the planning and management of groundwater from the generation of water quality indicator and multivariate statistical analysis to analyze parameters in groundwater; in addition, geographic information systems (GIS) were used to construct geospatial behavior maps to evaluate hydro-geochemical variables [38]. GIS is a commonly used tool to complement isotopic, statistical and groundwater quality parameter studies; as in Brazil, they were also used in the upper Blue Nile basin [39] and in the Modjo basin in Ethiopia [40]. Figure 6 displays the most cited authors and documents in the field of aquifer pollution risk.

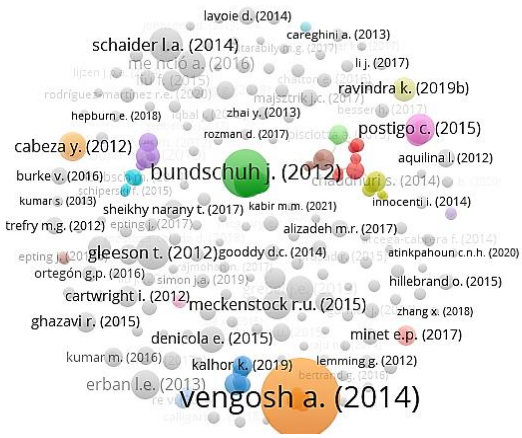

Figure 6. Authors and most cited documents at risk of aquifer contamination and management processes

3.3. Analysis of the most relevant authors and index of collaboration among authors

With R software, the collaboration rate among authors was determined is 4.47, the number of co-authors per document is 4.77, the documents per author is 0.23, the total number of authors in the 484 documents is 2047 authors, Likewise, according to the analysis Lotka’s law, 90% of authors produce a single article, while 0.5% produce four articles. In comparison to the yearly scientific production, there has been a significant growth in recent years. Particularly, 2021 witnessed a notable increase with a total of 74 publications. From 2012 to 2014, there was an increment from 34 to 55 publications, followed by a decrease in 2016 to 34 publications once again. However, from 2018 to 2021, there has been a significant upward trend. Despite the global impact of the COVID-19 pandemic, research and scientific output continued to rise. The most prominent authors in the field of aquifer pollution risk can be found in Figure 7.

The publications of the first authors have been oriented towards measuring stress or impact factors that generate stress in aquifers. The first author has participated in cooperation with others [41], for the development of research entitled “Identification of the long-term variations of groundwater and their governing factors based on hydro-chemical and isotopic data in a river basin”. In this study, the spatio-temporal variations of the hydro-chemical characteristics of groundwater were discriminated based on the results of grouping self-organized maps (SOM) From 2001 to 2017, hydrogen and oxygen variations were also studied in a hydro-chemical facies evolution diagram (HFE-D). This study resulted in articulated self-organized maps (SOM) with stable isotope analysis, the HFE diagram, and correlation analysis could be used successfully to interpret high-dimension, non-linear multivariate systems and provide information on the mechanisms that control groundwater evolution.

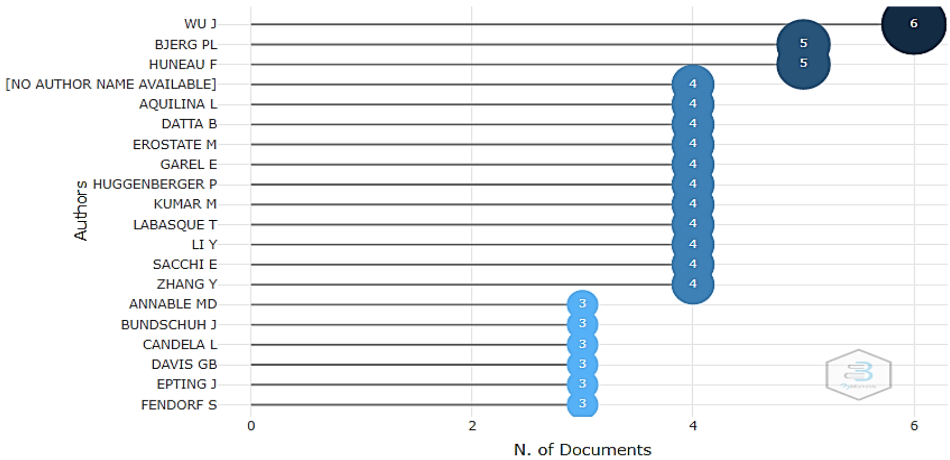

Figure 7. Most relevant authors on the risk of aquifer contamination

Another study by this author, co-authored with others, is entitled “Effect of groundwater quality on the sustainability of water resources: a case study in the Northern China Plain” [42], in which the authors focus on approaching the implications of pollutants for sustainability, a modular reaction code for reactive transport in three-dimensional aquifers (RT3D) was developed in order to simulate the reactive process of transporting nitrogen species into the groundwater system. Subsequently, the management optimization model was made together with the reactive nitrogen transport model considering the limitations of water quality to quantify and improve the sustainability of groundwater utilization in the study area.

As for the second author Bjerg highlights the publication entitled “Linking ecological health to co-occurring organic and inorganic chemical stressors in a groundwater-fed stream system” with other authors [43], where indications of the ecological consequences of the interaction of organic and inorganic chemical stress factors are presented, which are not normally evaluated together, which may provide a missing link that allows the reconnection of chemical and ecological findings, benthic meio-invertebrates were found to be promising bio-indicators of groundwater pollution.

Another research of Bjerg in cooperation with other authors has been entitled “Assessing the chemical contamination dynamics in a mixed land use stream system”, where the impacts on groundwater caused by stress factors are assessed, using three methods: i) massive discharge of pollutants into the stream for source quantification, ii) toxic units, and iii) environmental standards, in this research it was observed that the biggest pollutants came from pharmaceuticals [44].

One of the most recent articles is entitled “Shallow urban aquifers under hyper-recharge equatorial conditions and strong anthropogenic constrains. Implications in terms of groundwater resources potential and integrated water resources management strategies”. By the third author who appears in the above graph in co-authorship with other researchers [45] in which the water recharge rate was calculated through water balance and water table fluctuation methods, infiltration and groundwater flow conditions were also examined by combining hydro-geological and isotopic methods.

On the other hand, compared to the three-fields plot analysis and considering the fields of journals, authors and affiliations, it can be observed that the journal that has the highest number of publications is “Science of the total environment”, in which authors such as Huneau F have published, Garel E, Erostate, Huggenberger P, Aquilina, Labasque T, the main affiliation of the authors is from Université de Corse Pascal Paoli, Likewise, one of the authors who has worked the most study topic has been Wu J who has two affiliations Nanjing University and Technical University of Denmark, However, the journal where this author’s publications are mainly reported is “Journal of Contaminant Hydrology”.

Figure 8 displays the three-field analysis, which establishes the existing relationships between journals, authors, and universities. Thicker lines indicate stronger interconnections. It can be observed that the

University of Corsica Pascal Paoli maintains close relationships with various authors and journals, particularly with the science of the total environment.

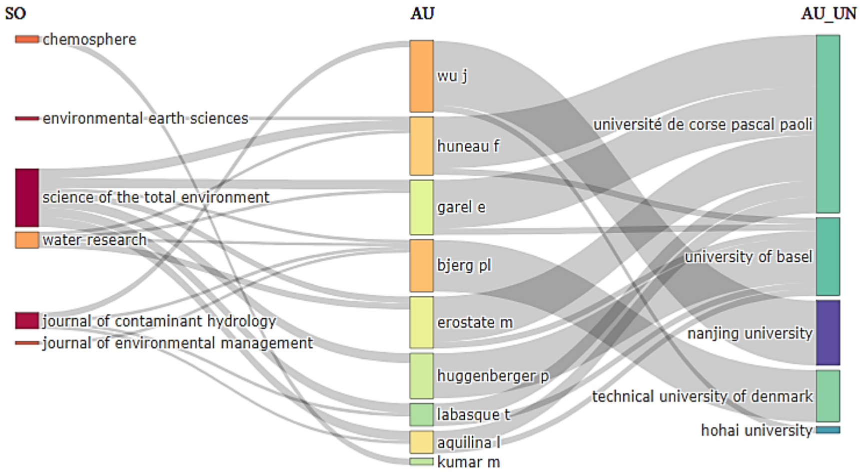

Figure 8. Analysis Three-fields plot

3.4. Knowledge gaps in the face of risks of wastewater pollution

It is necessary to consider a holistic approach to linking hydrogeology and eco-toxicology to positively influence the sustainable management of water resources at global level. New approaches are urgently needed to identify sources, pathways, and potential impacts relevant to the implementation of remedial measures and management of appropriate sources, further ecological and chemical analyses are needed for the study of underground sources. The publications emphasize that future research should include multiple compounds and compartments of currents and highlight the need for holistic approaches when assessing the risk of these dynamic systems. There are gaps in research regarding long-term management processes to avoid the risk of aquifer contamination.

The analysis of aquifer pollution has been more focused on the measurement of physical-chemical parameters, it is necessary to analyze different bio-indicators that allow generating a more comprehensive knowledge of the risk of water pollution, Likewise, there are gaps in knowledge regarding the behavior of pollutants over time, in few situations, it has got a retrospective of the status of aquifers in the past to make comparisons of what happens in the present. Another aspect related to gaps in scientific research regarding aquifers is the relationship of climate change with them, in the study "impacts of climate change on groundwater and dependent ecosystems" it is shown that there is uncertainty especially in management techniques and numerical modeling to understand this relationship [46]. The need for research into organic pollutants is also highlighted in the study entitled "Organic contaminants in African aquatic systems: Current knowledge, health risks, and future research directions" is mentioned the need to deepen research where it is necessary to deepen the reservoirs of critical points of CO, behavior and environmental fate, eco-toxicology, epidemiology, and interventions to minimize health risks [47]. The study "Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs" mentions that problems of access to water and sanitation need to be addressed within the framework of the United Nations Sustainable Development Goals by 2030 [48]. More comprehensive research of advanced statistical methods associated with the analysis of geospatial technologies is required to know the status of groundwater pollution [49].

4. CONCLUSION

Much of the research on groundwater pollution has been focused on those that have influence of sea water by intrusion of the same to fresh groundwater. Multidisciplinary and trans-disciplinary research between the hard sciences and the social sciences has been necessary to help generate management proposals for addressing groundwater pollution, that is, the social component from the perceptions and from the fundamental right must be incorporated in the processes of pollution management of water sources. One of the most important aspects of groundwater pollution has been drillings for hydrocarbons, nitrate concentrations due to agricultural systems and the presence of arsenic, which in some countries is high because it is mobilized from young volcanic rocks, and by the action of Sulphur-bearing minerals, Latin America is one of the most affected regions by this process.

The DRASTIC method is one of the most used for the analysis of the risk of water pollution which consists in considering for modeling different parameters such as net recharge, aquifer media, soil media, vadose zone impact and hydraulic conductivity. Some management models have been used to propose possible solutions to the risk of aquifer contamination, in which the most important thing has been the involvement of society in the process, some better-behaved used has been the fuzzy social choice. Other models for the management of aquifer pollution are the establishment of natural background levels (NBL) and threshold values (TV), which could be used as a reference for porous aquifers subject to a large amount of rain and become the basis for decision-making and planning against them.

The most current trends in aquifer research are related to the development of strategies and policies that promote the conservation, recharge, and efficient use of groundwater. Advanced monitoring and modeling: Advances in sensor technology, remote sensing, and computational modeling are enhancing the ability to monitor and understand aquifers. Researchers are using real-time data to develop accurate models that can predict aquifer behavior and make informed decisions regarding their management.

Surface-water groundwater interactions: there is a growing interest in understanding the interactions between surface water and groundwater, as they are closely interconnected. Studies investigate how human activities, such as irrigation or water extraction, affect the quality and quantity of water in both systems, and how to mitigate negative impacts. Treatment and remediation technologies: with the increasing concern over groundwater pollution, research is focused on the development of effective treatment and remediation technologies. Advanced purification methods and in-situ remediation techniques are being explored to address aquifer contamination.

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REFERENCES

[1] S. R. D. M. M. Foster, “Groundwater quality protection : a guide for water utilities, municipal authorities, and environment agencies,” pp. 1–114, *Washington, DC: World Bank*, 2002.
[2] L. C. Candelo and J. S. Díaz, “El Tesoro Enterrado De Candelaria : Sus Aguas Subterráneas,” *Territorio y Medio ambiente*, 2017.
[3] V. Henao-Céspedes, G. Y. Florez, and Y. A. Garcés-Gómez, “The internet of things in high andean wetland monitoring, historical review approach,” *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 3, pp. 1572–1579, 2021, doi: 10.11591/eei.v10i3.2653.
[4] I. Ouedraogo, P. Defourny, and M. Vanclooster, “Mapping the groundwater vulnerability for pollution at the pan African scale,” *Science of the Total Environment*, vol. 544, pp. 939–953, 2016, doi: 10.1016/j.scitotenv.2015.11.135.
[5] A. Pisciotta, G. Cusimano, and R. Favara, “Groundwater nitrate risk assessment using intrinsic vulnerability methods: A comparative study of environmental impact by intensive farming in the Mediterranean region of Sicily, Italy,” *Journal of Geochemical Exploration*, vol. 156, pp. 89–100, 2015, doi: 10.1016/j.gexplo.2015.05.002.
[6] D. Han, G. Cao, J. McCallum, and X. Song, “Residence times of groundwater and nitrate transport in coastal aquifer systems: Daweijia area, northeastern China,” *Science of the Total Environment*, vol. 538, pp. 539–554, 2015, doi: 10.1016/j.scitotenv.2015.08.036.
[7] D. Saha and F. Alam, “Groundwater vulnerability assessment using DRASTIC and Pesticide DRASTIC models in intense agriculture area of the Gangetic plains, India,” *Environmental Monitoring and Assessment*, vol. 186, no. 12, pp. 8741–8763, Dec. 2014, doi: 10.1007/s10661-014-4041-x.
[8] D. Agudelo and L. Sepulveda, “Gestión Del Riesgo a La Contaminación Del Acuífero En La Zona De Expansión Occidental Del Municipio De Pereira, Risaralda,” *Universidad Tecnológica de Pereira*, no. 1, p. 43, 2017.
[9] P. Gómez, “Evaluación de la vulnerabilidad hidrogeológica del acuífero Guadalupe en Tenjo Cundinamarca, con la implementación del modelo Drastic,” *Universidad de la Salle*, Bagota, 2017.
[10] L. M. B. Vallejo, “Análisis De Vulnerabilidad a La Contaminación De Los Acuíferos En El Municipio De Funza, Cundinamarca,” *Universidad Católica de Colombia*, 2015.
[11] V. Vergara, G. Gutierrez, and H. Flórez, “Vulnerability assessment to pesticides contamination via DRASTIC method in the Morroa aquifer,” *Ingeniería y Desarrollo*, vol. 26, pp. 51–64, 2009.
[12] F. Vasquez, “Propuesta metodológica para la evaluación del potencial de contaminación de aguas subterráneas en colombia, a partir del método drastic,” *Universidad Católica de Colombia*, 2017.
[13] H. Madrigal, A. Fonseca, C. Núñez, and A. Gómez, “Amenaza de contaminación del agua subterránea en el sector norte del acuífero Barva, Heredia, Costa Rica,” *Tecnología y Ciencias del Agua*, vol. V, no. 6, pp. 103–118, 2014.
[14] R. Hirata, “Carga Contaminante Y Peligros a Las Aguas Subterráneas,” *Latino-america de Hidrogeologia*, vol. 2, no. 0, pp. 81-90, 2002, doi: 10.5380/hg.v2i0.2624.
[15] A. Zghibi, J. Tarhouni, and L. Zouhri, “Assessment of seawater intrusion and nitrate contamination on the groundwater quality in the Korba coastal plain of Cap-Bon (North-east of Tunisia),” *Journal of African Earth Sciences*, vol. 87, pp. 1–12, 2013, doi: 10.1016/j.jafrearsci.2013.07.009.
[16] T. Sheikhy Narany, A. Z. Aris, A. Sefie, and S. Keesstra, “Detecting and predicting the impact of land use changes on groundwater quality, a case study in Northern Kelantan, Malaysia,” *Science of The Total Environment*, vol. 599–600, pp. 844–853, Dec. 2017, doi: 10.1016/j.scitotenv.2017.04.171.
[17] M. A. Rakib *et al.*, “Groundwater salinization and associated co-contamination risk increase severe drinking water vulnerabilities in the southwestern coast of Bangladesh,” *Chemosphere*, vol. 246, p. 125646, May 2020, doi: 10.1016/j.chemosphere.2019.125646.

[18] M. A. Akber, M. A. Islam, M. Dutta, S. M. Billah, and M. A. Islam, "Nitrate contamination of water in dug wells and associated health risks of rural communities in southwest Bangladesh," *Environmental Monitoring and Assessment*, vol. 192, no. 3, pp. 1-12, 2020, doi: 10.1007/s10661-020-8128-2.

[19] A. Vengosh, R. B. Jackson, N. Warner, T. H. Darrah, and A. Kondash, "A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States," *Environmental Science & Technology Online Supplemental Information*, vol. 48, no. 15, pp. 8334–8348, 2014, doi: https://doi.org/10.1021/es405118y.

[20] J. Bundschuh *et al.*, "One century of arsenic exposure in Latin America: A review of history and occurrence from 14 countries," *Science of The Total Environment*, vol. 429, pp. 2–35, 2012, doi: 10.1016/j.scitotenv.2011.06.024.

[21] K. Ravindra and S. Mor, "Distribution and health risk assessment of arsenic and selected heavy metals in Groundwater of Chandigarh, India," *Environmental Pollution*, vol. 250, pp. 820-830, 2019, doi: 10.1016/j.envpol.2019.03.080.

[22] C. Postigo and D. Barceló, "Synthetic organic compounds and their transformation products in groundwater: Occurrence, fate and mitigation," *Science of The Total Environment*, vol. 503–504, pp. 32–47, 2015, doi: 10.1016/j.scitotenv.2014.06.019.

[23] Q. Zhang, P. Xu, and H. Qian, "Groundwater Quality Assessment Using Improved Water Quality Index (WQI) and Human Health Risk (HHR) Evaluation in a Semi-arid Region of Northwest China," *Exposure and Health*, vol. 12, no. 3, pp. 487–500, 2020, doi: 10.1007/s12403-020-00345-w.

[24] M. Blarasin *et al.*, "Comparative evaluation of urban versus agricultural nitrate sources and sinks in an unconfined aquifer by isotopic and multivariate analyses," *Science of The Total Environment*, vol. 741, p. 140374, 2020, doi: 10.1016/j.scitotenv.2020.140374.

[25] X. Ji, R. Xie, Y. Hao, and J. Lu, "Quantitative identification of nitrate pollution sources and uncertainty analysis based on dual isotope approach in an agricultural watershed," *Environmental Pollution*, vol. 229, pp. 586–594, 2017, doi: 10.1016/j.envpol.2017.06.100.

[26] R. Hirata, A. Suhogusoff, and A. Fernandes, "Groundwater resources in the State of São Paulo (Brazil)," *Anais da Academia Brasileira de Ciências*, vol. 79, no. 1, pp. 141–152, 2007.

[27] A. Barilari, M. Quiroz Londoño, M. del C. Paris, M. L. Lima, and H. E. Massone, "Groundwater contamination from point sources. A hazard index to protect water supply wells in intermediate cities," *Groundwater for Sustainable Development*, vol. 10, p. 100363, Apr. 2020, doi: 10.1016/j.gsd.2020.100363.

[28] S. Saidi, S. Bouri, H. Ben Dhia, and B. Anselme, "Assessment of groundwater risk using intrinsic vulnerability and hazard mapping: Application to Souassi aquifer, Tunisian Sahel," *Agricultural Water Management*, vol. 98, no. 10, pp. 1671–1682, 2011, doi: 10.1016/j.agwat.2011.06.005.

[29] R. A. G. Herrera, B. S. I. A. Euán, I. A. Sánchez y Pinto, and J. H. O. Rodríguez, "El Acuífero Yucateco. Análisis Del Riesgo De Contaminación Con Apoyo De Un Sistema De Información Geográfica," *Revista Internacional de Contaminación Ambiental*, vol. 34, no. 4, pp. 667–683, 2018, doi: 10.20937/rica.2018.34.04.09.

[30] A. E. Jarrín, J. G. Salazar, and M. M.-F. Mestre, "Evaluación del riesgo a la contaminación de los acuíferos de la Reserva Biológica de Limoncocha, Amazonía Ecuatoriana," *Revista Ambiente e Agua*, vol. 12, no. 4, pp. 652–665, 2017.

[31] L. Locatelli, P. J. Binning, X. Sanchez-Vila, G. L. Søndergaard, L. Rosenberg, and P. L. Bjerg, "A simple contaminant fate and transport modelling tool for management and risk assessment of groundwater pollution from contaminated sites," *Journal of Contaminant Hydrology*, vol. 221, pp. 35–49, 2019, doi: 10.1016/j.jconhyd.2018.11.002.

[32] M. Erostate *et al.*, "Groundwater dependent ecosystems in coastal Mediterranean regions: Characterization, challenges and management for their protection," *Water Research*, vol. 172, p. 115461, 2020, doi: 10.1016/j.watres.2019.115461.

[33] T. Gleeson *et al.*, "Towards sustainable groundwater use: Setting long-term goals, backcasting, and managing adaptively," *Ground Water*, vol. 50, no. 1, pp. 19–26, 2012, doi: 10.1111/j.1745-6584.2011.00825.x.

[34] M. R. Alizadeh, M. R. Nikoo, and G. R. Rakhshandehroo, "Hydro-environmental management of groundwater resources: A fuzzy-based multi-objective compromise approach," *Journal of Hydrology*, vol. 551, pp. 540–554, 2017, doi: 10.1016/j.jhydrol.2017.06.011.

[35] L. Basco-Carrera, A. Warren, E. van Beek, A. Jonoski, and A. Giardino, "Collaborative modelling or participatory modelling? A framework for water resources management," *Environmental Modelling & Software*, vol. 91, pp. 95–110, 2017, doi: 10.1016/j.envsoft.2017.01.014.

[36] R. U. Meckenstock *et al.*, "Biodegradation: Updating the Concepts of Control for Microbial Cleanup in Contaminated Aquifers," *Environmental Science & Technology*, vol. 49, no. 12, pp. 7073–7081, 2015, doi: 10.1021/acs.est.5b00715.

[37] K. Kalhor, R. Ghasemizadeh, L. Rajic, and A. Alshawabkeh, "Assessment of groundwater quality and remediation in karst aquifers: A review," *Groundwater for Sustainable Development*, vol. 8, pp. 104–121, 2019, doi: 10.1016/j.gsd.2018.10.004.

[38] M. I. Silva *et al.*, "Assessment of groundwater quality in a Brazilian semiarid basin using an integration of GIS, water quality index and multivariate statistical techniques," *Journal of Hydrology*, vol. 598, p. 126346, 2021, doi: 10.1016/j.jhydrol.2021.126346.

[39] A. K. Tefera *et al.*, "Groundwater quality evaluation of the alluvial aquifers using GIS and water quality indices in the Upper Blue Nile Basin, Ethiopia," *Groundwater for Sustainable Development*, vol. 14, p. 100636, Aug. 2021, doi: 10.1016/j.gsd.2021.100636.

[40] N. S. Kawo and S. Karuppannan, "Groundwater quality assessment using water quality index and GIS technique in Modjo River Basin, central Ethiopia," *Journal of African Earth Sciences*, vol. 147, pp. 300–311, 2018, doi: 10.1016/j.jafrearsci.2018.06.034.

[41] Z. Yin, Q. Luo, J. Wu, S. Xu, and J. Wu, "Identification of the long-term variations of groundwater and their governing factors based on hydrochemical and isotopic data in a river basin," *Journal of Hydrology*, vol. 592, p. 125604, 2021, doi: 10.1016/j.jhydrol.2020.125604.

[42] M. Wu, J. Wu, J. Liu, J. Wu, and C. Zheng, "Effect of groundwater quality on sustainability of groundwater resource: A case study in the North China Plain," *Journal of Contaminant Hydrology*, vol. 179, pp. 132–147, 2015, doi: 10.1016/j.jconhyd.2015.06.001.

[43] A. T. Sonne, J. J. Rasmussen, S. Höss, W. Traunspurger, P. L. Bjerg, and U. S. McKnight, "Linking ecological health to co-occurring organic and inorganic chemical stressors in a groundwater-fed stream system," *Science of The Total Environment*, vol. 642, pp. 1153–1162, 2018, doi: 10.1016/j.scitotenv.2018.06.119.

[44] A. T. Sonne, U. S. McKnight, V. Rønde, and P. L. Bjerg, "Assessing the chemical contamination dynamics in a mixed land use stream system," *Water Research*, vol. 125, pp. 141–151, 2017, doi: 10.1016/j.watres.2017.08.031.

[45] B. Nlend, H. Celle-Jeanton, F. Huneau, E. Garel, S. N. Boum-Nkot, and J. Etame, "Shallow urban aquifers under hyper-recharge equatorial conditions and strong anthropogenic constrains. Implications in terms of groundwater resources potential and integrated water resources management strategies," *Science of The Total Environment*, vol. 757, p. 143887, Feb. 2021, doi: 10.1016/j.scitotenv.2020.143887.

[46] B. Kløve *et al.*, "Climate change impacts on groundwater and dependent ecosystems," *Journal of Hydrology*, vol. 518, pp. 250–266, 2014, doi: 10.1016/j.jhydrol.2013.06.037.

[47] W. Gwenzi and N. Chaukura, "Organic contaminants in African aquatic systems: Current knowledge, health risks, and future research directions," *Science of The Total Environment*, vol. 619–620, pp. 1493–1514, 2018, doi: 10.1016/j.scitotenv.2017.11.121.

[48] A. D. Werner, H. K. Sharp, S. C. Galvis, V. E. A. Post, and P. Sinclair, "Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs," *Journal of Hydrology*, vol. 551, pp. 819–844, Aug. 2017, doi: 10.1016/j.jhydrol.2017.02.047.

[49] D. Machiwal, V. Cloutier, C. Güler, and N. Kazakis, "A review of GIS-integrated statistical techniques for groundwater quality evaluation and protection," *Environmental Earth Sciences*, vol. 77, no. 19, pp. 1-30, 2018, doi: 10.1007/s12665-018-7872-x.

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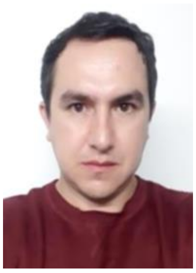

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