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Review

A Systematic Review of the Current State of Numerical Groundwater Modeling in Latin American Countries: Challenges and Future Research

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Abstract: In arid and semi-arid regions, groundwater is often the only available source of water. However, overexploitation and pollution have led to a decrease in both the quantity and quality of groundwater. Therefore, proper management of groundwater resources is essential to promote sustainable development. Numerical simulation has emerged as a valuable tool to address these challenges due to its ability to accurately and efficiently model groundwater systems. This systematic review aims to evaluate the current knowledge on the use of numerical groundwater flow models for planning and water resources management in Latin American countries. A total of 166 research articles published between years 2000 and 2024. We analyzed, summarizing details as: the study regions, numerical simulation methods and software, performance metrics, modeling units, modeling limitations, and prediction scenarios. In addition, we discuss alternatives to address the constraints and difficulties and suggests recommendations for future research. Continued research, improvement and development of numerical groundwater models is essential to ensure the sustainability of groundwater resources.

Keywords: FEFLOW, flow simulation, forecasting, groundwater, latin america, MODFLOW, numerical modeling

1. Introduction

Groundwater is an essential resource, especially in arid and semiarid areas with shortage of surface. In these areas groundwater is the main supply for different economical purposes such as: industry, agriculture, and domestic consumption [1,2]. Agriculture consumes about 70% of the global of water supplies, while the remaining 30% is attributed to industrial and domestic consumption [3,4]. The present-day global water demand for is 4,600 km^3 per year and it is estimated that will increase by 20% to 30% by 2050 and up to 5,500 to 6,000 km^3 per year [5]. The increase in water needs is attributed to the accelerated population growth and expansion of irrigated agriculture [6–8]. It is estimated that water deficit will reach 35% and 45% of the population needs by 2030 and 2050 respectively [9–11].

Global climate change and variations in the hydrological cycle are exacerbating this problem, creating complex scenarios that worsen the challenges related to estimate groundwater quantity, quality, and availability [6,7]. In recent years, aquifer systems have faced a critical level of stress due to both climatic and anthropogenic factors [12]. The Intergovernmental Panel on Climate Change

(IPCC) predicts that the global average surface temperature will rise from 2 to 4 °C by the end of this century [13,14]. This increase of temperature in the global climate poses a threat to groundwater recharge in aquifers and the availability of surface water. Cuthbert et al. [7] report that 44% of aquifers worldwide will be affected by climate change.

More than 35% of global water resources are contained within Latin America territories [15]. However, some regions still face significant challenges related to groundwater availability and management. Mexico and other Latin American countries as Canada, United States, Brazil, Argentina, Chile, Bolivia and Peru are increasingly dependent on groundwater resources, especially in arid or semi-arid regions [16,17]. Canada and the United States have significant groundwater resources, utilizing approximately 23% of available water. In South America, between 40% and 60% of available water is utilized, while in Central America and Mexico, this figure reaches 65% [17,18]. For example, in Mexico, 111 of the 653 aquifers have been declared as overexploited [19]. Due to a continuous population growth and demand for water, combined with change in land use, Latin America is facing challenging issues related to the overexploitation of groundwater resources.

Hydrogeological systems are vulnerable to overexploitation and contamination, particularly in arid and semi-arid areas, due to inadequate water management accomplishing a serious threat to their sustainability. Depletion of piezometric levels, seawater intrusion, soil salinization, land subsidence and ecosystem degradation are as a result of overexploitation in hydrogeological systems [20,21]. This issues related to overexploitation of groundwater have been exacerbated by an imbalance between supply and demand, which is worsened by the impacts of climate change and population growth [3,20,22]. In Latin America the 25% of the population inhabits in water-stressed regions, mostly in cities in countries along the west coast of the continent [17]. In these areas, groundwater can be the unique source of water. Therefore, it is crucial to accurately measure the current water volume and future water availability.

Due to the severity of the current hydrological stress situation in arid and semiarid areas it is important to carry out a systematic planning of groundwater management to assure a sustainable supply. Providing reliable estimates of available groundwater is essential for an efficient use of the groundwater resources and to mitigate future conflicts [8]. Thus, numerical simulation tools (NST) are powerful tools that provide information for remediation and sustainable groundwater management [23–25]. NST simplify complex hydrogeological systems making it easier to investigate specific phenomena or forecast future groundwater and aquifer behavior. However, the challenge is to simplify reality without compromising the accuracy or the ability of the model to achieve it's objectives [24,26]. In last years, groundwater models have become essential tools for assessing, developing, and water resources management. These models are useful because they can simulate both groundwater quantity and quality using holistic and multidisciplinary approaches. They can also project various conditions and analyze future management and prediction scenarios [1,2,11,27,28]. With massive increase in computational power and vast availability model software, numerical models have proven to be useful and essential tools for management of water resources and addressing challenges such as climate change, overexploitation, land use changes, and urbanization and additionally being helpful to the understanding of the complex hydrological and geochemical processes of aquifers. Therefore, it is important to make a review of the actual and available scientific literature to understand the current state of art and to propose future research opportunities in this field of study.

This study provides a comprehensive systematic review of research on numerical groundwater flow modeling, with a focus on it's application in water resources planning and management in Latin America from 2000 to February 2024. In this work we consider several key research questions, such as: what are the most commonly used software in numerical groundwater flow modeling? Is numerical modeling an effective tool for water supply and demand planning and management? Can it predict the future impacts of climatic and anthropogenic factors? Does it contribute to promoting groundwater resource sustainability? This systematic review is organized as follows: Section 2 details the methods used for the systematic review, research design, and literature selection process. Section 3 presents the results obtained and discussion. Section 4 addresses the identified challenges and suggests possible directions for future research. Finally, Section 5 presents the main conclusions derived from this review.

2. Materials and Methods

2.1. Methodology

A systematic literature review (SLR) was conducted to analyze numerical modeling of groundwater flow for groundwater resources planning and management. The SLR was performed using the methodology proposed by De León Pérez et al. [29], which combines the guidelines outlined by Nguyen & Singh [30] and Kitchenham [31] with the steps suggested by Muka et al. [32]. This method synthesizes all available literature on a given topic or field of research, providing a structured and objective approach that improves the quality and reliability of the information obtained. It also helps to identify important insights, research gaps, and future research topics [33–35]. The methodology developed in this systematic review is displayed in the flowchart shown in Figure 1. Figure 1 displays the flowchart of the methodology developed in this systematic review [29].

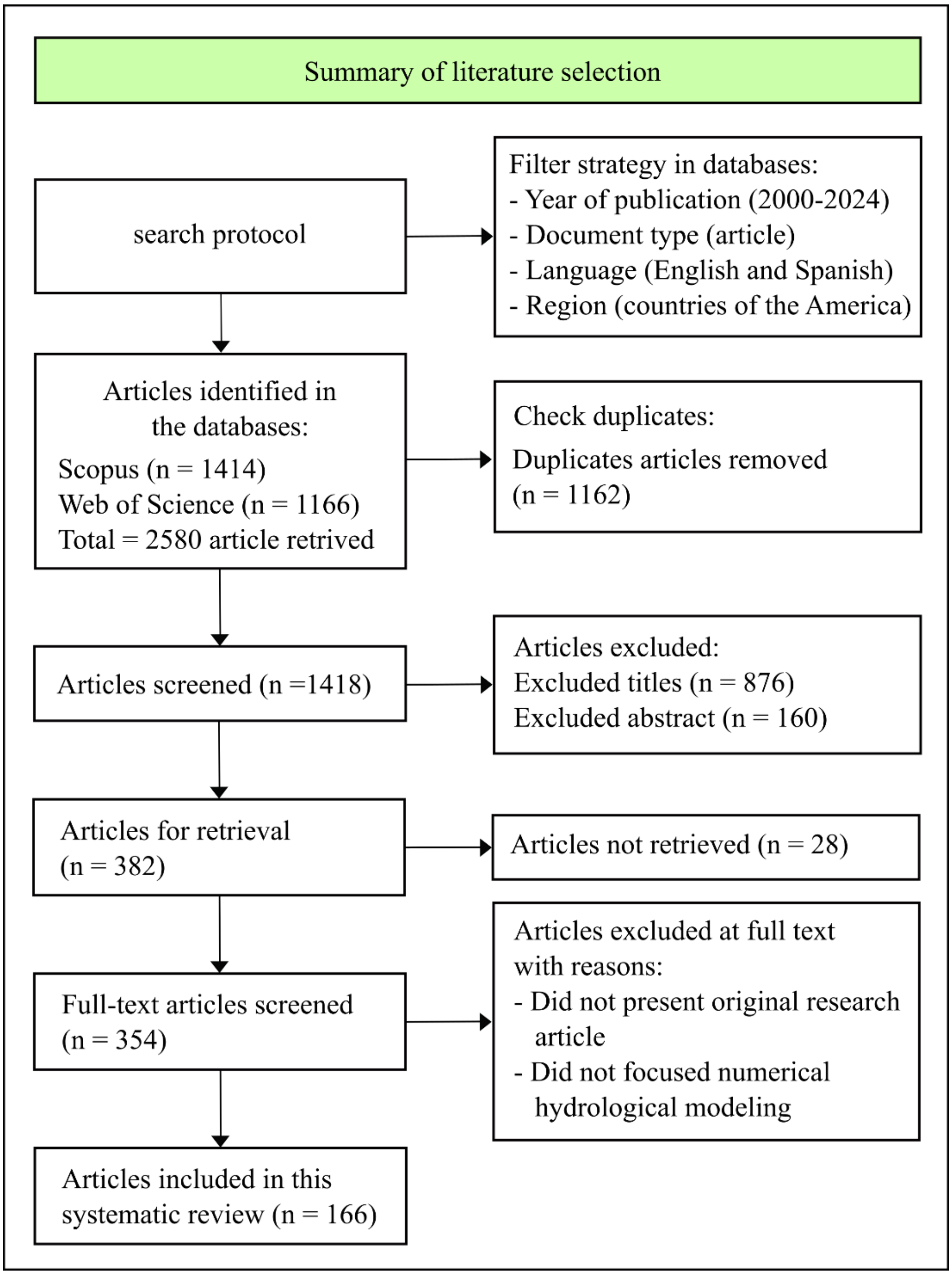

Figure 1. Process flowchart for the selection of articles using the methodology proposed by De León Pérez et al. [29].

2.2. Selection of Literature

Elsevier's Scopus and Clarivate's Web of Science bibliographic databases were used to conduct the search protocol [36]. The search string for each database was customized using the keywords listed in Table 1. Four sequential filters were applied as inclusion and exclusion criteria: year of publication (2000-2024), document type (article), language (English and Spanish), and region (Latin American countries), taking advantage of the automatic tools available in the databases.

A total of 2580 journal articles in English and Spanish from 2000 to 2024 were reviewed (1414 from Scopus and 1166 from Web Science). The articles were downloaded and stored in the reference management software Mendeley. Duplicates were removed using the 'Check for Duplicates' tool. After excluding duplicates, 1418 articles were assesed based on their title and abstract using the following inclusion criteria:

(1) Study Topic: the research article should focus on a case study, such as a basin, aquifer, or river-aquifer interaction.

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(2) Application of groundwater flow modeling software: the article should use software to assess and manage groundwater resources (e.g., MODFLOW, FEFLOW).

(3) Model calibration and validation: numerical model fitting should be performed with performance metrics (e.g., R^2, RMSE, MAE, NSE).

(4) Scenario evaluation and forecasting: simulation of future scenarios for a period of time (e.g., climate change, pumping rate, recharge-discharge, population growth, water demand, pollution).

After filtering, 1036 manuscripts were discarded and from the remaining 382 only 354 were available in full text. The full text manuscripts retrieved were read completely and the methodology, results, and conclusions were assessed. We only selected the texts that provided relevant information to answer the research questions that were selected. Finally, after the filtering selection applied 188 articles were discarded and the database was enclosed with 166 research articles for this systematic review (Appendix A and B, online supplementary material).

Table 1. Search string for Scopus and Web of Science databases.

Scopus search string
TITLE-ABS-KEY((“numerical groundwater model” OR “simulation groundwater model” OR “groundwater modeling” OR “hydrogeological modeling” OR “MODFLOW” OR “FEFLOW”) AND ((“aquifer” OR “aquifers”) OR (“basin” OR “Watershed”) OR “groundwater” OR “groundwater flow” OR “groundwater levels” OR “groundwater recharge” OR “groundwater management” OR “groundwater resources” OR “hydrogeological system” OR “forecast” OR “scenarios” OR “water resources management” OR “decision-making process” OR “uncertainty”)) AND (LIMIT-TO (PUBYEAR, 2024) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010) OR LIMIT-TO (PUBYEAR, 2009) OR LIMIT-TO (PUBYEAR, 2008) OR LIMIT-TO (PUBYEAR, 2007) OR LIMIT-TO (PUBYEAR, 2006) OR LIMIT-TO (PUBYEAR, 2005) OR LIMIT-TO (PUBYEAR, 2004) OR LIMIT-TO (PUBYEAR, 2003) OR LIMIT-TO (PUBYEAR, 2002) OR LIMIT-TO (PUBYEAR, 2001) OR LIMIT-TO (PUBYEAR, 2000)) AND (LIMIT-TO (SRCTYPE, “j")) AND (LIMIT-TO (DOCTYPE, “ar")) AND (LIMIT-TO (LANGUAGE, “English") OR LIMIT-TO (LANGUAGE, “Spanish"))
Web of Science search string
((TS=((“numerical groundwater model” OR “simulation groundwater model” OR “groundwater modeling” OR “hydrogeological modeling” OR “MODFLOW” OR “FEFLOW”) AND ((“aquifer” OR “aquifers”) OR (“basin” OR “Watershed”) OR “groundwater” OR “groundwater flow” OR “groundwater levels” OR “groundwater recharge” OR “groundwater management” OR “groundwater resources” OR “hydrogeological system” OR “forecast” OR “scenarios” OR “water resources management” OR “decision-making process” OR “uncertainty”))) AND DT=(Article)) AND PY=(2000-2024)

3. Results and Discussion

This section examines publication trends from 2000 to 2024, the distribution of editorial journals, the geographic location of the analyzed studies, and the presence of concurrent keywords. It also presents and discusses the software used for groundwater flow and transport modeling, along with the study units, as well as the metrics used to evaluate their performance.

3.1. Trends in publication

The number of publications with thematic based on numerical modeling of groundwater flow for planning and management of water resources has increased significantly since 2019 (Figure 2).

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The trend of publications has increased form an average of 6 to an average of 14 papers per year. No research articles with the specified keywords were found in 2000. The number of articles published between 2000 and 2005 was low, with less than four articles per year. The trend between 2006 and 2018 ranged from 4 to 8 publications per year. The number of publications has significantly increased since 2019, with a maximum of 16 records for that year, and reaching a peak of 19 records in 2023. As of February 2024, seven articles related to this field of research have been documented.

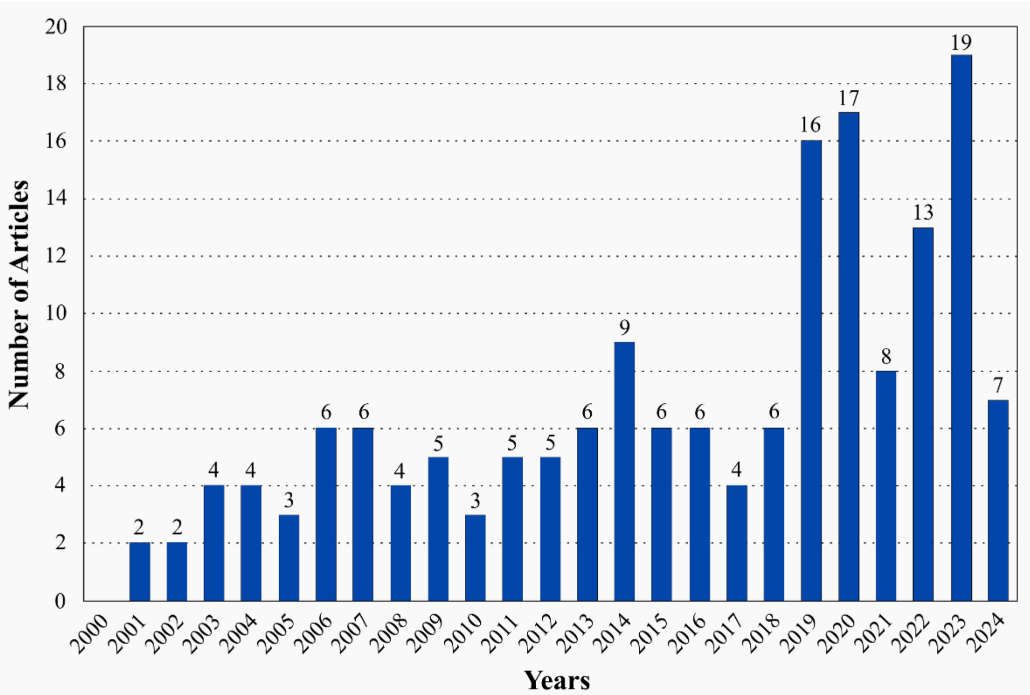

Figure 2. Trends of publication on numerical modeling of groundwater flow over time.

3.1.1. Published Journal

The SLR included scientific articles published in 62 different journals. Figure 3 shows the top 10 journals and the number of reviewed articles for each. Hydrogeology journal and Journal of Hydrology had the highest number of publications, with 19 articles each, followed by Water, Environmental Earth Sciences, and Sciences of the Total Environment with 15, 10, and 8 articles, respectively. The remaining five journals had fewer than eight articles.

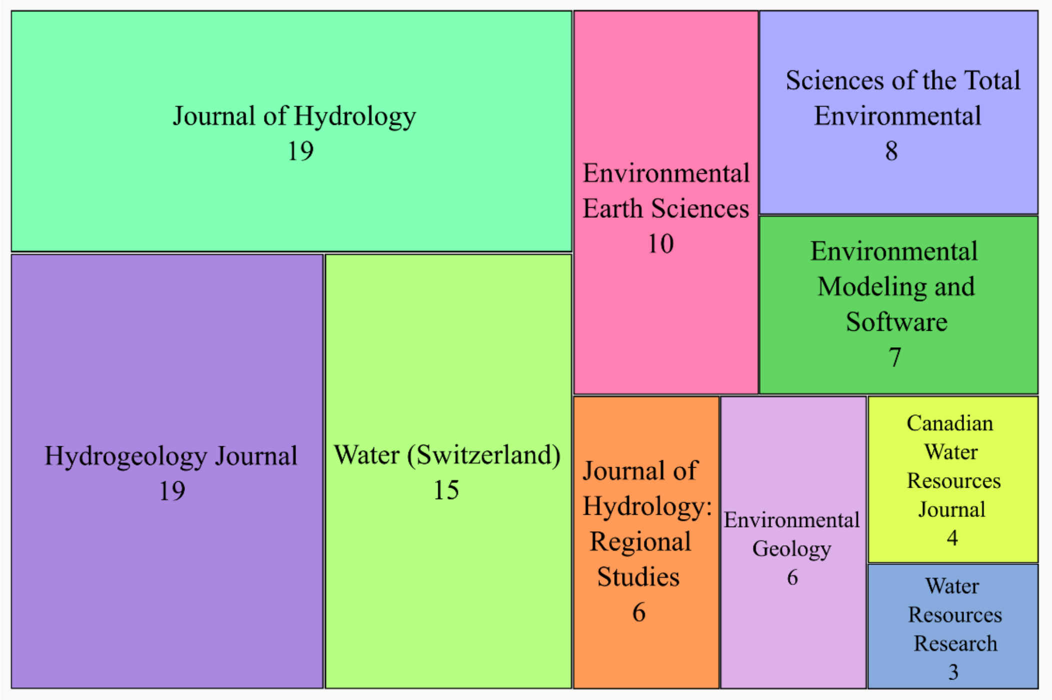

Figure 3. Tree map with top ten journals with high numbers of records observed.

3.1.2. Geographic location

The study reviewed scientific articles collected from 12 countries. Figure 4 displays the geographical distribution of the articles by country. The United States (41%), Mexico (16%), and Canada (14%) have the highest percentage of publications. South American countries, such as Argentina (4%), Chile (4%), Colombia (2%), and Uruguay (1%), have less research compared to North American countries, with the exception of Brazil (14%). The Central American region has received little research attention. It accounts for only 4% of publications. Numerical modeling studies have been conducted in countries such as Nicaragua, Cuba, Guatemala, and Haiti [37–39]. However, this may change in the future, as water scarcity is already a critical issue in some regions due to climate change variations and increase in water demand.

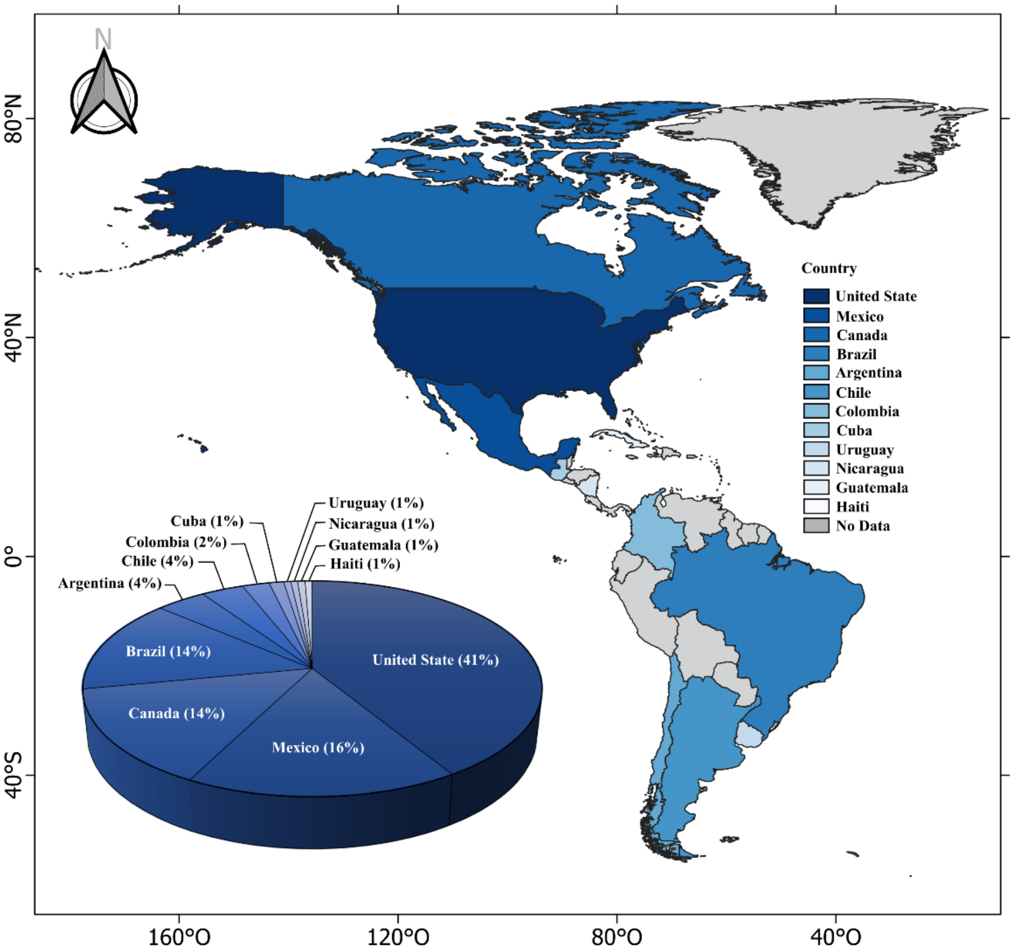

Figure 4. Geographic distribution of the 166 articles conducted per country.

3.1.3. Co-occurrence of keywords

To evaluate the semantic structure of the research field, we performed a co-word/co-occurrence analysis using the authors keywords instead of the automatically extracted ones because are less specific and understandable than the keywords contributed by the authors [40–42]. We used VOSviewer software to visualize the results, which are presented in Figure 5. To create this network, only keywords that appeared five or more times (110 out of 1469 keywords) were used. The size of each node in the network represents it's frequency. The more important a word is, the larger it's label and circle. In addition to the distance between nodes represents the strength of the relationship between keywords [43]. Applying this method revealed that the most frequently occurring keywords are groundwater resources (74), groundwater flow (67), aquifers (63), groundwater (60), aquifer (57), United States (54), MODFLOW (47), hydrological modeling (39), hydrogeology (38), and water management (35). The proximity of these keywords in the diagram suggests that the research topic primarily focuses on hydrological modeling of groundwater resources. Furthermore, this analysis verified that this selection comprised pertinent articles containing keywords related to the research questions.

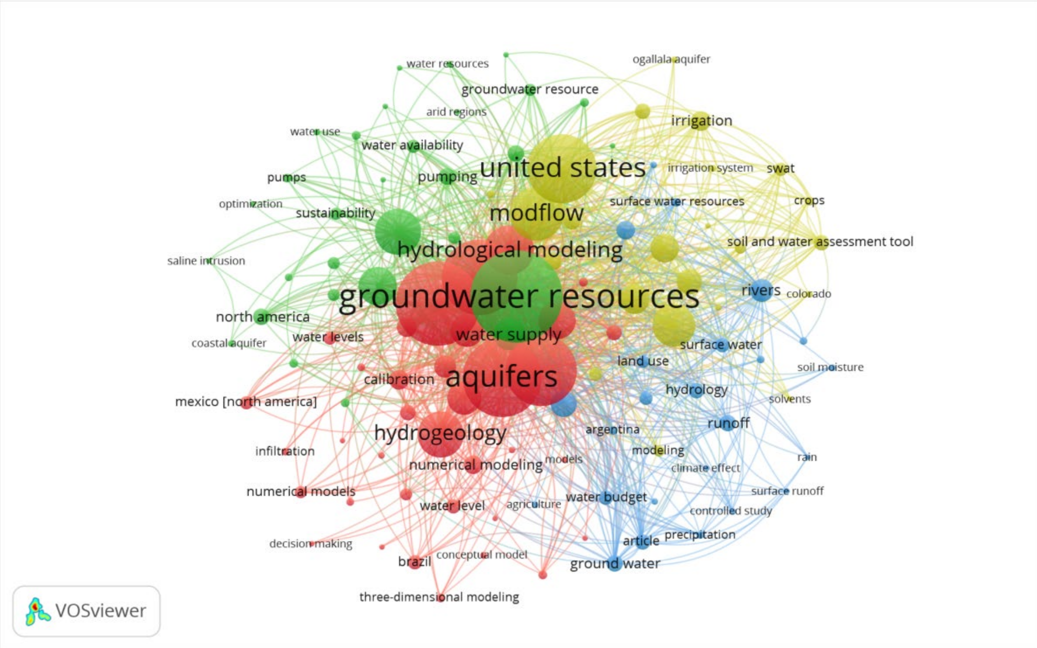

Figure 5. VOSviewer author's keyword co-occurrence.

3.2. Groundwater models

Currently, there are various codes and model software available for studying groundwater dynamics. The most commonly used numerical methods are the finite difference (FD) and finite element (FE) methods [44]. Table 2 shows examples of codes and software used in groundwater flow and transport modeling. The software and codes selected were exclusively focused on groundwater modeling, excluding integrated hydrological process software such as ParFlow [45], HydroGeoSphere [46], MikeSHE [47], CATHY [48], or SWAT [49].

It's important to note that in this study there is a wide dominion in the use of MODFLOW (saturated flow; [50]) and FEFLOW (saturated and unsaturated flow; [51]) software. It's use has been proven suitable for successfully simulating and predicting groundwater flow and transport conditions, as well as groundwater-surface water interactions, from simple to complex problems. For example, modeling aquifers with sudden density changes, as occurs in coastal aquifers in Canada [52–54], the United States [55,56], Mexico [57,58], Brazil [59,60], and the salt flats of northern Chile [61,62].

The software most commonly used in this field of research are Visual MODFLOW [63], MODELMUSE [64], GROUNDWATER Vistas (GV; [65]), and Groundwater Modeling System (GMS; [66,67]). These programs are based on finite difference and contain the MODFLOW code [50]. They are commonly used to simulate flow in a saturated medium. Finite element-based software, such as FEFLOW [51], HYDRUS [68], and GMS-FEMWATER [55], can model flow in both saturated and unsaturated media. These software types (FD and EF) are widely used for numerical modeling of granular, fractured, karst, and coastal aquifers, as well as for simulating solute transport in saturated and unsaturated media. The decision of which software to use is often not an easy one since it depends on the conceptual model of the aquifer, the modeling objectives, available data, available time to perform the study, the size (one, two or three size), scale, complexity of the groundwater system, and local expertise. For example, many numerical groundwater models suffer from weak conceptual models of the aquifer, rather than inaccurate numerical resolution [23,24].

This category also includes codes for simulating groundwater vulnerability, specifically solute transport. These codes are used in conjunction with groundwater flow models. Examples of widely reported numerical codes in the scientific literature include MODPATH [69], MT3DMS [70], and PMWIN [71], among many others reviewed by Machiwal et al. [72]. The SEAWAT [73], SWI2 [74], SUTRA [75], MODHMS [76], and FEMWATER [55] codes are commonly used to model saltwater

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intrusion in coastal aquifers and salt flats. These codes simulate flow and transport in a coupled manner, and model groundwater flow under 3D variable density conditions [77,78].

Table 2. Numerical groundwater codes/softwares [23,24,79].

Numerical method	Codes/softwares
Finite Difference	MODFLOW, MODELMUSE, VISUAL MODFLOW, FTWORK, HST2D/3D, INVFD, PLASM, GMS, GROUNDWATER VISTAS, HST3D, MICROFEM, MODFLOWT, MODPATH, MODTECH, MT3DMS, PATH3D, PMWIN, SEAWAT, SUTRA, SWANFLOW, SWIFT, TARGET, TRACR3D, MODHMS-SURFACT, MARTHE, TOUGH3, SWI2, BIOPLUMEIII, MOCDENS3D, FRACFLOW, FLOWPATH II, HSSM, SWACROP, VIRTUS, VS2DT.
Finite Element	FEFLOW, ABCFEM, AQUIFEM-N, FEMWATER, MicroFEM, MODFE, MULAT, PTC, GMS, HYDRUS-2D/3D, TRANSIN, OpenGeoSys, MOTRANS, NAPL Simulator, SUTRA, SvFlux, SWICHA, IWFM, 3DFEMFAT, AQUA3D, AQÜIMPE, CANVAS, SEEP/W, TRAFRAP-WT, FLONET/TR2, VS2DI/VS2TI, HYDRUS-1D, ChemFlux, VAM2D, WinTran, CODESA-3D, SWICHA.

3.2.1. Model calibration and validation: Performance metrics (PM's)

Performance metrics are important statistical parameters for calibrating and validating hydrological models [80–82]. Calibration can be performed in steady-state or transient conditions. Two criteria are used to evaluate calibration: manual calibration (trial-and-error calibration) and automatic calibration using inverse modeling algorithms, such as PEST (Parameter ESTimation Software; [83]), SUIF-2 (Sequential Uncertainty Fitting; [84]), HOB (Head Observation; [85]), UCODE 2014 [86], PSO (Particle Swarm Optimization; [87]), among others. These software programs can be used for uncertainty analysis and sensitivity analysis. In the reviewed articles, manual calibration was the method most commonly used, and PEST software was the algorithm most frequently used for automatic calibration. Calibration success can be evaluated quantitatively or qualitatively by using performance metrics (PM's). Both assessments are necessary to evaluate the uncertainty of the numerical model performance [80,81]. The validation of the model performance is essential because most of the input variables or parameters such as recharge input, hydraulic conductivity, specific yield coefficient, specific storage coefficient, and other model inputs cannot be accurately measured [25,88,89]. Numerical models can provide appropriate information and be used as a decision-making tool to properly manage groundwater resources after proper validation [82]. Moriasi et al. [82] suggest that using multiple PM's can improve the consistency and reliability of model performance. Figure 6A shows the number of PM's used to evaluate a model, while Figure 6B displays the percentages of the most commonly used performance metrics for determining the best fit of numerical models. According to Moriasi et al. [82], the most frequently used statistical methods for evaluating numerical models are RMSE (29%), R^2 (15%), and NSE (14%). Other statistical metrics used include MAE (11%), R (9%), NRMSE (9%), PBIAS (7%), and ME (4%). The “Other” category includes cumulative metrics with a frequency of ≤1%, such as RSR, mNSE, KGE, or NOF. Only 42% studies evaluated the performance of hydrologic models using two or more metrics.

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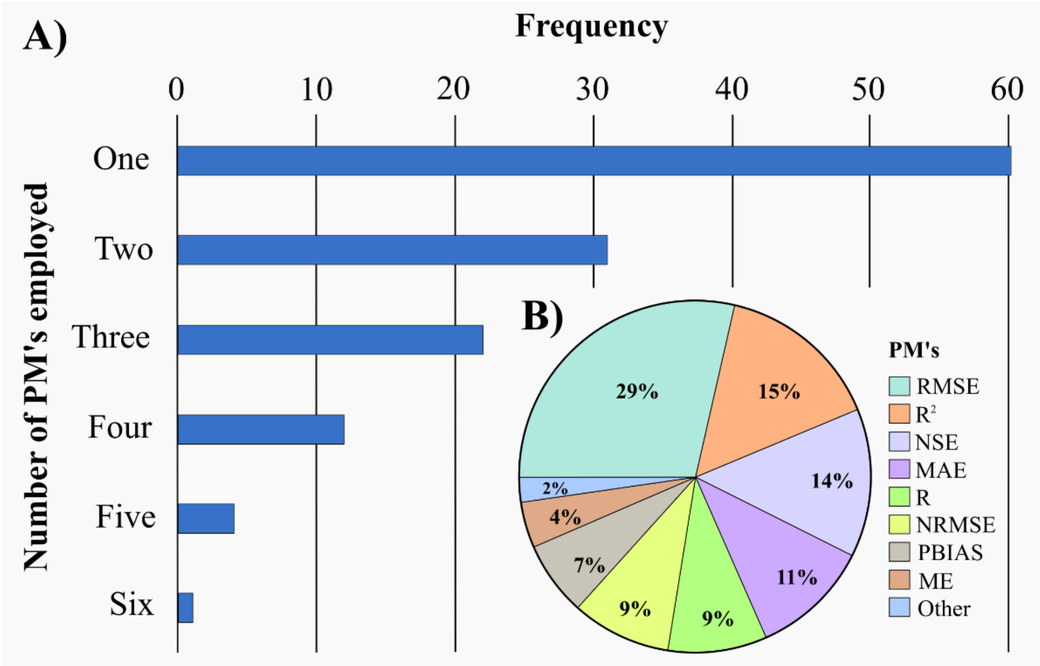

Figure 6. Performance metrics employed for calibrating and validating hydrological models. A) Combination of PM's used and B) Pie chart of the PM's used. Performance metrics: root mean square error (RMSE), Coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), Mean absolute error (MAE), Correlation coefficient (R), Normalized root mean square error (NRMSE), Percentage of bias (PBIAS), Mean error (ME), kling-Gupta efficiency (KGE), modified Nash-Sutcliffe Efficiency (mNSE), standard deviation of measured data (RSR), and normalized objective function (NOF).

3.2.2. Modeling at different scales: Study Unit

For groundwater management purposes, countries have been divided it's territory into basins and aquifers. Basins are defined by the area's topography, while aquifers are defined by subsurface geological formations. Basins and aquifers are the fundamental units for water resource planning and management [90,91]. Data is typically more accessible at these scales, where organizations contribute to knowledge acquisition and data availability [20]. Most of the research numerical groundwater hydrological models developed in the last decade have been implemented at these scales. The hydrogeological units of study in the reviewed papers are shown in Figure 7. Publications were divided by the modelling scale; 37% of the articles are analyzed at a basin scale, while 63% focused on modeling an aquifer as the target unit. The type of aquifer conceptualized in the studies are unconfined aquifer (33%), confined aquifer (10%), semi-confined aquifer (9%), coastal aquifer (7%), and karst aquifer (4%). Over time, researchers have attempted to quantify groundwater resources at large spatial and temporal scales (regional, continental or global scale), but this remains challenging due to the lack of in situ hydrogeological data and detailed descriptions of aquifer properties in many regions [3,4,92–95].

It's important to acknowledge that even with a well calibrated and accurate numerical model; it will not provide a perfect representation of subsurface and hydrogeologic processes due to the inherent limitations of research tools. In practice, many models are simplified as they cannot fully reflect the heterogeneity and complexity of subsurface processes. The success of the model depends on it's usage and scale, with the latter being critical to balancing the necessary complexity and level of detail. A local numerical model may require highly accurate data, while a regional one can achieve satisfactory results with slightly larger average deviations. However, it's important to keep in mind that at a larger scale, accuracy may decrease due to the need for more data, which can lead to errors, inconsistencies, and uncertainty [89,96,97].

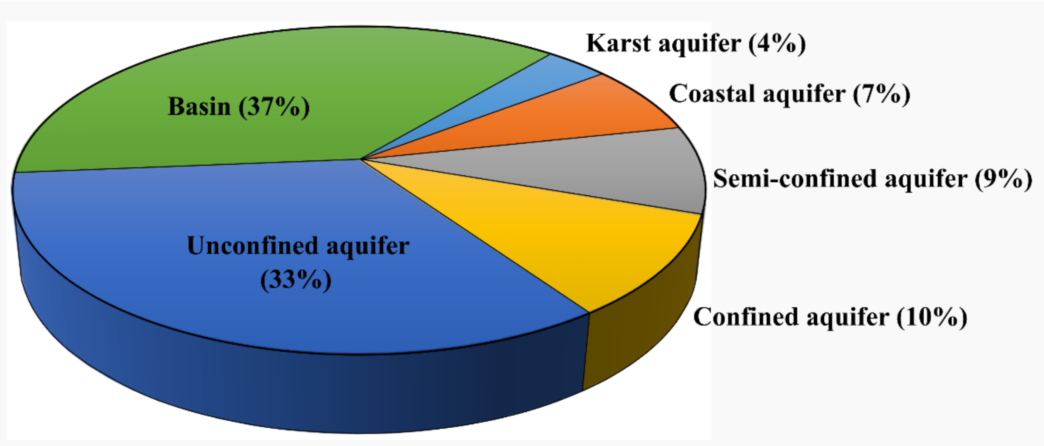

Figure 7. Study hydrogeological units in the reviewed articles.

3.2.3. Modeling limitations: Data collection

Numerical groundwater models are important tools for planning and groundwater resources management [27,98,99]. However, constructing accurate models can be challenging due to the complex architecture of aquifers systems [1]. The software and hardware needed for modeling are widely available and advanced [27]. The problem lies in the availability and quality of data [1,2,27,100]. To accurately simulate the quantity and quality of groundwater resources, these models require a wide range of information, such as geology, geophysics, hydrogeology, hydrogeochemistry, hydrology, climatology, geography, and other supplementary information [44]. However, the collection of such information, particularly in developing regions as Latin America, presents a challenge and suffers from a high degree of uncertainty [21,101,102]. Researchers in these countries face a lack of reliable, available, and measured long-term data; therefore, simplifications are often necessary [100]. The limited availability and scarcity of these data often render inaccurate numerical models [1]. Uncertainties in groundwater modeling results and predictions are mainly caused by the lack of field data, errors in observation data, and simplifications in conceptual model construction [25,27]. To model groundwater resources in a reliable context it is necessary to perform a detailed monitoring in the aquifer and integrate several hydrogeological data; extraction rates, groundwater levels, quantify aquifer recharge, obtain specific yield value and asses water quality and seawater intrusion [21,27,58,101].

It's important to note that to collect detailed hydrogeological field observations can be expensive in large regions. In this context, geophysical surveys are a valuable source of data for aquifer modeling. They offer a non-invasive, cost-effective approach to characterizing aquifer dimensions and stratigraphy. These surveys enhance geological understanding and hydrostratigraphic characterization, providing information on hydraulic properties, spatial extent, and flow directions [89,103]. In addition, the use of remote sensing data can serve as a complementary alternative to provide information on several relevant hydrological variables [95,104]. For example, The Gravity Recovery and Climate Experiment (GRACE; [105]) and it's successor GRACE-FO are capable of estimating changes in groundwater storage by measuring variations in the gravity field. However, their spatial and temporal resolutions are only approximate [95]. Despite the basic spatial and temporal resolution of GRACE and GRACE-FO data, their high level of accuracy makes them particularly valuable for large-scale modeling, compensating for the limitations of observational data. However, further research is still needed to improve the accuracy and spatial and temporal resolution of these data, enabling their full exploitation [95,104,106].

3.3. Studied regions: Challenges and Future research

3.3.1. Studied regions

Many of the regions studied are located in arid and semi-arid zones, including western and central Canada and the United States, as well as northwestern, northern, and central Mexico, and western South America. These regions face significant challenges in groundwater management due to overexploitation and contamination resulting from increased water demand. Climate change and population growth are the primary factors that are putting pressure on groundwater resources, worsening these issues.

Overexploitation of groundwater for anthropogenic supply leads to significant declines in groundwater levels and is a continuous concern in these American countries. The increase in water demand is mainly due to population growth, industrial activity, agricultural needs, and the impact of climate change. Additionally, to inefficient water management and competition among economic sectors for it's consumption. It is important to note that these regions have been facing difficulties with groundwater sustainability even before the threat of climate change was identified [22,107–109]. In these regions, groundwater sustainability faces other significant threats, such as groundwater quality degradation due to contamination by natural and anthropogenic sources. Contamination of aquifer systems is frequent in coastal areas due to seawater intrusion and groundwater salinization as a result of aquifer overexploitation and through recharge of polluted surface water into aquifers [110,111]. Researchers have shown a great deal of interest in water resources management in coastal areas. However, understanding the groundwater dynamics of coastal aquifers remains a significant challenge [112]. In recent years, there has been an increase in these concerns, highlighting the importance of describing and understanding the behavior of aquifer systems. Planning and evaluating water management strategies to address these emerging challenges is crucial. It's also important to develop numerical models that cover unexplored regions as dictated by stakeholders and water managers.

Transboundary numerical groundwater modelling is principally assessed in transboundary basins located between Canada, USA and Mexico in North America and between Brazil, Argentina, Paraguay and, Uruguay in South America [92,113–116]. Despite this trend, numerical models have not been implemented for planning and managing shared groundwater resources in the southern border between Mexico, Guatemala, and, Belize [21].

Despite the undeniable trend of groundwater degradation, aquifer overexploitation and vulnerability to climate change in the central region of the American continent, there has been given little scientific attention to develop numerical groundwater modelling. The lack of research in this area can be attributed to various factors, including the apparent abundance of groundwater resources, limited research funding in the region and lack of political and/or scientific interest [17,21]. However, the implementation of numerical models could be highly beneficial, these models can help to analyze and solve critical issues such as floods or droughts in vulnerable communities, assess water availability, monitor water quality degradation, and develop equitable water allocation systems among users and countries [17,18,21].

The numerical models used in these regions have significantly contributed to our understanding of complex aquifer systems; they assess both current and alternative groundwater management strategies, predict the impacts of climate change, pollution, and increased pumping on aquifer behavior, and mitigate it's adverse effects. Additionally, these models have highlighted the limitations, uncertainties, and data gaps that exist in this field of research. It's important to remark that while these models provide an approximate representation of real aquifer systems, they do not directly solve water management problems. However, they can provide valuable information to support planning and decision-making for sound groundwater resource management. It's essential to address these vulnerabilities and promote social resilience building. Despite the challenges and limitations, researchers are encouraged to continue developing and refining numerical groundwater models in these regions. This will expand their spatial scope and improve our knowledge and understanding of potential future effects on aquifers.

3.3.2. Evaluating and forecasting future scenarios

Numerical models enable simulation of groundwater flow in the aquifer under different conditions and predictive scenarios, facilitating visualization of it's behavior in the short, medium, and long term. Scenario simulation is crucial for groundwater management. Each scenario is designed to address the specific issues of the region and is implemented over a defined period of time. During this period, parameters that primarily affect groundwater recharge and storage, such as population growth and climate change, are modified [100]. Fifty-one percent of the reviewed studies performed scenario simulations to predict future outcomes. Simulations estimated the effects of changes in groundwater extraction based on different projections of population growth and groundwater demand (urban, agricultural, and industrial use) on extraction and recharge scenarios (30%). However, only 16% of published studies have examined the impacts of climate change on groundwater resources based on predictive scenarios, and just 5% have focused on pollution. Furthermore, 35% of studies did not consider the impact of climate change on numerical models. This omission reduces the effectiveness of the studies. It's important to include climate change as a variable in these studies, as it significantly affects groundwater resources. Therefore, future studies should consider the effects of climate change on groundwater management and perform long-term transient state simulations to assess the impact of temporal variability and aquifer storage potential. Additionally, it is important to evaluate other anthropogenic pressures, such as land use alterations, pollution, and increasing pumping rates for irrigation, drinking water or industrial purposes [20,27].

Numerical models have the potential to be decisive tools for proactive decision-making. However, their practical application has so far been mostly restricted to steady-state scenarios that ignore aquifer storage potential [27]. In the future, these models will be essential for optimizing groundwater resource management and meeting these challenges. However, to achieve this goal, it's crucial that the models operate in a transient mode that fully incorporates time variations in system inputs and outputs. This will require a significant amount of data. The main obstacle to addressing groundwater challenges is the lack of sufficient field data to feed predictive models [20,21,27].

4. Conclusions

This work summarized the current state of numerical groundwater flow models used to evaluate water resources management in Latin America from 2000 to 2024. Research studies from Scopus and Web of Science databases were collected and reviewed. We found that Visual MODFLOW, MODELMUSE, GMS, GV, and FEFLOW are the most commonly used software for visual numerical groundwater simulation. In practice, they have proven to be effective modeling tools that provide valuable information for developing adaptation and mitigation strategies to face of future challenges such as climate change, increased water demand due to population growth and agricultural and industrial development. Additionally, scenario simulation and assessment of aquifer system responses should be included in future activities. It's important to simulate the combined effects of climate change and other pressures. The root mean square error (RMSE) was the most commonly used performance metric for model calibration and validation. These models were developed mostly in arid and semi-arid regions, where groundwater management challenges are most significant. Numerical models have significantly contributed to the understanding of aquifer systems and have successfully supported water management processes. However, numerical modeling faces numerous challenges and limitations. The availability of data to construct or validate conceptual models is often inadequate. In addition to the scarcity of studies and data in some areas, climate change also presents challenges to groundwater sustainability. Arid and semi-arid regions will be particularly affected by this phenomenon, making them a priority for future research. Continued research, improvement and development of numerical groundwater models is essential to ensure the sustainability of groundwater resources.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Appendix A. Full-text eligibility checklist; Appendix B. Full list of the articles included in the review.

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