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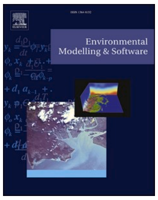

Integrated models of nutrient dynamics in lake and reservoir watersheds: A systematic review and integrated modelling decision pathway

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ABSTRACT

Eutrophication of inland water bodies is a serious environmental threat. This review explores current integrated models for lake and reservoir ecosystems that focus on nutrient dynamics at a catchment scale. Many studies applied either watershed or lake/reservoir models, however, 49 studies were finally selected that combined both. We derived a list of 21 watershed models, 23 lake/reservoir models, and 6 hybrid models in different sets of combinations, with a range of objectives (e.g. understanding the natural processes, predicting, and analysing climate change and land-use scenarios, or evaluating the different management options). Some integrated models had multiple applications whereas others were only applied once, with an uneven global geographical distribution.

To aid model selection by future users, we present a support tool discriminating the models by their features and application fields. This study encourages the development of open-source tools aiding interdisciplinary collaborations and further research in the field of integrated modelling.

1. Introduction

1.1. Nutrient pollution in freshwaters

1.1.1. Nutrient effects

Nutrient pollution poses a considerable global challenge for freshwater ecosystems worldwide (Fink et al., 2018; Moss, 2011; Tammeorg et al., 2023). As of 2012, 63% of the world's inland water bodies were classified as eutrophic, covering 31% of the total surface area of all water bodies (Zhang et al., 2021). In lakes and reservoirs, nutrient dynamics and eutrophication are influenced by various factors, including nutrient inputs from land uses, hydrological regimes, and climatic conditions that drive increased runoff (Singh et al., 2023; Yates et al., 2022). For example, agricultural runoff can contribute up to 70% of the phosphorus load in some lake catchments (Carpenter et al., 1998). Nutrient cycles, particularly phosphorus and nitrogen, play a key role in eutrophication, affecting phytoplankton biomass and productivity (Noori et al., 2021; Petty et al., 2020). Eutrophication, characterised by excessive nutrient enrichment, can result in harmful cyanobacteria blooms (Huisman et al., 2018) and oxygen depletion (Soares et al., 2023), impacting water quality and lake and reservoir ecosystems (Noori et al., 2021; Zamani et al., 2018). In addition, eutrophication can cause a shift from a clear, stable state to a turbid, and impaired state in shallow lakes (Scheffer et al., 1993). Eutrophication also degrades ecosystem functions and ecosystem services of lakes and reservoirs, leading to economic impacts such as increased water treatment costs

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(Thornton et al., 2013). For instance, eutrophic conditions can double the expenses for drinking water purification (Dodds et al., 2009). Geographically, Oceania has 23.1% of large oligotrophic lakes, while Europe has the highest proportion of mesotrophic lakes at 35.2%. Conversely, Africa has the highest proportion of large lakes experiencing eutrophication, with 88.8% impacted (Zhang et al., 2021). Understanding and quantifying the global impact of eutrophication is essential for developing effective management strategies to preserve lake and reservoir ecosystems and services.

1.1.2. *Nutrient pollution abatement strategies*

Globally, various policies and management strategies aim to restore and prevent freshwaters from eutrophication (Geist and Hawkins, 2016; Jeppesen et al., 2017). The primary approach in most countries is to reduce nutrient inputs to rivers and lakes through policies, legislative measures, or comprehensive planning frameworks. Examples include the European Union's Water Framework Directive, River Basin Management Plans in Europe (Fink et al., 2018; Hering et al., 2010; Skoulikaris and Zafirakou, 2019); Clean Water Act (Dodds et al., 2009; Smith, 2003), Great Lakes Water Quality Agreement Protocol between Canada and USA (Krantzberg, 2012), or Water Quality Standards in China (Zhao et al., 2018). Despite these efforts, many countries face challenges in managing nutrient loads and mitigating the consequent eutrophication of their water bodies (Fink et al., 2018; Schindler, 2006). For instance, 60% of freshwater bodies in Europe fail to meet good ecological status criteria (EEA, 2020) and 55% of lakes and reservoirs in the USA are classified as "impaired" (Dodds et al., 2009; EIP, 2022; Smith, 2003). In developing countries, particularly in South America, insufficient legislation and limited resources for environmental protection exacerbate threats to freshwater habitats (Torremorell et al., 2021).

To translate these regulatory efforts into effective action, states often adapt by implementing new monitoring programs, revising land-use regulations, and updating urban planning to meet established nutrient limits. However, identifying the most critical areas and predicting the effectiveness of these actions requires integrating empirical monitoring with advanced water quality modelling. Various water quality modelling tools have been developed to assess freshwater nutrient dynamics (Cox, 2003; Mooij et al., 2010; L. Yuan et al., 2020). These models are crucial for water management as they provide a quantitative framework for predicting outcomes of various management scenarios, which aids in informed decision-making (Bennett et al., 2013). Compared to empirical nutrient monitoring, models can reproduce a holistic picture of a complex ecosystem, simulate the interactions among multiple variables without much field cost and predict long-term impacts under varying conditions (Mooij et al., 2010; Voinov and Bousquet, 2010). Models can support policy development by incorporating regulatory limits on nutrient inputs or other boundary conditions and simulating the impacts of policy measures on water quality. They can integrate legislative frameworks and regulatory guidelines by simulating scenarios that reflect compliance with established standards, incorporating long-term monitoring data and adaptive management strategies to ensure ongoing alignment with regulatory objectives. For instance, they can be used to evaluate the effectiveness of nutrient reduction targets set by legislation or the outcomes of various regulatory scenarios (Crossman et al., 2019).

1.1.3. *Modelling lakes and reservoirs*

Notable differences exist between reservoirs and lakes, but the models used to model these two different environments are often the same. Reservoirs are subject to more significant human influence through regulation and management practices and may require models that account for artificial modifications in hydrology. Unless specific operations are conducted within the reservoir, such as dredging due to excessive silting or draining and refilling to facilitate maintenance of the outlet tunnels, the primary concern from a modelling perspective is the treatment of boundary conditions. Many contemporary models are sufficiently adaptable to simulate both lakes and reservoirs by adjusting these boundary conditions and incorporating additional features tailored for reservoir simulation. This paper aims to offer an overview of integrated models used to assess the impacts of nutrient loads on lake and reservoir ecosystems at a catchment scale. To this end, we categorised water-quality models into two main types: (i) watershed models and (ii) lake/reservoir models (referred to as "lake models" hereafter).

Watershed models are designed to capture the hydrological and nutrient inputs from the entire catchment area, making them effective for understanding how land-use changes, climate variability, and anthropogenic activities influence nutrient loads entering lakes, reservoirs, or coastal zones. However, watershed models often lack the detailed representation of in-lake processes, particularly in systems with large water volumes and long retention times, where mixing nutrient dynamics and biological interactions are more complex (Cardille et al., 2007).

Lake models, on the other hand, are optimised for simulating internal processes in lakes and reservoirs, including complex biological interactions, stratification, and nutrient cycling. They provide high-resolution insights into in-lake dynamics. However, using a lake model alone may not fully capture the influence of external nutrient inputs from the watershed, particularly when upstream activities, such as agriculture or urban runoff, play a significant role in shaping in-lake nutrient dynamics. By integrating watershed and lake models, external nutrient inputs and in-lake processes can be captured, offering a comprehensive understanding of nutrient dynamics across catchments and aquatic systems.

Varied land covers and upstream point sources contribute significantly to nutrient loads in watersheds. Agricultural lands and urban areas often contribute higher levels of nitrogen and phosphorus due to fertilisers and runoff, while forests and wetlands contribute less, with wetlands acting as nutrient sinks. Upstream point sources like wastewater treatment plants or industrial discharges also add to the nutrient load. Effective mitigation strategies include integrated watershed management, best management practices, and continuous monitoring to reduce nutrient pollution and improve water quality. To effectively capture nutrient dynamics, watershed models can be enhanced by incorporating detailed soil profiles to simulate nutrient transformations and vertical fluxes within soil layers potentially contributing through groundwater to the overall nutrient load e.g. INCA, SWAT, HSPF models (Donigian et al., 1995; Jackson-Blake et al., 2016; R. Douglas-Mankin et al., 2010). However, in those cases where an accurate knowledge of the soil stratigraphy and groundwater inputs is not available for validation, such a prominent level of detail might lead to the risk of over-parameterisation.

Both types of models play a crucial role in assessing the effectiveness of different management strategies, providing policymakers and managers with testable scenarios for water quality management actions (Fong et al., 2023; Wu et al., 2006; Zhan et al., 2023). However, most studies apply a single type of model. Thus, the integration of different models to holistically represent interconnected aquatic ecosystems remains limited (Alam and Dutta, 2021; Koelmans et al., 2001; Sunaryani et al., 2021). Together, watershed and lake models offer a comprehensive understanding of nutrient dynamics across catchments and in-lake systems, emphasising the importance of integrated modelling approaches. By combining elements of empirical, process-based, hydrological, or integrated models (e.g., PERSiST & INCA; SWAT, HSPF), these approaches can effectively capture interactions within soil layers and between terrestrial and aquatic systems.

1.2. *Importance of model integration*

Model integration refers to the process of combining multiple models or components into a unified framework to simulate complex systems more comprehensively. Integration, also known as "coupling," can be achieved in diverse ways. A common way to categorise model integration is based on whether the coupling is offline or online (Grell et al., 2004). Offline coupling involves running individual models separately and exchanging information in a one-way direction (outputs of one model serve as inputs to the second model) at specific time steps or intervals. Such an approach is often used because it simplifies the modelling chain, is computationally less demanding, and is suitable for one-way systems. For instance, offline coupling is often a sufficient way to model watershed-lake systems where nutrients flow from upstream to downstream, or when individual models have different time scales (Couture et al., 2014; Crossman et al., 2019). Online coupling, on the other hand, implies the simultaneous execution of different models, providing dynamic feedback to each other. This approach can enable a more realistic representation of the two-way interaction between the system components. For such reasons, online integration is more suitable for dynamic and tightly coupled systems (Baklanov et al., 2014; Mackay et al., 2009).

The integration of watershed and lake models is pivotal in evaluating the nutrient status of water bodies (Akomeah et al., 2021; Mankin et al., 2003), predicting long-term water quality trends and conducting impact assessments under diverse scenarios such as land-use changes or management options (Fong et al., 2023). The approach enhances prediction accuracy, supports adaptive management, and prevents misinterpretations that could arise from using models separately. Indeed, when models are used individually, important processes - for instance, the boundary conditions of a lake model or the retention capacity of lakes in a catchment may be oversimplified (Hejzlar et al., 2009). This can lead to incomplete or wrong interpretations of how the ecosystem works. Furthermore, the application of models is context-dependent, and the combination of watershed and lake models allows for targeted results based on the specific ecosystem context, where mitigation scenarios in both watershed and lake may be simulated.

1.3. *Research gap and objectives*

In the existing literature, numerous watershed and lake models are tailored to specific contexts and ecosystems, based on diverse theories and algorithms, resulting in divergent outcomes in their simulation results when applied to the same system. This diversity may represent real process uncertainty, and can unintentionally trigger confusion among users, leading to disparate management decisions if model validation with locally measured data cannot be performed. Moreover, the choice of a model can depend on familiarity rather than objective selection criteria (see e.g. “Chapter 5 - Model Selection and Use” in (National Research Council, 2007)). The increasing use of modelling approaches requires a structured method for identifying and categorising model combinations, aiding researchers in selecting suitable models for their studies or guiding water management policies. To address this need, we conducted a systematic literature review focusing on integrated modelling tools (watershed and lake models) that assess (i) nutrient runoff from land to surface waters and (ii) their impacts on lake and reservoir ecosystems. The main aims of this systematic review are (1) to offer an overview of integrated models employed to evaluate the impacts of nutrient loads on freshwater ecosystems, and (2) to provide an integrated modelling decision pathway tool based on this overview. We distinguish the modelling methodologies, the performance metrics, the application context, and the simulated scenarios to aid in adaptive measures and management decisions.

To achieve such aims, this review addresses five main objectives: (1) Identify the publication trends and the various applications of integrated models; (2) Identify the specific attributes of the watershed model used for the assessment of nutrient sources, fluxes, and nutrient loading; (3) Identify the specific attributes of lake models employed for evaluating the impact of eutrophication and assessing water quality in lakes or reservoirs; (4) Delineate the various configurations of model integration existing between watershed models and lake/reservoir models; (5) Develop an integrated modelling decision pathway tool aimed at guiding future modellers or researchers in the selection of appropriate models adapted to their specific research inquiries.

2. Material & methods

2.1. *Protocol and eligibility criteria*

The systematic review protocol followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Protocol 2020 checklist (Page et al., 2021), ensuring methodological transparency and consistency throughout the study (see Supplementary Table A1). The review question was framed based on the PECO-ST approach (Population, Exposure, Comparison, Outcome, Study type) as outlined in the methodology proposed by (Morgan et al., 2018). To begin, (i) the population of interest encompassed the combination of watershed and lake models employed in lake or reservoir ecosystems. Subsequently, (ii) the exposure of interest included the nutrient sources (nitrogen, phosphorus), fluxes, and nutrient loads within freshwaters. (iii) The comparison of interest incorporated the validation and performance assessment of the models. (iv) The outcome of interest constituted the nutrient loads impacting lakes or reservoirs at a catchment scale. (v) Study types encompassed diverse literature formats, including articles, reviews, or conference proceedings. The eligibility criteria, detailed in Table 1, were formulated to emphasise the recent integration of models applied to lake or reservoir ecosystems, specifically targeting studies addressing nutrient pollution dynamics at a catchment scale.

2.2. *Search strategy*

The literature search strategy was systematically developed by i) identifying the key concepts underpinning our research (see Supplementary Table B1). (ii) devising appropriate search terms for each concept (iii) employing Boolean operators (i.e. AND, OR; see Table 2); on our databases to combine the search terms effectively.

Given the broad scope of our research question, we executed our search across two primary databases (i.e. Scopus and Web of Science) and the combination of results from two distinct search strategies within each (see Table 2). Our objective was to maximise inclusivity while maintaining specificity in our research inquiries. All articles published up to the search date of July 4, 2022, were considered, while those preceding the year 2000 were excluded to focus on recent model applications. Furthermore, we combined database searches with manual searches conducted by various co-authors to guarantee comprehensive identification and selection of pertinent literature. This last step did not result in any additional papers, demonstrating the robustness of our automated search methodology.

2.3. *Selection process*

2.3.1. *Level 1 screening – title & abstract*

The PRISMA flow diagram was executed for this review, consisting of four primary steps: (i) identification, (ii) screening, (iii) eligibility, and (iv) inclusion (Fig. 1). During the initial step of identification, (i) the records obtained through our search strategy were compiled and organised in the reference manager Endnote (Hupe, 2019). From the two databases, 1007 records (articles, reviews, conference reports) were identified from Web of Science and 1114 records from Scopus. Subsequently, a successive removal of duplications was processed resulting in a pool of 1403 unique records which underwent a systematic screening procedure. Then, (ii) all the records were evaluated by scrutinising the titles and abstracts (level 1 screening). This preliminary screening phase involved checking for coherence with the eligibility criteria based on the titles and abstracts with the question: Is this reference pertinent to the scope of our review? (Yes/No/Maybe).

Table 1
Eligibility criteria for the inclusion of studies in the systematic review. Studies must meet all the criteria listed below to be included in the review.

Inclusion Criteria
1. The study was published in the year 2000 or later (to ensure the inclusion of recent model combinations).
2. The study is written in English (to facilitate comprehension and analysis)
3. The study applied a lake or reservoir model with a primary focus on nutrient pollution.
4. The study applied a watershed model with a primary focus on nutrient pollution.
5. The models were applied at a catchment scale (watershed model) and for a lake or a reservoir (lake model).
6. The study employed either online or offline integration of at least two models, encompassing both a watershed and a lake model, with a focus on nutrient pollution.

Table 2
Search terms in each database (TS = Topic; AK = Author Keywords; "TITLE_ABS-KEY" = Search only in title, abstract, and keywords). The asterisk (*) represents a wildcard character used in Web of Science/Scopus searches to include variations of a keyword.

Databases	Search Terms
Web of Science: search 1	(((TS=(nutrient* OR eutrophication)) AND TS=(catchment*)) AND TS=(lake* OR reservoir*)) AND TS=("integrat*model*" OR model*)
Web of Science: search 2	((((TS=(nutrient* OR eutrophication)) AND TS=(lake* OR reservoir*)) AND TS=("integrat*model*" OR model*))) AND AK=(catchment* OR basin* OR watershed)
Scopus: search 1	TITLE-ABS-KEY (("integrat*model*" OR model*) AND (nutrient* OR eutrophication) AND catchment* AND (lake* OR reservoir*))
Scopus: search 2	TITLE-ABS-KEY (("integrat*model*" OR model*) AND (nutrient* OR eutrophication) AND (catchment* OR basin* OR watershed) AND (lake* OR reservoir*))

Then, four co-authors independently performed a level 1 screening on citations that had received a "maybe" label during the original screening phase. A total of 1217 records were excluded resulting in 186 papers selected based on the level 1 screening process (see Supplementary Table C1).

2.3.2. *Level 2 screening – full-text*

A full-text screening (level 2) was then performed, following the criteria we established for the paper selection (Table 1). Each paper underwent a double screening process, performed independently by two co-authors to minimise potential biases. Conflicting instances were discussed among the two co-authors and a third impartial co-author's opinion was solicited to make the final decision following the eligibility criteria. Subsequently, 27 papers were excluded from further consideration due to the unavailability of full-text documents, leaving 159 papers for the eligibility assessment. Then, (iii) the eligibility assessment of the screening process (level 2) was performed, leading to the exclusion of 110 papers considered irrelevant to the scope of our research. As a result, for the last step (iv), 49 papers that met the eligibility criteria were selected for this systematic review. In conclusion, our systematic review research demonstrated efficacy with a broad scope, mitigating the risk of overlooking any relevant papers.

2.4. *Data extraction and risk of bias*

All screened publications were acquired in full-text format. The data was then extracted and compiled in an online Excel database. Two co-authors analysed each paper to avoid any potential bias at this phase. In the initial phase, raw information was collected, guided by the general understanding of the data considered pertinent to our research scope. This process resulted in the creation of a data file (see Supplementary Table D1) containing two categories of metadata.

(i) **Model metadata:** This includes metadata about the models, incorporating the categories such as model name, model types, description, application area, temporal and spatial scales, inputs, outputs, accessibility, model documentation, application references and application frequency.

(ii) **Paper metadata:** This includes metadata on the model application, including authors' names, year of publication, title, journal, models applied, study area, country, data collection methods, model validation processes, performance measures, the purpose of model integration, the type of research question addressed.

Table 3
Summary of reviewed papers by characteristics, including study type, climate, data collection methods, model validation, performance metrics, integration purpose, and research questions.

Paper Characteristics	Number of papers	% of papers	Paper Characteristics	Number of papers	% of papers
Study case			Good – N load	4	40%
Lake	31	63%	Moderate – N load	3	30%
Reservoir	18	37%	Low – N load	3	30%
Climate			Good – P load	5	42%
Temperate	26	53%	Moderate – P load	3	25%
Tropical	3	6%	Low – P load	4	33%
Continental	17	35%	**Lake model performance**		
Dry	3	6%	Good – N load	4	31%
Data collection			Moderate – N load	6	46%
Based on literature	6	12%	Low – N load	3	23%
Environmental agency	41	84%	Good – P load	5	42%
Governmental data	25	51%	Moderate – P load	4	33%
Measured by researcher	6	12%	Low – P load	3	25%
N/A	3	6%	**Integration Purpose**		
Model validation			Watershed/Lake process interaction	49	100%
Comparison with observation	41	84%	Land-use scenario	17	35%
Compared with literature	3	6%	Management scenario	22	45%
N/A	5	10%	Climate scenario	13	27%
Validation methodology			Others	2	4%
Independent validation data	20	41%	**Research question Type**		
Calibration data	22	45%	Scenario analyses	31	63%
N/A	7	14%	Understanding mechanisms	26	53%
Watershed model performance			Model evaluation/ Optimisation	6	12%
Good - Flow	14	88%	Prediction	17	34%
Moderate - Flow	2	12%			
Low – Flow	0	0%			

Following the initial data extraction, a standardisation process was implemented to harmonise information across different models,

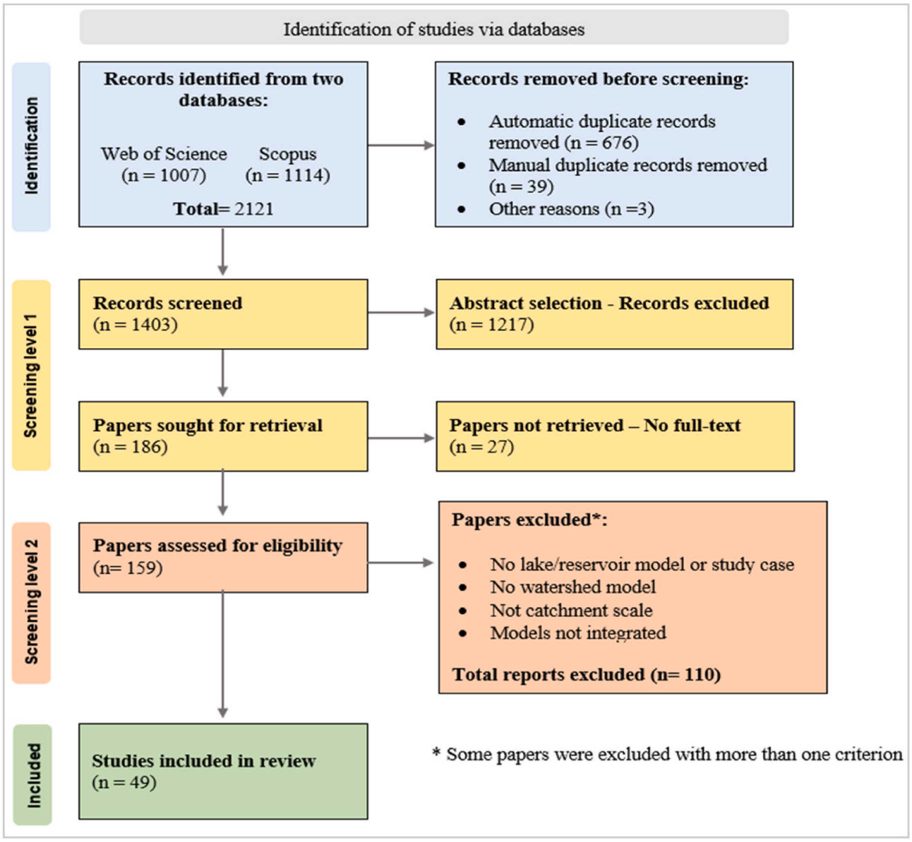

Fig. 1. PRISMA flow diagram for the systematic review.

facilitating later analyses and comparisons. To achieve this objective, a data extraction form was devised, including queries and primary outcomes (see Supplementary Table B2). This form contains 29 questions aimed at collecting information on both papers and the models. This standardisation approach was developed based on the information extracted from the articles. Certain categories that lacked data in specific papers, were omitted from further analysis. Following standardisation, co-authors independently validated the data extraction results.

Data extraction form (see Supplementary Table B2) considered several qualitative aspects of the reviewed papers related to the risk of bias. Such aspects included data sources, model validation methods, and performance measures. Although performance metrics were considered in the data extraction, a meta-analysis of model performance is beyond the scope of this review given the diversity of the models and their applications. Therefore, we do not express here any judgment about the validity of the models screened.

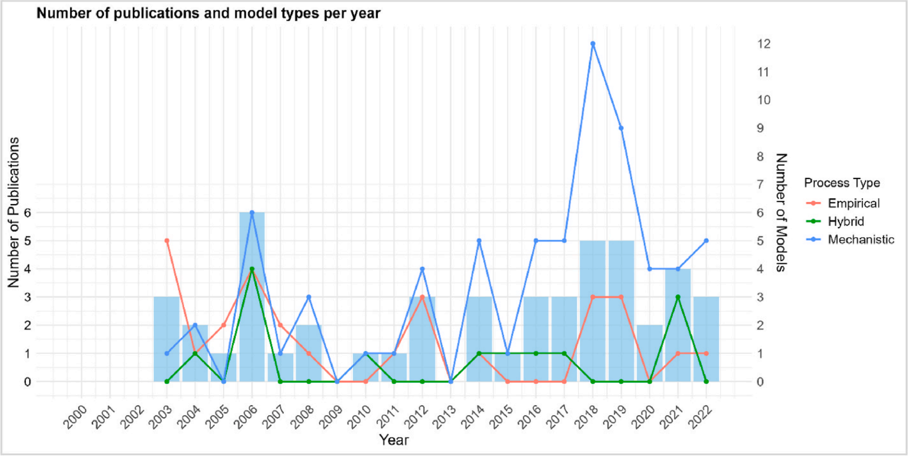

Fig. 2. Global trends of publication on model's integration approaches over time. The bars represent the number of papers applying integrated models for each year. The lines show the types of models applied in these papers, categorised as empirical (red), hybrid (green), or mechanistic (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results & discussion

3.1. Publication characteristics

3.1.1. The trends over time

Fig. 2 illustrates the temporal trend of (i) research publications on the integrated modelling approaches, specifically those integrating watershed and lake models and (ii) the temporal trend of the modelling process types. While the overall volume of publications has shown relative stability across preceding years, a noticeable increase is clear during the latter decade (2012–2022). Significant gaps in publication years are noted, with no records identified between 2000 and 2003, as well as in 2009 and 2013. However, a comparison between the periods (2000–2011 and 2012–2022) reveals a twofold increase in the mean publication rate, indicative of an escalating research interest in integrated modelling. Nevertheless, it is imperative to acknowledge the potential influence of broader trends, such as the overall expansion of scientific literature that can also explain this increase (Larsen and Von Ins, 2010). In addition, we did not observe a significant shift in model process types through the years despite having a trend of modelling processes driven by mechanistic models (see Fig. 2 and Table 4).

3.1.2. Geographic and climatic application trends

Table 3 provides an overview of the included papers which summarise the online accessible Excel file (Papers metadata) detailing their associated characteristics. Out of the 49 studies included, 31 articles (63%) applied their models to lakes, whereas 18 focused on reservoirs (37%). The model applications exhibited a global geographic distribution, with a notable concentration in Europe (31%), North America (33%), and Asia (22%), especially in China (Fig. 3). The majority of studies originated from developed countries, likely reflecting greater funding opportunities and subsequent publication volume (Ritz et al., 2010). However, the current application of modelling may be driven by the imperative to comply with directives and water quality regulations (section 1.1.2), particularly in developed countries such as the USA with specific standards and regulations to address nonpoint source pollution (Milon, 1987) or the EU (EEA, 2020; Ejigu, 2021). The concentration of study cases in these regions corresponds proportionally to the ongoing effort to restore or protect waterbodies such as lakes or reservoirs, for water quality purposes (EEA, 2020; Li et al., 2021; Tammeorg et al., 2023; Zhao et al., 2018). However, there is a noticeable scarcity of literature on the application of integrated models (watershed + lake) for nutrient management in developing regions, such as in South America, Africa, and some parts of Asia, despite eutrophication being a significant concern in lakes in these regions (Burigato Costa et al., 2019; Ongley, 2001). In these regions, the limited availability of accurate input data and existing knowledge gaps related to landscape and in-stream biogeochemical processes pose significant challenges to modelling water quality and nutrient transport (Ongley, 2001; Rode et al., 2010).

Table 4
Descriptive summary of the model variables.

Model characteristics	Number of models	% of models	Model characteristics	Number of models	% of models
Environment			**Spatial resolution watershed**		
Watershed	21	42%	Distributed	10	37%
Lake	23	46%	Semi-distributed	15	55%
Hybrid	6	12%	Lumped	1	4%
Processes			N/A	1	4%
Empirical	14	28%	**Spatial resolution Lake**		
Mechanistic	34	68%	0D	7	24%
Hybrid	2	4%	1D	12	41%
Data type			2D	5	17%
Deterministic	45	90%	3D	7	24%
Stochastic	3	6%	**Temporal resolution**		
Hybrid	2	4%	Event-based	2	4%
Time variation			Continuous	47	94%
Dynamic	44	88%	Both	1	2%
Steady state	5	10%	**Accessibility**		
Both	1	2%	Open source	22	44%
Application area watershed			Request license (free)	10	20%
Urban	3	11%	N/A	18	36%
Non-urban	8	30%	**Application frequency**		
Both	16	59%	1–2	38	76%
			2–4	8	16%
			>4	4	8%

Most model applications were situated in temperate (53%) or continental (35%) climates, with only 12% of the model applications in other climates such as tropical and dry regions. Additional insights can be found in Supplementary B Fig. B.1 and Fig. B.2 which picture the relationship between the model applications and their distribution across different climates. However, it is crucial to acknowledge that although the models featured in this review have been utilised within specific climatic domains, their applicability is not inherently limited to these regions (Qi et al., 2017). Indeed, various models in this review such as SWAT, AGNPS, HSPF, CE-Qual-W2, DYRESM-CAEDYM or PCLake have been applied in different climatic regions (Bucak et al., 2018; Wang et al., 2019; Wu et al., 2006; Zhang et al., 2018). We would argue that most of the models from this review could probably be applied in other climatic conditions potentially with further development, thereby making their potential range of application larger than shown in this review. While the main geographic and climatic limitations for model applications may depend on the model components and model functioning itself, specific modifications may be needed for biogeochemical processes in certain environments such as continental regions with eventual ice periods during winter (Shrestha and Wang, 2019). However, the main limitation often lies in the availability and quality of spatiotemporal data in the study area or regions for model inputs, calibration, and validation (Iqbal et al., 2018).

3.1.3. Model applications & methodology

Globally, among the 49 papers, the models used diverse types of data collection for their model inputs, primarily sourced from environmental agencies (84%) and/or based on governmental data (51%). 69% of the studies assessed both nitrogen and phosphorus, while 20% focused exclusively on phosphorus, and 6% concentrated solely on nitrogen. Model validation was predominantly conducted by comparing model outputs with field observations within a time series of observations (84%). Among the studies analysed, 41% employed independent validation datasets collected during different periods from those used for calibration, ensuring a robust assessment of model performance. Conversely, 45% of the studies used the same dataset for both calibration and validation, which may introduce bias and overestimate model accuracy. Notably, 14% of the studies lacked transparency, as they did not provide explicit details regarding their validation methodologies, raising concerns about the reliability of their findings (Eddy et al., 2012). Among the diverse performance metrics adopted, the most common metrics were Root Mean Squared Error (RMSE) (35%), R^2 (51%), and Nash-Sutcliffe Efficiency (NSE) (37%) e.g. Supplementary D Table D.1. However, despite the variety of metrics, only 16 out of 49 papers provided performance data for the watershed modelled specifically related to water flow. In terms of nutrient modelling, only 12 studies reported performance metrics for nitrogen (N) and/or phosphorus (P) loads within watershed models. Similarly, for lake models, only 14 studies included performance data on N and/or P loads, highlighting a significant gap in the reporting of comprehensive model performance across key environmental variables. Performance was categorised into three groups based on the values of key metrics: (i) good performance, characterised by R^2 values between 0.6 and 1 and NSE values between 0.5 and 1; (ii) moderate performance, with R^2 values ranging from 0.4 to 0.6 and NSE values between 0 and 0.5; and (iii) low performance, where R^2 values fell between 0 and 0.4, and NSE values were less than 0 (e.g., see Table 3). As for the aims of the investigated

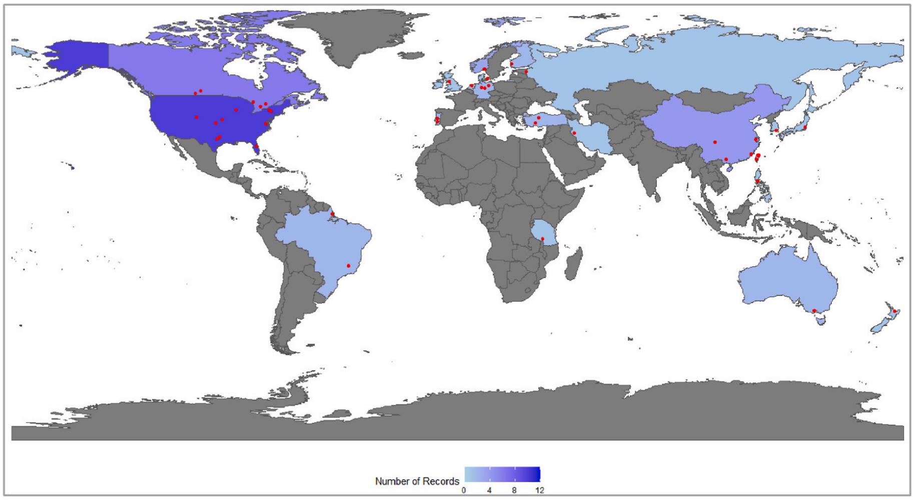

Fig. 3. Geographic distribution of the 49 studies. Red dots indicate the exact location of considered studies, while the colormap provides the total number of studies recorded in each country. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

studies, the purpose of model integration was primarily to gain a better understanding of the relationship between the watershed and its water body in a specific area (100%), to simulate management scenarios (45%), to explore various land-use scenarios (35%) and/or climate scenarios (27%). The studies included in this review were used to answer several types of research questions or objectives such as understanding ecosystem mechanisms (53%), scenario analyses (49%), prediction (34%), or policy support (29%).

3.2. Model characteristics

3.2.1. The models

A detailed description of the characteristics of the models and papers included in this literature review is provided in the online Excel file, (see Supplementary D Table D.1). Table 4 describes a comprehensive synthesis of various model types and associated variables. The online Excel file offers deeper insights into the model characteristics. Furthermore, a glossary containing the definition of model terminologies used in the papers is available in the supplementary material (**Supplementary B Glossary**). A total of 50 distinct models were analysed from 49 selected papers, with 42% of the models classified as watershed models, 46% as lake/reservoir models, and 12% as hybrid models, thereby demonstrating the substantial diversity in contemporary model applications (L. Yuan et al., 2020). Different model types serve various objectives: empirical models provide quick assessments based on observed data (Taylor et al., 2009); mechanistic models simulate detailed processes to predict impacts of land use and management practices (Bairda et al., 2003); hybrid models combine these approaches for a balance of simplicity and detail (Wang et al., 2022); stochastic models account for variability and uncertainty (Cai et al., 2018); integrated models assess interactions across environmental processes.

Building on Cox's (2003) taxonomy, the models were further categorised into empirical (28%), mechanistic (68%) or hybrid (4%) processes. These models mostly used deterministic (90%) data, occasionally incorporating stochastic (6%) data, and exhibited dynamic (88%) or steady-state (10%) temporal variability. Most models from this review are designed to simulate chemical and/or biological processes within the boundaries of a system. Models focusing on chemical processes within watersheds simulate the movement and transformation of chemicals across the landscape, while models concentrating on chemical and biological processes within lakes or reservoirs extend their focus to include interactions between chemicals and the biological components of aquatic ecosystems, such as nutrient cycling, algal growth dynamics, and organism behaviour. Our findings indicate that most models identified are characterised by their mechanistic nature, deterministic framework, and dynamic simulation capabilities (**see Supplementary B Glossary**), emphasising the aim of representing real-world processes and predicting system behaviour over time. These are indeed the primary objectives of the research studies conducted in the reviewed papers: (i) predicting long-term changes or (ii) understanding nutrient mechanisms and their impacts on water bodies' ecology (see Supplementary D table D.1). Indeed, mechanistic models are often better suited than empirical models to simulate changes in flow rate and water quality within catchments or lakes when appropriately calibrated but also to test different scenarios (Cox, 2003; Zhang et al., 2018). Moreover, deterministic models are prevalent in our selected publications due to the observed strong relationship between inputs (nutrient sources) and outputs (nutrient loads) within integrated catchment/lake systems (Reckhow and Chapra, 1999). Lastly, the predominance of dynamic models in our review sample reflects their ability to assess ecosystem changes over time, capturing both spatial and temporal variability, which is crucial for addressing predictive inquiries (Cox, 2003; Shaolin, 2005).

The application areas of the watershed models were grouped into urban (11%), non-urban (30%) or both (59%). The last category applies to those catchments including both natural and anthropogenic areas. Out of the 21 watershed models in this review, 37% were distributed, 55% were semi-distributed, and 4% were lumped, indicating variations in the spatial representation and complexity of the models (**see Supplementary B Glossary**). The high proportion of distributed/semi-distributed hydrological models compared to the lumped models can be explained by their ability to simulate spatial variability of rainfall and physicochemical features within a basin with better performance than the lumped model (Smith et al., 2004). However, some studies have shown that distributed modelling approaches do not always provide a better simulation than lumped modelling approaches (Reed et al., 2004). Lake models were classified based on their dimensional attributes, including 0D (24%), 1D (41%), 2D (17%), and 3D models (24%) with some models being flexible in their spatial resolutions. The dimensions simulated by a particular model will reflect its physical complexity and also its suitability for specific applications and study cases (Cox, 2003). For instance, a 3D lake model might be used to simulate the thermal structure and nutrient dynamics of a large and deep, stratified water body like the Feitsui reservoir, where horizontal variations in temperature, dissolved oxygen, and nutrient concentrations play significant roles in ecosystem dynamics and water quality management (Chen et al., 2021). The main input requirements and outputs for each model including various environmental data were outlined (see Supplementary D Table D.1). Additionally, our assessment of model accessibility revealed that out of the 50 models, 44% of them were open sources, 20% of them requested licenses usually free for research purposes, and 36% of them lacked the availability of source codes. Furthermore, documentation, application references, and application frequency were included in the model metadata sheet for comprehensibility. As for the application frequency, 76% of the models were applied only once or twice, 16% between two and four times, and only 8% were applied more than four times.

3.2.2. Model integrations

Fig. 4 illustrates the integration of watershed models with their corresponding lake models. The watershed models were grouped into distributed, semi-distributed, and lumped models, while lake models were categorised based on whether they included food-web dynamics or not. Hybrid models, combining watershed and lake components, are further divided into three groups: distributed models without food-web dynamics, distributed models with food-web dynamics, and semi-distributed models with food-web dynamics. For every model, we considered how many times they were applied individually as well as the frequency of integration with other models.

The watershed models SWAT (Srinivasan and Arnold, 1994), HSPF (Donigian et al., 1995) and INCA (Whitehead et al., 1998) emerged prominently in the current literature, dominating other models in terms of application frequency in integrated studies (SWAT: 11, HSPF: 6, INCA: 5) and displaying the most diverse integrations with lake models (see Fig. 4). When only considering lake models, the top three models employed were CE-QUAL-W2: 11 (Wells, 2006), PCLake: 4 (Janse and van Liere, 1995) and DYRESM-CAEDYM: 3 (Luo et al., 2018). The most used models are open source (see Table 3 and Supplementary D Table D.1) which facilitates their application. The exception is INCA, which is only open for use to academics upon request, or DYRESM-CAEDYM where its open accessibility was not found. Various models were coupled to other model(s) with a frequency of integration ranging between one and three times (see Fig. 4). Thus, only a few individual models were applied multiple times and most modelling combinations found in the literature consist of a single integration with no combination exercises with other models e.g. Catchload ~ CHAIN-Lake (Bilaletdin et al., 2005, 2008); NDP ~ NDP-Pond (Cui et al., 2022; Huang et al., 2018) and A2EM ~ RHESSys (Zia et al., 2016). Among the 50 watershed models reviewed, 22 models lacked clear citation of download sources. This absence has significant implications for reproducibility as it prevents other researchers from easily accessing the same tools to validate findings. The lack of transparency not only hinders trust in scientific results but also restricts the broader application of these models. Consequently, some models may be underused or confined to specific research areas, reducing their broader applicability and impact on advancing integrated modelling approaches. However, many lake models applied several times have often been integrated into watershed models such as AGNPS (Young et al., 1987), INCA, PERSIST(Futter et al., 2014), HSPF, and SWAT, while most applied watershed models have been coupled with lake models such as WASP (Ambrose et al., 1993), TRAM (Kneis et al., 2006), CE-QUAL-W2, and PCLake. This indicates that further combination of models is possible even for those not applied yet or only in a few studies. Alternatively, modellers could explore the various integration options or choose a different approach. With the diverse array of combinations, linking a watershed model with a lake model using an offline approach remains feasible for most cases. It seems that using the outputs of a watershed model in terms of N and P loading, for example, matches well with the boundary conditions of many lake models. Additionally, several lake modules were initially developed within the watershed model resulting in hybrid models e.g. MIKE-SHE (Refsgaard and Storm, 1990; Sonnenborg et al., 2012); WaterGap3.2 (Fink et al., 2018), CNHS (Cobourn et al., 2018) or Nice-lake (Nakayama and Watanabe, 2008).

3.3. Integrated pathways - decision support

This systematic review demonstrated the current availability of peer-reviewed publications documenting integrated modelling approaches for lakes and reservoirs at a catchment scale. However, selecting the appropriate models for a particular study case can be challenging. Many of the models presented in this review vary widely in their complexity, which relates to watershed models (spatial resolution/representation; components, processes, inputs/outputs, etc.) as well as lake models (spatial dimensions, temporal resolution, food-web integration, etc.) making it difficult to evaluate and compare the data demands and expertise necessary for model applications. To aid modellers in model selection when adopting an integrated modelling approach, we developed an integrated modelling pathway used as a decision support tool based on the models and papers metadata Excel sheet of this review (see Supplementary D Table D.1). Fig. 5 represents this decision support pathway to help and guide modellers to choose either a watershed or lake model individually or a combination of both based on this review by using filter options within the model or paper metadata tables. However, it is important to note that this decision support tool is non-exhaustive, and further investigations on the specific models should be considered for definitive selection. These tools are intended to be used as initial guidance for supporting model selections and comprise several steps before final selection. Future modellers can follow the suggested steps and select different criteria from the model and paper metadata to filter the model list systematically.

Step 1 – Define the research question: It is crucial to clearly define the purpose of the study and the modelling approaches used: What research questions must the models address? We categorised the applications of the papers of this review based on their primary research question and the intended purpose of the modelling approach. The categories identified are as follows:

(i) **Prediction** refers to estimating future states or outputs based on a model. In our review, we distinguish between two types of prediction depending on the research question:
  - Short-term forecasting: This involves predicting specific future values based on current or historical data. It typically aims to provide early warnings or real-time predictions for immediate management or decision-making, e.g., forecasting harmful algal blooms in response to sudden changes in nutrient levels (Kuo et al., 2006). Empirical or machine-learning models are often preferred for this type of prediction due to their ability to identify patterns and relationships in the data (Moreido et al., 2021).
  - Long-term projection: This focuses on estimating potential future outcomes based on a set of predefined scenarios or assumptions e.g., predicting the impacts of climate change on water quality over the next 40 years (Zia et al., 2016). Process-based models are typically better suited for long-term projections, as they incorporate underlying physical, chemical, and biological processes, allowing for the exploration of different future scenarios (Hanus et al., 2021).

(ii) **Scenario analyses** involve using models to evaluate the potential outcomes of different hypothetical situations, management actions or support policymakers. This approach is designed to answer "what-if" questions and to compare the effects of various scenarios on the system being modelled e.g., the impact of different land-use strategies on nutrient loading in a watershed (Barlund, 2006; Silva et al., 2019).

(iii) **Understanding current mechanisms** by using models to investigate and gain deeper insights into the underlying processes and interactions within the catchment system. This approach aims to enhance scientific understanding of complex relationships e.g., studying how nutrient dynamics affect primary productivity in a lake (Kuo et al., 2006).

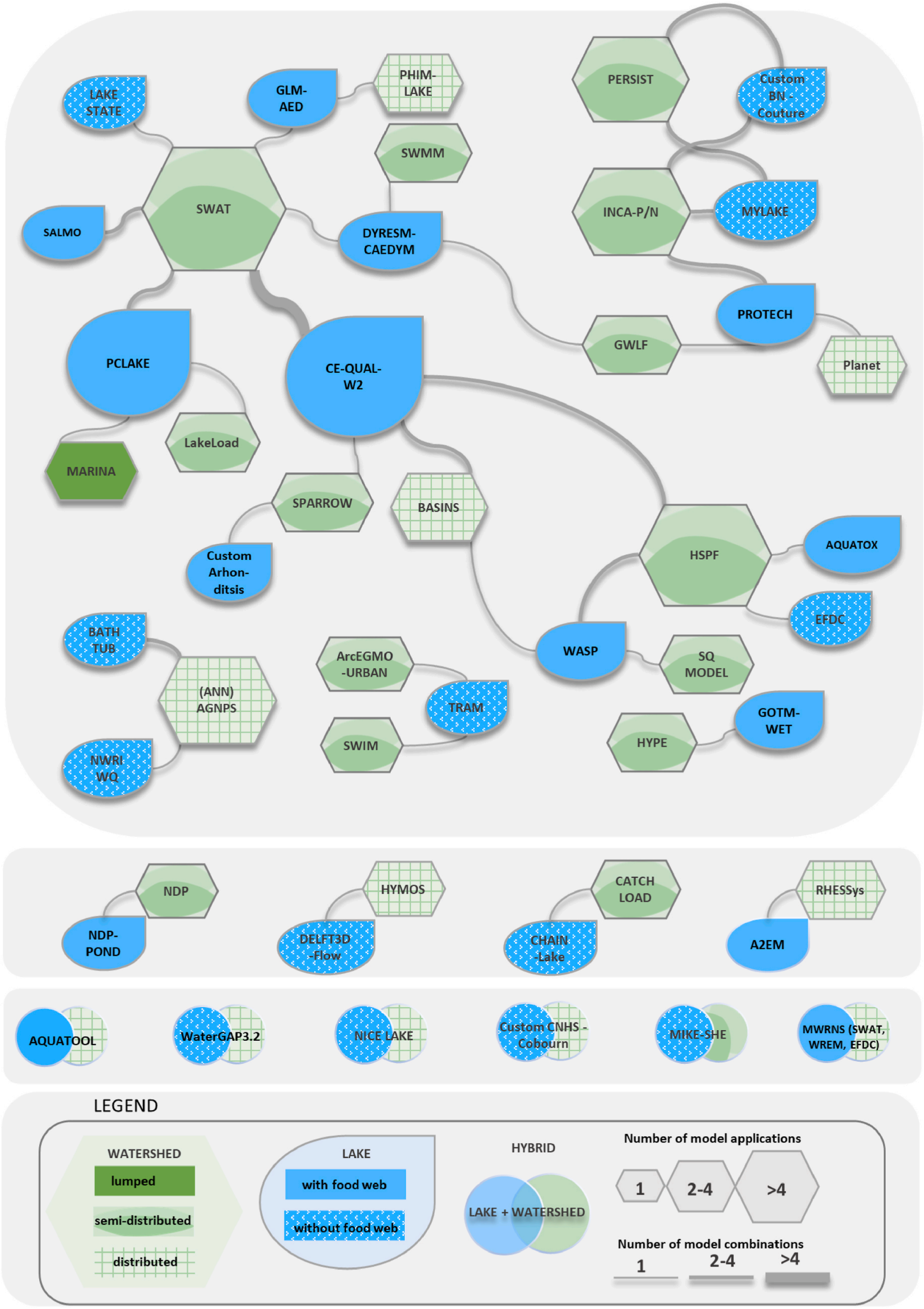

Fig. 4. Model integrations and applications frequency | Watershed models are in green, patterns shapes represent lumped, semi-distributed and distributed. Lake models are in blue, patterns represent with or without food web. Hybrid models are blue and green. The size of the shape represents the model application frequency. The grey line represents the integration link with another model, line thickness represents the integration frequency. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

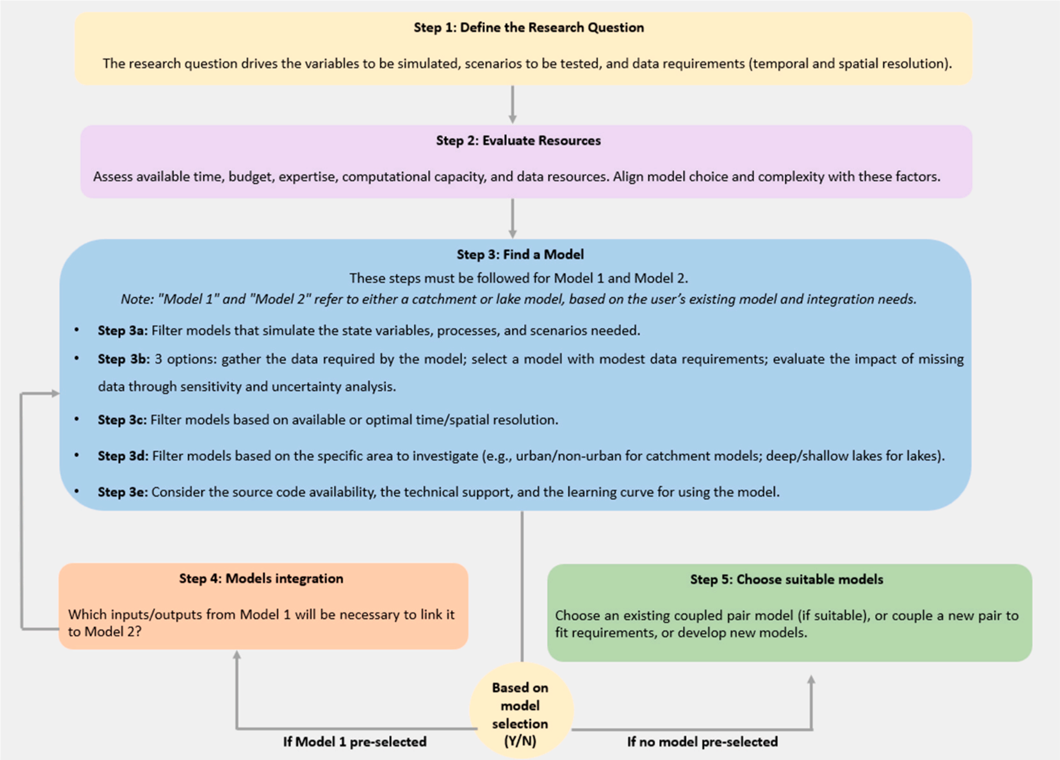

Fig. 5. Schematic representation of the integrated modelling decision pathways. The figure outlines a step-by-step approach for selecting and integrating watershed and lake models based on research objectives, available resources, and model requirements. The pathway accommodates scenarios where either a catchment or lake model is pre-selected or where no pre-selection has been made.

(iv) **Model evaluation and optimisation** refer to the assessment, calibration, and refinement of models to improve their performance and accuracy. This process involves validating model outputs against observed data, adjusting parameters, and evaluating the model's sensitivity and robustness (e.g., calibrating a hydrological model to better simulate streamflow based on observed data). The aim is to enhance model reliability, reduce uncertainties, and ensure that the model is fit for its intended application.

This first step will facilitate the identification of the main purpose(s) of the modelling approach but also the screening of the relevant parameters to consider such as the temporal and spatial scale, data requirements, model, etc. As an example, the aim of (Kong et al., 2022) "To study the effect of deforestation linked to climate change on the nutrient loads in a reservoir" could be categorised under scenario analyses, prediction, and understanding current mechanisms. The watershed model would need to consider processes such as nutrient transformation in forest soils to run the scenarios effectively. The temporal scale of the calibration and validation data should be chosen based on the process that needs to be assessed (e.g. the influence of short-term runoff events). The users may require a lake model capable of simulating long-term trends with limited computational cost, particularly if the study aims to assess the cumulative impacts of climate change (e.g., changes in nutrient dynamics over several decades). However, it is also common in climate change modelling to simulate shorter periods under projected future climate conditions, e.g., using climate scenarios for 2050 or 2070 (IPCC, 2018). While this approach may involve certain assumptions, it can be computationally efficient. In cases where large spatial heterogeneity exists, a 2D or 3D model might be preferable to a 1D model, which assumes limited spatial variability.

Step 2 – Evaluate resources: Before selecting or developing a model, it is essential to evaluate the resources available for the project. The choice of a model and approach should align with available time, budget, expertise, computational capacity, and data resources, as these factors influence decisions regarding model complexity, data requirements, and computational needs. For example, small projects often use open-source or familiar commercial models, while larger projects may develop new models, modify existing ones, or use ensembles to address uncertainty. Similarly, smaller projects rely on existing data, whereas better-resourced projects can design studies to fill knowledge gaps.

The availability of expert model developers, domain specialists, and software engineers determines whether automated calibration and optimisation are feasible, or simpler, manual approaches are models more practical. Computational capacity also plays a role, as lake model runtimes increase with complexity. Small projects prioritise minimising costs, while larger ones use advanced computing for comprehensive sensitivity and uncertainty analyses. Projects with similar budgets but differing time constraints may make different trade-offs. For example, time-sensitive projects might prioritise robust numerical uncertainty characterisation for urgent decisions, while less time-sensitive projects allocate resources to data collection and model refinement. Ultimately, aligning modelling choices with project goals and resources ensures optimal outcomes.

Step 3 – Select a model: Users can further refine the available models by focusing on watershed, lake or both models depending on the initial purpose of the research question. Then, these steps can be followed in two ways: (i) searching for integrated models directly or (ii) focusing on one type of model (watershed or lake) and using step 4 to identify suitable models for integration.

Step 3. A: Based on the model's purposes, it is essential to retain models simulating the state variables, processes, and scenarios required by the study. For instance, to forecast harmful algal blooms (HABs), lake models should include the most likely HAB species in the lake in question and sufficient detail of the processes believed to drive HABs in that system. Depending on the lake, these processes may include runoff of nitrogen and phosphorus from nearby irrigated land after a rain event, stratification and destratification driven by meteorological conditions, phosphorus release from lake sediments (Z. Yuan et al., 2020), top-down control by grazers, changes in dissolved N ratios in lake surface waters, or other relevant processes. Selecting models that adequately represent these key factors ensures the accuracy and relevance of the forecasts.

Step 3. B: Models may require specific types or resolutions of data that the users do not have access to. In such cases, it is important to assess whether the data availability of the study meets the model requirements. If data limitations exist, users have three options: (1) gathering additional data to meet the model's needs, (2) choosing a model with more modest data requirements, or (3) conducting a sensitivity and uncertainty analysis to evaluate the impact of missing data on the model's outcomes. In some cases, data interpolation techniques, such as splining can be used (Larson et al., 2023).

Step 3. C: The model purpose may also require a minimum of temporal and spatial resolution to answer the specific research question. For instance, studying phytoplankton bloom dynamics that change within a day often necessitates a model with an hourly time step. However, the appropriate time step and spatial resolution depend heavily on the underlying drivers of these subdaily changes. For example, if the phytoplankton bloom is driven by stratification, where buoyant phytoplankton rises to the surface due to reduced vertical mixing, the model would additionally require sufficient vertical resolution to capture the effects of hourly wind mixing and solar heating. In contrast, if blooms are driven by horizontal aggregation due to wind-driven transport towards a particular shore, a 3D model with fine horizontal spatial resolution would be more suitable.

Step 3. D: Depending on the study case and research question, the application area may be important for model selection, especially for the watershed models and the catchment characteristics. For example, some models like SWMM (Metcalf, 1971) are more suited for urban areas with their incorporation of grey infrastructures such as drainage or sewage systems (Silva et al., 2019).

Step 4 – Model integration: If the users performed **Steps 1, 2 and 3** only for either a watershed or a lake model, they should assess what inputs/outputs the model needs/provides and repeat **Step 3** for the accompanying model.

Step 5 – Choose suitable models: The users can select from the remaining listed models. If they are left with multiple options, they can consider the combination examples from this review or create a new model combination depending on their needs. Conversely, in case none of the models are listed, the users should either make less strict requirements, search for additional modelling approaches, or consider creating customised models for their purpose.

Nevertheless, it is important to remember that this review is not exhaustive, other combinations of models are possible, and many models applied individually in the literature were excluded from this review (see Supplementary Table C1) For example, some models, such as INCA, SWAT, GLM-AED, and GOTM-WET, have been used for educational purposes, often as tools for teaching model application, environmental processes, or decision support. While educational applications were not often identified in our review, they remain significant and may be more commonly discussed in grey literature or informal settings, which were not within the scope of this review. Thus, in this selection process, the users should also consider model combinations that were not included in this review.

3.4. Limitation and contribution of the review

While this study employed a systematic review methodology, certain limitations may persist. There is always a risk that not all relevant papers and reports are included. However, the expansive scope of our research and the substantial number of exclusions, coupled with the diverse literature search methodologies employed (section 2.2), minimise the likelihood of significant omissions. Nevertheless, a considerable number of papers identified during the level 1 screening (i.e. 27 papers, see Fig. 1) were inaccessible due to institutional access limitations, unavailability, or language barriers. In addition, a substantial amount of integrated watershed-lake modelling may be conducted within industry, government, and consultancy contexts. Much of this work falls under 'grey literature,' which is often not accessible through traditional academic channels, limiting our ability to include it in this review. Furthermore, our focus was on integrated models addressing nutrient pollution, excluding other applications such as coupling watershed models with climate, heavy metals, plastics, or groundwater models (Hoellein and Rochman, 2021; Li et al., 2021; Refsgaard et al., 2007). Similarly, integrated models focusing on ecosystems other than lakes—such as rivers, estuaries, or marine systems (Karthe et al., 2017; Trolle et al., 2019)—were beyond the scope of this study. We also excluded studies integrating watershed and lake models but focusing solely on water quantity or studies that used observed nutrient loading data rather than coupling models.

The findings of this review provide significant insights into modelling approaches and applications (section 1.4). Specifically, the review highlights the diverse characteristics of watershed and lake models, identifies various model integration configurations employed over the past decades, and proposes an integrated modelling decision pathway to guide modellers. While many applications successfully integrate watershed and lake models and demonstrate flexibility in model integration options, our review includes limited evaluation of model performance, focusing primarily on reported model validation approaches and outcomes rather than an in-depth analysis. Notably, many of the reviewed papers did not provide details about the model validation specifically highlighting a significant gap in the reporting of comprehensive model performance across key environmental variables. However, the authors of these studies generally expressed confidence in their models' ability to simulate key processes such as nutrient dynamics, hydrological conditions, and water quality, while also acknowledging inherent uncertainties due to sparse observational data and system complexity. To address these limitations, the reviewed studies emphasised the importance of careful parameterisation, continuous model refinement, improved calibration techniques, and extensive scenario planning, particularly under changing climate conditions.

3.5. Research direction and prospect

This review underscores the significance of modelling integration approaches in improving prediction accuracy, supporting adaptive management, and minimising potential misinterpretations inherent in using models individually (section 1.3). Despite advancements in environmental modelling and computational engineering, integrated watershed and lake model applications remain scarce in the scientific literature, with most studies concentrated in regions such as North America, Europe, and China. The absence of regions like Southeast Asia, Latin America, and Africa, which are facing similar, if not intensified, water pollution issues, underscores the need to promote an integrated modelling approach globally.

The review also highlights the vast diversity of models, suggesting that further exploration of potential combinations of models is possible (section 3.3.2), and supporting the utilisation of diverse modelling approaches for lake management (Mooij et al., 2010, 2019). The purpose of model integration is to improve the understanding of how the watershed dynamics affect lakes and reservoirs in combination with various forms of scenario studies. Particularly promising are scenario studies facilitated by integrated models, offering insights into how watershed dynamics under various scenarios. Leveraging climate scenario projections could further enhance the utility of these models, particularly in predicting the impacts of climate mitigation efforts.

Regarding model selection, considerations should primarily revolve around the research question, data availability, and model suitability. However, limitations may arise due to expertise, learning curves, and time constraints (section 3.4). Therefore, to facilitate easier application of integrated models, the adoption of open-access models, open data sources, and updated user manuals is recommended. Promotion of platforms dedicated to model integration, such as the “Mobius” framework, could assist in the development or the improvement of integrated watershed and lake models (Norling et al., 2021). Additionally, interdisciplinary collaboration is encouraged, given the interdisciplinary nature of integrated model simulations. Lastly, enhancing online decision support platforms (e.g. online Excel) by incorporating additional models or updating existing ones in collaboration with model experts could improve accessibility and usability.

4. Conclusion

In conclusion, our systematic review, conducted according to PRISMA guidelines, analysed integrated modelling approaches in lake and reservoir ecosystems, focusing on nutrient pollution dynamics at a catchment scale. We identified and analysed 49 relevant studies through stringent methodology, including eligibility criteria formulation and extensive database searches. In total, 50 models were identified: 21 as watershed models, 23 as lake models, and 6 as hybrid lake-catchment models. The models identified were mechanistic and deterministic. The most popular models found are SWAT among the watershed models and CE-QUAL-W2 among the lake models. Most of the models were applied once or twice (76%) with a high integration variability, highlighting diverse approaches existing within this research field. We observed a notable increase in research publications on integrated modelling in the past decade, indicating a growing interest which is driven by the application of mechanistic models. However, up until now, the number of publications remains limited with 3 publications per year on average. Geographic distribution showed a concentration in developed regions like Europe, North America, and China, with a dearth of literature in developing regions despite urgent water quality management needs. In addition, to assist model selection, we developed a decision support pathway based on model and paper metadata, facilitating better decision-making for researchers and practitioners. We acknowledge limitations such as publication bias and exclusion of further potential integrations, and we encourage future research to enhance model accessibility, interdisciplinary collaborations, and integrated modelling in neglected regions. Overall, our review depicts the wide panorama of integrated modelling of watersheds and lake/reservoir ecosystems. It offers insights, on the current challenges, and opportunities for sustainable water resource management through evidence-based decision-making.

CRediT authorship contribution statement

Floran Clopin: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ilaria Micella:** Writing – review & editing, Resources, Methodology, Data curation. **Jorrit P. Mesman:** Writing – review & editing, Visualization, Resources, Methodology, Data curation. **Ma Cristina Paule-Mercado:** Writing – review & editing, Methodology, Data curation. **Marina Amadori:** Writing – review & editing, Visualization, Resources, Methodology, Data curation. **Shuqi Lin:** Writing – review & editing, Resources, Methodology, Data curation. **Lisette N. de Senerpont Domis:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Jeroen J.M. de Klein:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT 3.5 to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2025.106321.

Data availability

All data used for this research can be found on the SM and all the data will be published online

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