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Hydrological Modeling and Transport of Pollutants In Water Basins: A Systematic Review

Modelagem Hidrológica e Transporte de Poluentes em Bacias Hidrográficas: Uma Revisão Sistemática

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ABSTRACT

Environmental incidents around the world have been causing rapid deterioration of water quality, causing serious economic losses, impacting aquatic ecological environments and causing illness and death to surrounding residents. The precise determination of the surface water flow, based on the mathematical description of the hydrological processes on the natural basins, is of primordial importance for the evaluation of the impact of the transport of pollutants. This article intends to identify and map the main software used to study the trajectory of pollutants in watersheds, aiming to understand mathematical concepts, to identify the main methods and techniques used, as well as to verify the main contaminants studied by the scientific community today. The Method used of a systematic review protocol to gather evidence and support answers to research questions outlined with the help of the PICOC framework. On results was observed a convergence of authors to use the Soil and Water Assessment Tool (SWAT) software, either alone or in combination with other modules, to study the trajectory of pollutants. Among the studies, the predominance of pollutants was observed: Nitrate, Phosphate and Nitrogen, which suggests that these are the most studied substances today. The results presented in this article bring together and summarize the last decade of development in the field of studying the trajectory of pollutants in watersheds.

Palavras-chave: transport of pollutants. hydrological modeling. trajectory study. hydrographic basins

RESUMO

Os incidentes ambientais ao redor do mundo vêm causando rápida deterioração da qualidade da água, trazendo sérias perdas econômicas, impactando os ambientes ecológicos aquáticos e levando doenças e morte aos residentes de entorno. A determinação precisa do fluxo de águas superficiais, baseada na descrição matemática dos processos hidrológicos sobre as bacias naturais, é de importância primordial para a avaliação do impacto do transporte de poluentes. Este artigo pretende identificar e mapear os principais softwares utilizados para o estudo da trajetória de poluentes em bacias hidrográficas, visando compreender os conceitos matemáticos, identificar os principais métodos e técnicas utilizados, assim como, verificar os principais contaminantes estudados pela comunidade científica na atualidade. O método utilizou um protocolo de revisão sistemática para reunir evidências e subsidiar respostas às questões de pesquisa delineadas com auxílio do framework PICOC. Nos resultados foi observada uma convergência de autores para a utilização do software Soil and Water Assessment Tool (SWAT), seja de forma isolada ou em combinação com outros módulos, para o estudo da trajetória de poluentes. Dentre os estudos, observou-se a predominância dos poluentes: Nitrato, Fosfato e Nitrogênio, o que sugere que essas sejam as substâncias mais estudadas na atualidade. Os resultados apresentados neste artigo reúnem e resumem a última década de desenvolvimento no campo de estudo da trajetória de poluentes em bacias hidrográficas.

Keywords: transporte de poluentes. modelagem hidrológica. estudo de trajetória. bacias hidrográficas.

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1. INTRODUCTION

Water pollution incidents are becoming major environmental events in the world. They have caused a rapid deterioration of water quality, leading to illness and death of surrounding residents, bringing serious economic losses and impacting aquatic ecological environments both in the short and long term (LONG et al., 2016; ZHANG et al., 2011).

Accurate determination of surface water flow is of primary importance when assessing the sediment and pollutant transport, like as the impact generated on the watershed physical characteristics and on water quality (MITA; CATSAROS, 2012; RAUTELA et al., 2022).

The decrease in flow in the watershed can compromise the supply of water for human consumption and the availability of water for agriculture, industry and electricity generation (COSTA et al., 2022). On the other hand, increased flow leads to flooding (AMORIM et al., 2022).

The mathematical description of hydrological processes over natural basins requires a detailed representation of the topography, over which accurate determination of terrain and channel flow trajectories often presents difficulties (MITA; CATSAROS, 2012).

Estimating discharge flow is an essential component of planning and decision-making. It is highly correlated with many development activities involving water resources (BRÊDA et al., 2021; RAUTELA et al., 2022).

The determination of the volumetric concentration at the deposition limit is of great importance, as it defines a rate of sediments that the flow can transport without deposition, avoiding, for instance, obstructions and reducing the discharge capacity of storm sewers (ROMERO; OTA, 2021), as well as such as silting up of the reservoirs and damage to the mechanical components of the turbines (RAUTELA et al., 2022).

Issuing early and accurate warnings for floods is challenging when the rains that trigger these natural disasters occur on a very short space-time scale (LIMA; SCOFIELD, 2021). Hydrological models are one of the most effective ways of assessing water behavior and flood risk, although the quality of their results is determined by the representativeness of the input data (AMORIM et al., 2022), the mathematical description of hydrological processes over natural basins requires a detailed representation of the topography, on which the precise determination of flow paths often presents difficulties (MITA; CATSAROS, 2012).

Considering that several scientific works study the transport of pollutants in hydrographic basins and the modeling of the trajectory of the pollutant in the water body, the objective of this work is to gather the publications of the scientific bases worldwide recognized Scopus Elsevier and Web of Science, through a protocol systematic review in order to answer the following research question:

RQ1 - Which main pollutants were studied?

RQ2 - What main software were used to study the trajectory of pollutants in watersheds?

RQ3 - What main methods were used to study the trajectory of pollutants in watersheds?

2. MATERIAL AND METHODS

In this article, it was adopted a systematic review protocol for to gather evidence and support impartial answers to the proposed questions, evaluating, identifying and interpreting articles related to the field of study. The used databases were Scopus and the Web of Science.

Aiming define the scope of the literature for the review, ensuring that the qualification thresholds are aligned with the stated objective was used the PICOC framework (Table 1).

Table 1. Appliance of PICOC flamework

Population	P	Studies on hydrological and computational modeling
Intervention	I	Transport of pollutants in water courses and their trajectory
Comparison	C	Techniques and models used in case studies to determine the trajectory
Output	O	What are the most used methods to estimate the trajectory of pollutants in water courses
Context	C	Computer modeling research studies.

Source: Prepared by the authors (2023)

This research is classified as applied (as it is concerned applying existing knowledge), quantitative (since it translates the researched reality into numbers to receive analytical and statistical study) and exploratory-descriptive (as it has the objective of familiarizing the problem, in order to make it more explicit, in relation to the procedures).

The central part of this systematic review is to synthesize and extract relevant information from selected articles. It will lead this review to a structured supporting article, suppressing any chance of a biased look on the topic. In this sense, this article aims: to map which are the main contaminants studied by the scientific community in issue of transport of pollutants; identify the most used software used to study the trajectory of this pollutants in hydrographic basins, aiming understand the types of mathematical concepts; identify the

main methods were used to study, seeking understand which techniques, methods and concepts were most used by researchers in the field of pollutant transport.

In order to set up a strategy to search and execute this research in the scientific bases, it was necessary to assemble a series of keywords and carry out some research tests in order to identify which words and expressions are most used in the articles of interest. Below is a list of words and expressions used as reference: Hydrology; Hydrological; Watershed; Drainage basin; Mathematical Modeling; Math modeling; Model; Pollutant transport; Pollutant transportation; Trajectory; Direction.

After that, the search was performed using different compositions of search strings. The obtained results are showed on Table 2.

Table 2 – Results by scientific basis

Search terms (query string)	Quantity of results	
	Scopus	WoS
("hydrology" OR "hydrological") AND ("watershed" OR "drainage basin") AND ("Mathematical Modeling" OR "math modeling" OR "Model") AND ("pollutant transport" OR "pollutant transportation") AND ("trajectory" OR "direction") AND (LIMIT-TO (DOCTYPE,"ar"))	271	4

Source: Prepared by the authors (2023)

Like inclusion criterion was considered the complete articles that deal exclusively with the theme of the trajectory of pollutants in water bodies with a focus on rivers.

The exclusion Criteria were: study without full text access; publications that was not scientific article; studies prior to 2011; studies where the pollutant trajectory in any environment other than in water bodies (rivers); studies in groundwater; studies in any language other than English; out of scope studies. The Figure 1 show a schematic of inclusion and exclusion criteria applying the PRISMA method.

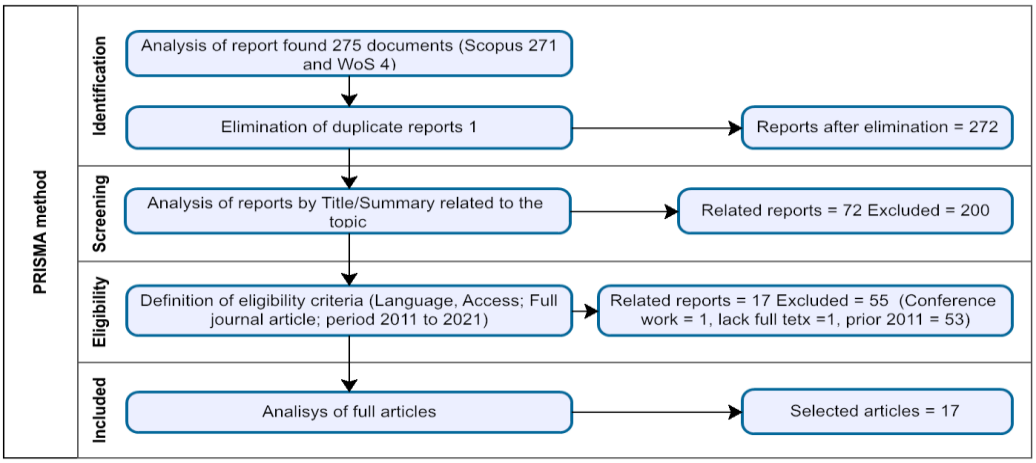

Figure 1. PRISMA method

Source: Prepared by the authors (2023)

3. RESULTS AND DISCUSSIONS

The results were able be grouped on the following categories.

3.1 Research publication journals and indexes

Identifying the journals is of paramount importance to categorize and estimate a future research path. There are several indicators around the world to assess the importance of a magazine's coverage. This work used the SJR impact index and the H-index, based on the SCImago Journal & Country Rank.

The H-index balances the number of publications with their citations by other researchers. The high scores indicate that the article has been cited several times over the years, which characterizes it as a relevant work. The JCR quartile index is obtained by dividing the total quantity of journals in a category by 4, allowing their classification into Q1, Q2, Q3 and Q4. If a journal belongs to Q1, it means it performs better than at least 75% of journals in the same category.

The Table 4 presents the list of articles by authors, years of publication, affiliation, countries, publication journal, Quartile and H-index.

Table 4. List of articles by authors, years of publication, affiliation, countries, journal, Quartile and H-index

Nº	Author / Year	Country	Journal	Quartiles	H-INDEX
1	(ZHANG et al., 2012)	China	Environmental Monitoring and Assessment	Q2	109
2	(CUI; WELTY; MAXWELL, 2014)	United States	Computers and Geosciences	Q1	123
3	(FICKLIN; LUO; ZHANG, 2013a)	United States	Hydrological Processes	Q1	161
4	(ANTONOPOULOS; GEORGIOU; ANTONOPOULOS, 2015)	Greece	Environmental Processes	Q2	25
5	(YU et al., 2015)	China	Marine Pollution Bulletin	Q1	179
6	(LI; YAO, 2015)	China	Water (Switzerland)	Q1	55
7	(PANAGOPOULOS et al., 2014)	United States	Journal of Soil and Water Conservation	Q1	75
8	(KANNAN et al., 2017)	United States	Journal of Soil and Water Conservation	Q1	75
9	(CVETKOVIC et al., 2012)	Sweden	Water Resources Research	Q1	217
10	(MITA; CATSAROS, 2012)	Greece	Central European Journal of Chemistry	Q3	39

11	(KERAGA; KIFLIE; ENGIDA, 2019)	Ethiopia	Modeling Earth Systems and Environment	Q2	25
12	(LONG et al., 2016)	China and United States	Water (Switzerland)	Q1	55
13	(JEON et al., 2019)	United States and South Korea	Science of the Total Environment	Q1	244
14	(MENG et al., 2018)	China	Science of the Total Environment	Q1	244
15	(BOULANGE et al., 2014)	Japan and United States	Journal of Hydrology	Q1	226
16	(QIU; WANG, 2014)	United States and Canada	Journal of Hydrologic Engineering	Q2	89
17	(FICKLIN; LUO; ZHANG, 2013b)	United States	Hydrological Processes	Q1	161

Source: Prepared by the authors (2023)

This table presents a list of scientific articles, organized by author, year of publication, country, journal, Quartile, and H-index. It is possible to observe that most articles were published in high-impact journals, with Quartiles Q1 and Q2, indicating significant relevance in the field of study. Additionally, the majority of articles were published by authors from the United States and China, with few articles from other countries. It is also interesting to note that some authors published more than one article and that some articles were published by authors from more than one country (Figure 2). The H-index, which measures researchers' productivity and impact, varies between 25 and 244, showing a wide variation among different articles and authors. Overall, the table provides an overview of geosciences research and its recent publications in important scientific journals.

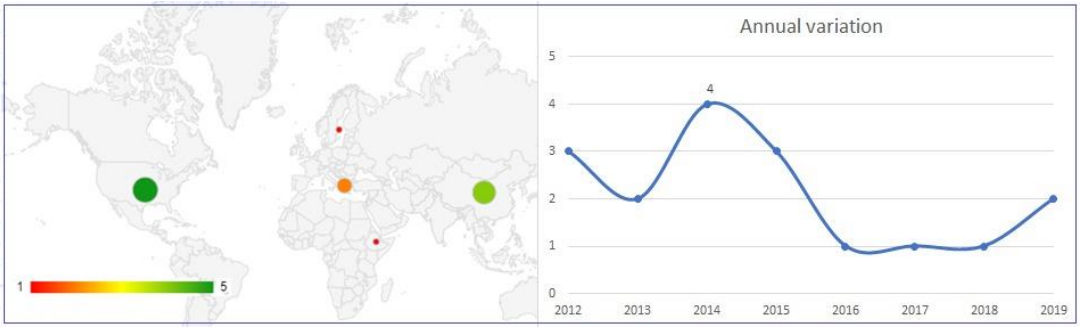

Figure 2. Presence and intensity of publications by country e distribution of publications on year

Source: Prepared by the authors (2023)

Another interesting observation from the table is the diversity of research topics and approaches within the field of geosciences. The articles cover a wide range of areas such as environmental monitoring and assessment, hydrological processes, marine pollution, soil and water conservation, and modeling earth systems. This indicates a multidisciplinary

approach to geoscience research, with contributions from various subfields such as chemistry, physics, and biology. Additionally, the authors represent different institutions and backgrounds, suggesting a collaborative effort in geoscience research across countries and continents. Overall, the table reflects a dynamic and evolving research landscape in geosciences, highlighting the complexity and importance of the field in addressing environmental challenges and improving our understanding of natural systems.

Considering the quantity of publications, there was highlight for the journals: Hydrological Processes, Water (Switzerland), Journal of Soil and Water Conservation and Science of the Total Environment with two publications each one. The highlight is on the journal Science of the Total Environment with biggest impact factor.

3.2 Detailing of articles and research questions

Seventeen scientific articles were selected, according to the selection criteria. The Table 5 summarize the answers obtained on each article for the research questions.

Table 5. Answers for the research questions.

N	Title	Q1 - What pollutants were studied? (Pollutants)	Q2 - What software were used? (Software)	Q3 - What methods were used? (Methods)
1	Response of non-point source pollutant loads to climate change in the Shitoukoumen reservoir catchment (ZHANG et al., 2012)	NH_4^+-N and total phosphorus	SWAT and HadCM3	Statistical downscaling method
2	Modeling nitrogen transport and transformation in aquifers using a particle-tracking approach (CUI; WELTY; MAXWELL, 2014)	Nitrogen (Biodegradation; Denitrification)	RWPT and Maxima, A Computer Algebra System	Particle-tracking model / Reactive-transport model / Groundwater transport model
3	Climate change sensitivity assessment of streamflow and agricultural pollutant transport in California's Central Valley using Latin hypercube sampling (FICKLIN; LUO; ZHANG, 2013a)	Streamflow and Sediment runoff and Nitrate	SWAT and Latin hypercube climate change	LHS method (Latin hypercube sampling)
4	Dispersion Coefficient Prediction Using Empirical Models and ANNs (ANTONOPOULOS; GEORGIOU; ANTONOPOULOS, 2015)	Distribution of concentration or the variation of maximum concentration along the river for pollutants	Dispersion Coefficient Prediction Using Empirical Models and of artificial neural networks	Analytical Fischer method
5	Modeling increased riverine nitrogen export: Source tracking and integrated watershed-coast management (YU et al., 2015)	Dissolved inorganic nitrogen (DIN)	The global NEWS model	The method is not clearly described in this article.
6	Estimation of transport trajectory and residence time in large river-lake systems: Application to Poyang Lake (China) using a combined model approach (LI; YAO, 2015)	Estimation of Transport Trajectory and Residence Time in Large River–Lake Systems	Hydrodynamic model (MIKE 21) and with transport and particle-tracking sub-models	Lagrangian random-walk technique

7	Surface water quality and cropping systems sustainability under a changing climate in the Upper Mississippi River Basin (PANAGOPOULOS et al., 2014)	Nitrogen (N) and Phosphorus (P)	Soil and Water Assessment Tool (SWAT)	The method is not clearly described in this article.
8	Estimating sediment and nutrient delivery ratios in the Big Sunflower Watershed using a multiple linear regression model (KANNAN et al., 2017)	Pollutant delivery ratios (DR) from subbasins. Total nitrogen (N) and Total phosphorus (P)	The Comprehensive Environmental and Economic Optimization Tool (CEEOT) modeling system, consisting of the Soil and Water Assessment Tool (SWAT) and Agricultural Policy and Environmental Extender (APEX) models	Multiple linear regression framework
9	Water and solute transport along hydrological pathways (CVETKOVIC et al., 2012)	Water and solute transport along hydrological pathways	The software is not clearly described in this article.	The LaSAR methodology (Lagrangian Stochastic Advection Reaction)
10	Simulating pollutant transport over complex terrain: The hydrological component (MITA; CATSAROS, 2012)	Simulating pollutant transport over complex terrain	The software is not clearly described in this article.	DELTA/HYDRO model
11	Evaluation of SWAT performance in modeling nutrients of Awash River basin, Ethiopia (KERAGA; KIFLIE; ENGIDA, 2019)	Nitrate and Phosphate	Soil and Water Assessment Tool (SWAT) and SWAT-CUP Calibration and Uncertainty Program.	The method is not clearly described in this article.
12	Simulating the impacts of an upstream dam on pollutant transport: A case study on the xiangjiang river, China (LONG et al., 2016)	Simulating the impacts of an upstream dam on pollutant transport	MIKE zero	The method is not clearly described in this article.
13	Evaluating the influence of climate change on the fate and transport of fecal coliform bacteria using the modified SWAT model (JEON et al., 2019)	Fecal Coliform Bacteris - FCB	Soil and Water Assessment Tool (SWAT)	The method is not clearly described in this article.
14	A heavy metal module coupled with the SWAT model and its preliminary application in a mine-impacted watershed in China (MENG et al., 2018)	Zinc (Zn) and Cadmium (Cd)	Soil and Water Assessment Tool (SWAT) and SWAT-laden heavy metal module (SWAT-HM)	The method is not clearly described in this article.
15	Development and validation of a basin scale model PCPF-1@SWAT for simulating fate and transport of rice pesticides (BOULANGE et al., 2014)	simulating fate and transport of rice pesticides	Soil and Water Assessment Tool (SWAT) and PCPF-1@SWAT model	The method is not clearly described in this article.
16	Hydrological and water quality assessment in a suburban watershed with mixed land uses using the SWAT model (QIU; WANG, 2014)	total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP)	Soil and Water Assessment Tool (SWAT)	The method is not clearly described in this article.
17	Watershed modelling of hydrology and water quality in the Sacramento River watershed, California (FICKLIN; LUO; ZHANG, 2013b)	streamflow, sediment, nitrate, chlorpyrifos and diazinon loads.	Soil and Water Assessment Tool (SWAT)	The method is not clearly described in this article.

Source: Prepared by the authors (2023)

The Table 5 presents a summary of different research studies that aimed to answer questions related to various aspects of pollutants and their transport. The studies covered a

range of pollutants, including nitrogen, phosphorus, sediment runoff, heavy metals, and fecal coliform bacteria, and utilized various software and methods to model and analyze the pollutant transport.

Most of the studies employed the Soil and Water Assessment Tool (SWAT) software to model pollutant transport, although other software such as RWPT and Maxima, A Computer Algebra System, MIKE 21, and DELTA/HYDRO were also used. Additionally, a variety of modeling and statistical methods were employed, including statistical downscaling method, particle-tracking model, reactive-transport model, groundwater transport model, Latin hypercube sampling, Lagrangian random-walk technique, multiple linear regression framework, and LaSAR methodology.

The information provided in this table can be used to gain insights into the range of pollutants and methods used in the field of pollutant transport research, as well as to identify gaps and opportunities for future research. Additionally, it can help researchers in selecting appropriate software and methods for their own studies.

Article 1 deals with a statistical downscaling model that was used to generate future local scenarios of meteorological variables, such as temperature and precipitation. Then, the reduced meteorological variables were used as input to the calibrated and validated SWAT (Soil and Water Assessment Tool). The calibration and validation results showed that the SWAT model was able to well simulate water flow and pollutant loads from diffuse sources, with a coefficient of determination of 0.7 and a Nash-Sutcliffe efficiency of about 0.7 for both calibration and validation periods (ZHANG et al., 2012).

Article 2 studies multispecies biodegradation and geochemical reactions in an existing particle tracking code to simulate reactive transport in three-dimensional media with varying saturation, focusing on nitrification and denitrification processes (CUI; WELTY; MAXWELL, 2014).

Article 3 used the SWAT in conjunction with a Latin hypercube climate change sampling algorithm to build a 95% confidence interval (95CI) around current flow, sediment load and forecasts of nitrate load under climate change for Sacramento and San Joaquin River watersheds in California's Central Valley. Comparisons of watershed sensitivities indicate that the San Joaquin River basin is more sensitive to climate change than the Sacramento River basin, which is largely caused by the high density of agricultural land (FICKLIN; LUO; ZHANG, 2013a).

The article 4 research the concentration of a conservative pollutant is changed along a river, as a result of the transport processes. In this work, the dispersion coefficient was estimated in a stretch of the Axios river, with the analytical procedure of the Fischer method, under different hydrological and hydrodynamic conditions. The most accurate equations for the dispersion coefficient were used to predict the concentration of conservative toxic pollutants released instantly into the Axios River upstream of Greece's border with the Former Yugoslav Republic of Macedonia (FYROM) (ANTONOPOULOS; GEORGIOU; ANTONOPOULOS, 2015).

In the Article 5 a NEWS global model was calibrated and then used to quantify the long-term trend of dissolved inorganic nitrogen (DIN) exports from two tributaries of the Jiulong River (southeast China). Scenario analysis and source tracking suggest that reductions in anthropogenic N inputs of at least 30% in North River (emphasis on fertilizers and manure) and 50% in West River (emphasis on fertilizers) could significantly improve crop quality. water and mitigate eutrophication in both river and coastal waters (YU et al., 2015).

Article 6 used a hydrodynamic model (MIKE 21) in conjunction with transport submodels and particle tracking to provide a comprehensive investigation of transport behaviors in Lake Poyang. Model simulations reveal that the water flow patterns prevailing in the lake cause a unique transport trajectory that mainly develops from the mouth of the catchment river to the downstream area along the lake's main flow channels, similar to the transport behavior From Rio. The pollutant transport trajectory and residence time of Lake Poyang are believed to have important implications for the steady deterioration of water quality and the associated rapid environmental changes during the flood period (LI; YAO, 2015).

Article 7 used an integrated UMRB modeling system, with a highly refined 12-digit sub-basin structure based on SWAT water quality model, which is capable of estimating landscape and water in the stream and yields pollutants in response to a wide range of alternative crop and/or management strategies and climatic conditions. All scenarios behaved similarly under historical and future climate, generally resulting in reduced erosion and nutrient loads to surface water bodies compared to baseline agricultural management (PANAGOPOULOS et al., 2014).

Article 8 described the identification of the dominant delivery mechanisms of pollutants in the watershed, the estimation of pollutant delivery rates in the flow (DR) from the sub-

basins to the outlet of the watershed and the development of a tool to estimate changes in the DR of pollutant in the stream for what-if scenarios. The Comprehensive Economic and Environmental Optimization Tool (CEEOT) modeling system, which consists of the SWAT and Agricultural and Environmental Policy (APEX) models, was used to develop a multiple regression equation to estimate the DRs of sediments and nutrients for this watershed. The models used 32-year climate data from 1981 to 2012. Results indicate that the flow of each sub-basin is the dominant factor that affects the DR for this basin (KANNAN et al., 2017).

Article 9 addresses two specific questions: How do temporal fluctuations affect forward and backward time distributions of water displacement when combined with spatial variability? and can mass transfer processes be quantified using conditional probabilities in spatially and temporally variable flow? Space-time trajectories are studied for generic flow conditions, with fully ergodic or only spatially ergodic velocity (CVETKOVIC et al., 2012).

In the 10th article, the hydrological component of the DELTA code aims to provide valuable information in this direction by using the DELTA/HYDRO semi-irregular triangulated (semi-TIN) topography model to establish surface flow paths that can reliably represent the natural features of a watershed, addressing several major physical hydrodynamic processes. The encouraging results obtained demonstrate the promising application potential of the model, which can be additionally complemented with a pollutant transport component to address the interactions of soluble chemicals between the soil surface and the terrestrial flow/channel, in the context of a model. fully integrated (MITA; CATSAROS, 2012).

Article 11 calculated the performance of the SWAT by modeling nitrate and phosphate at the basin scale. The most sensitive parameters for flow and nutrients were identified using the t stat and p values from the SWAT-CUP global sensitivity analysis. The goodness of fit of the monthly calibration measured by the coefficient of determination, Nash-Sutcliffe efficiency and standard deviation ratio of root mean square error observations were, respectively, 0.79, 0.64 and 0.60 for flow; 0.73, 0.71 and 0.54 for nitrate and 0.77, 0.76 and 0.49 for phosphate. During validation, the objective functions were, respectively, 0.81, 0.52 and 0.70 for flow; 0.68, 0.63 and 0.61 for nitrate and 0.82, 0.81 and 0.44 for phosphate. The results suggest that the simulated values of the variables adjust well to those observed and, therefore, SWAT shows promise to simulate nutrients in the watershed (KERAGA; KIFLIE; ENGIDA, 2019).

Article 12 constructed a hydraulic water quality model for the lower reaches of the Xiangjiang River in China using the hydrodynamic module and the convective diffusion module of MIKE21. Six pollution incident scenarios were simulated to investigate the pollutant transport process as affected by an upstream dam structure, the Changsha Comprehensive Control Project (CCCP) dam. Analysis of the results suggests that CCCP plays an essential role in controlling the transport and transformation of pollutants. With CCCP, the transport process is weakened and the dispersion effect is strengthened. (LONG et al., 2016).

The 13th aims to analyze the impacts of climate change on the fate and transport of FCB (fecal coliform bacteria). Forty GCM-RCM bias correction projections were applied to the modified SWAT model to examine various future climatic conditions at the end of this century (2076–2100). The modified SWAT model presented a satisfactory performance with regard to the seasonal variability of soil FCB values and FCB loading in water bodies. The modified SWAT model showed substantial proliferation of FCB in the soil (30.1% –147.5%) due to the increase in temperature (25.1%). Furthermore, the increase in precipitation (53.3%) led to an increase in FCB loads (96.0% –115.5%) from the soil to the water body. In the in-stream environment, stream bed resuspension was the dominant process that affected the amount of FCB in the stream. Therefore, the final loads of the FCB increased by 71.2% due to the increase in the peak velocity of the channel and the volume of water used due to the increase in precipitation (JEON et al., 2019).

In the Article 14 a heavy metal transport and transformation module is combined with the well-established SWAT model with the purpose of simulating the fate and transport of metals at the watershed scale. As a demonstration, the SWAT loaded heavy metal module (SWAT-HM) was calibrated to simulate the dynamics of zinc (Zn) and cadmium (Cd) in a watershed upstream of the Liuyang River in China, which was impacted by the activities mining for decades. The model simulations agreed reasonably well with the monitored results. After a 6-year simulation (2009-2014), the simulated concentrations of Zn and Cd were used as a surrogate for the Predicted Environmental Concentration (PEC), whereby an ecological risk assessment was conducted for the demonstrative mining area (MENG et al., 2018).

The 15th article studied modeling procedures to simulate the fate and transport of pesticides in a Japanese watershed. They have been demonstrated by providing model parameters related to hydrology, land use, pesticide fate and rice field management

methods. The water flows predicted by the PCPF-1 @ SWAT model in the Sakura River basin were accurate throughout the simulation year, with R2 and ENS Statistics greater than 0.74 and 0.71, respectively, for daily flow. The PCPF-1 @ SWAT model successfully simulated the fate and transport of mefenacet in the Sakura River, in which measured mefenacet concentrations peaked shortly after the initial herbicide application in May, and gradually decreased during the months of June and July (BOULANGE et al., 2014).

The 16th article simulated flow and water quality parameters, including total suspended solids (SST), total nitrogen (TN) and total phosphorus (TP), were compared to values measured in the watershed. The model satisfactorily simulated the flow of the river, but underestimated the variability of the flow (i.e., the brightness of this suburban watershed). With the built-in algorithms and parameters used to simulate the hydrological and water quality responses on urban lands, the SWAT model reasonably simulated the hydrological and water quality conditions in this suburban watershed. Modeling results confirmed that both TSS and TP were water quality concerns under current land use and management conditions in the watershed (QIU; WANG, 2014).

In the 17th and last selected article, the hydrology, sediment, nitrate and pesticide transport components of the SWAT were evaluated for the Sacramento River basin. The monthly Nash-Sutcliffe coefficients at the outlet of the watershed ranged from 0.48 to 0.82, indicating that the model was able to successfully predict water flow and transport of agricultural pollutants after calibration. The predicted sediment loads were highly correlated with river flow, while nitrate, chlorpyrifos and diazinon were moderately correlated with river flow. This indicates that the timing of farm management operations plays a role in the runoff of agricultural pollutants (FICKLIN; LUO; ZHANG, 2013b).

4. FINAL CONSIDERATIONS

This work carried out a systematic review protocol to investigate the most studied methods, software and pollutants in the contamination of watersheds. The main objective was to improve the understanding of the stage in which science is, providing relevant information to advance in this field.

As can be seen in Table 5, there is a convergence of authors in using the Soil and Water Assessment Tool (SWAT) software or in the combination of SWAT with other modules.

Considering the 17 selected works, although different substances such as pesticides, cadmium, zinc, fecal coliforms and sediments were addressed, the main substances studied were summarized as nitrogenous compounds (ammonium, nitrate, nitrogen or total nitrogen), with 9 occurrences and phosphate compounds (phosphate, phosphorus or total phosphorus), with 6 occurrences. The results found in this review may be useful to the scientific community, as it brings together and summarizes the last decade of development in this aforementioned field.

For future work, it is suggested to explore other databases in order to collect articles that may not be present in the databases covered by this work.

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REFERENCES

AMORIM, L. F. et al. Hydrological modeling using distributed rainfall data to represent the flow in urban watersheds. **RBRH**, v. 27, 28 nov. 2022.

ANTONOPOULOS, V. Z.; GEORGIOU, & P. E.; ANTONOPOULOS, Z. V. Dispersion Coefficient Prediction Using Empirical Models and ANNs | SpringerLink. **Environ. Process.**, n. 2, p. 379–394, 2015.

BOULANGE, J. et al. Development and validation of a basin scale model PCPF-1@SWAT for simulating fate and transport of rice pesticides. **Journal of Hydrology**, v. 517, p. 146–156, 19 set. 2014.

BRÊDA, J. P. L. F. et al. Modeling coordinated operation of multiple hydropower reservoirs at a continental scale using artificial neural network: the case of Brazilian hydropower system. **RBRH**, v. 26, 2 jun. 2021.

COSTA, F. DE P. D. et al. Impact of climate change on the flow of the Doce River basin. **RBRH**, v. 27, 5 dez. 2022.

CUI, Z.; WELTY, C.; MAXWELL, R. M. Modeling nitrogen transport and transformation in aquifers using a particle-tracking approach. **Computers & Geosciences**, v. 70, p. 1–14, 1 set. 2014.

CVETKOVIC, V. et al. Water and solute transport along hydrological pathways. **Water Resources Research**, v. 48, n. 6, 2012.

FICKLIN, D. L.; LUO, Y.; ZHANG, M. Climate change sensitivity assessment of streamflow and agricultural pollutant transport in California's Central Valley using Latin hypercube sampling. **Hydrological Processes**, v. 27, n. 18, p. 2666–2675, 2013a.

FICKLIN, D. L.; LUO, Y.; ZHANG, M. Watershed modelling of hydrology and water quality in the Sacramento River watershed, California. **Hydrological Processes**, v. 27, n. 2, p. 236–250, 2013b.

JEON, D. J. et al. Evaluating the influence of climate change on the fate and transport of fecal coliform bacteria using the modified SWAT model. **Science of The Total Environment**, v. 658, p. 753–762, 25 mar. 2019.

KANNAN, N. et al. Estimating sediment and nutrient delivery ratios in the Big Sunflower Watershed using a multiple linear regression model. **Journal of Soil and Water Conservation**, v. 72, n. 5, p. 438–451, 1 set. 2017.

KERAGA, A. S.; KIFLIE, Z.; ENGIDA, A. N. Evaluation of SWAT performance in modeling nutrients of Awash River basin, Ethiopia. **Modeling Earth Systems and Environment**, v. 5, n. 1, p. 275–289, 1 mar. 2019.

LI, Y.; YAO, J. Estimation of Transport Trajectory and Residence Time in Large River–Lake Systems: Application to Poyang Lake (China) Using a Combined Model Approach. **Water**, v. 7, n. 10, p. 5203–5223, out. 2015.

LIMA, G. R. T. DE; SCOFIELD, G. B. Feasibility study on operational use of neural networks in a flash flood early warning system. **RBRH**, v. 26, 12 maio 2021.

LONG, Y. et al. Simulating the Impacts of an Upstream Dam on Pollutant Transport: A Case Study on the Xiangjiang River, China. **Water**, v. 8, n. 11, p. 516, nov. 2016.

MENG, Y. et al. A heavy metal module coupled with the SWAT model and its preliminary application in a mine-impacted watershed in China. **Science of The Total Environment**, v. 613–614, p. 1207–1219, 1 fev. 2018.

MITA, C.; CATSAROS, N. Simulating pollutant transport over complex terrain: the hydrological component. **Open Chemistry**, v. 10, n. 4, p. 1223–1235, 1 ago. 2012.

PANAGOPOULOS, Y. et al. Surface water quality and cropping systems sustainability under a changing climate in the Upper Mississippi River Basin. **Journal of Soil and Water Conservation**, v. 69, n. 6, p. 483–494, 1 nov. 2014.

QIU, Z.; WANG, L. Hydrological and Water Quality Assessment in a Suburban Watershed with Mixed Land Uses Using the SWAT Model. **Journal of Hydrologic Engineering**, v. 19, n. 4, p. 816–827, 1 abr. 2014.

RAUTELA, K. S. et al. Application of ANNs for the modeling of streamflow, sediment transport, and erosion rate of a high-altitude river system in Western Himalaya, Uttarakhand. **RBRH**, v. 27, 10 out. 2022.

ROMERO, A.; OTA, J. J. Using artificial neural networks to determine sediment concentration at limit of deposition in storm sewers. **RBRH**, v. 26, 9 ago. 2021.

YU, D. et al. Modeling increased riverine nitrogen export: Source tracking and integrated watershed-coast management. **Marine Pollution Bulletin**, v. 101, n. 2, p. 642–652, 30 dez. 2015.

ZHANG, B. et al. SD–GIS-based temporal–spatial simulation of water quality in sudden water pollution accidents. **Computers & Geosciences**, v. 37, n. 7, p. 874–882, 1 jul. 2011.

ZHANG, L. et al. Response of non-point source pollutant loads to climate change in the Shitoukoumen reservoir catchment. **Environmental Monitoring and Assessment**, v. 184, n. 1, p. 581–594, 1 jan. 2012.