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NATURE'S CONTRIBUTIONS TO PEOPLE: SYSTEMATIC MAPPING OF STUDIES AND INVENTORY OF METHODOLOGIES AND INDICATORS FOR QUANTIFYING HYDROLOGICAL ECOSYSTEM SERVICES

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ABSTRACT

Objective: Evaluate the estimation of nature's contributions to people - NCP (i.e. ecosystem services - ES) through bibliographic mapping and systematization of methodologies, tools and indicators of hydrological ecosystem services (HES).

Theoretical Framework: Predatory exploitation of ecosystems is causing increasingly severe impacts on humanity. Accelerated by population growth, changes in land use and the decoupling of measures recommended by science from those adopted by nations, climate change is triggering alterations in the global hydrological cycle. Adaptation strategies depend on the production of information on the supply and flow of HES.

Method: Consultation of the Web of Science, Scopus and Science Direct databases, and systematic bibliographic mapping (2014-2024), with bibliometric analysis in the VOSviewer software, and recording of information on NCP, ES, metrics, methodologies for quantifying HES and respective indicators.

Results and Discussion: A total of 743 abstracts were analyzed and 196 articles were selected. Of these, 103 estimated HES, with a predominance of studies on a river basin scale. Seventy-nine indicators were mapped, mostly biophysical, associated with water flow regulation and water quality. China was the most represented country in terms of mapped area. The most widely used models were InVEST and SWAT.

Research Implications: Systematization of information for users interested in mapping and quantifying HES, with an indication of established aspects, methods, and knowledge gaps.

Originality/Value: Mapping based on HES indicators, aggregation of studies under different ES frameworks and provision of a dynamic results panel, with spatialization of studies and various data filtering possibilities.

Keywords: Hydrological Ecosystem Services, Methodologies, Models, Indicators.

CONTRIBUIÇÕES DA NATUREZA PARA AS PESSOAS: MAPEAMENTO SISTEMÁTICO DE ESTUDOS E INVENTÁRIO DE METODOLOGIAS E INDICADORES PARA A QUANTIFICAÇÃO DE SERVIÇOS ECOSSISTÊMICOS HIDROLÓGICOS

RESUMO

Objetivo: Avaliar a estimação de contribuições da natureza para as pessoas - NCP (i.e. serviços ecossistêmicos - SE) através de mapeamento bibliográfico e sistematização de metodologias, ferramentas e indicadores de serviços ecossistêmicos hidrológicos (SEH).

Referencial Teórico: A exploração predatória de ecossistemas provoca impactos cada vez mais severos à humanidade. Acelerada pelo crescimento populacional, por mudanças no uso da terra e pelo desacoplamento entre

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medidas recomendadas pela ciência e aquelas adotadas pelas nações, a mudança do clima desencadeia alterações no ciclo hidrológico global. Estratégias de adaptação dependem da produção de informação sobre a provisão e fluxo de SEH.

Método: Consulta às bases Web of Science, Scopus e Science Direct, e mapeamento bibliográfico sistemático (2014-2024), com análises bibliométricas no software VOSviewer, e registro de informações sobre NCP, SE, métricas, metodologias de quantificação de SEH e respectivos indicadores.

Resultados e Discussão: Foram analisados 743 resumos e selecionados 196 artigos. Destes, 103 estimaram SEH, com predominância de estudos em escala de bacias hidrográficas. Foram mapeados 79 indicadores, majoritariamente biofísicos, associados à regulação do fluxo hídrico e qualidade da água. A China foi o país mais representado em área mapeada. Os modelos mais utilizados foram InVEST e SWAT.

Implicações da Pesquisa: Sistematização de informações para usuários interessados em quantificar SEH, com indicação dos aspectos e métodos já consolidados e lacunas do conhecimento.

Originalidade/Valor: Mapeamento de indicadores de SEH, agregação de estudos sob diferentes frameworks e disponibilização de painel dinâmico de resultados, com espacialização dos estudos e possibilidades diversas de filtragem de dados.

Palavras-chave: Serviços Ecossistêmicos Hidrológicos, Metodologias, Modelos, Indicadores.

LAS CONTRIBUCIONES DE LA NATURALEZA A LA GENTE: MAPEO SISTEMÁTICO DE ESTUDIOS E INVENTARIO DE METODOLOGÍAS E INDICADORES PARA CUANTIFICAR LOS SERVICIOS DE LOS ECOSISTEMAS HIDROLÓGICOS

RESUMEN

Objetivo: Evaluar la estimación de las contribuciones de la naturaleza a las personas - NCP (es decir, servicios de los ecosistemas - ES) a través de la cartografía bibliográfica y la sistematización de metodologías, herramientas e indicadores de los servicios de los ecosistemas hidrológicos (HES).

Marco teórico: La explotación depredadora de los ecosistemas está causando efectos cada vez más graves en la humanidad. El cambio climático, acelerado por el crecimiento demográfico, los cambios en el uso de la tierra y la desvinculación de las medidas recomendadas por la ciencia de las adoptadas por las naciones, está provocando alteraciones en el ciclo hidrológico mundial. Las estrategias de adaptación dependen de la producción de información sobre el suministro y el flujo de los servicios de salud y seguridad.

Método: Consulta de las bases de datos Web of Science, Scopus y Science Direct, y cartografía bibliográfica sistemática (2014-2024), con análisis bibliométrico en el software VOSviewer, y registro de información sobre NCP, ES, métricas, metodologías para cuantificar HES e indicadores respectivos.

Resultados y Discusión: Se analizaron 743 resúmenes y se seleccionaron 196 artículos. De ellos, 103 estimaban el HES, con predominio de estudios a escala de cuenca. Se cartografiaron 79 indicadores, en su mayoría biofísicos, asociados con la regulación del caudal de agua y la calidad del agua. China fue el país más representado en términos de área cartografiada. Los modelos más utilizados fueron InVEST y SWAT.

Implicaciones de la investigación: Sistematización de la información para los usuarios interesados en cartografiar y cuantificar las EES, con indicación de los aspectos establecidos, los métodos y las lagunas de conocimientos.

Originalidad/Valor: Mapeo basado en indicadores HES, agregación de estudios bajo diferentes marcos de ES y provisión de un panel dinámico de resultados, con espacialización de estudios y diversas posibilidades de filtrado de datos.

Palabras clave: Servicios Ecosistémicos Hidrológicos, Metodologías, Modelos, Indicadores.

1 INTRODUCTION

Recent assessments indicate that there is no consistent progress towards achieving Sustainable Development Goal (SDG) 6 - Water and sanitation for all, which translates into a serious threat to the resilience of ecosystems, living organisms and human well-being in several aspects (food security, health, energy production, industrial and economic development), due to their water-dependent nature and increasing vulnerability to the impacts of climate change (U.N. Secretariat, 2023).

To make matters worse, the summary reports of the Intergovernmental Panel on Climate Change (IPCC) indicate that continued global warming is expected to intensify changes in the global water cycle, including its variability in space and time and the occurrence of extreme precipitation and drought events from year to year (Calvin et al., 2023). The effects of climate change on the hydrological cycle become more urgent every year, as was the case with the catastrophic floods that hit the state of Rio Grande do Sul, Brazil, in April and May 2024, resulting in the deaths of hundreds of people, the displacement of more than 580,000, the loss of agricultural crops, the devastation of public and private infrastructure in hundreds of municipalities, and the contamination of the population by diseases associated with flooding, such as leptospirosis, among others (Canofre, 2024). The social, economic, and environmental impacts of this and other tragedies of similar magnitude could have been mitigated by the development of appropriate land use planning strategies capable of protecting natural environments important for flood control.

The development of such strategies, including nature-based solutions such as the Sponge Cities watershed management project for flood control in China (Wanghe et al., 2022), depends on the availability of sufficient information that is representative of the socio-ecological complexity of local landscapes. In this sense, the first step towards developing local and regional solutions for the appropriate management of water resources is to produce, quantify and qualify information in a spatially explicit, comprehensible and useful way.

One of the tools available to guide such information generation is the systematic map, which offers a reliable means of synthesizing and describing evidence related to environmental topics (James et al., 2016). Considering that several countries still need to produce and systematize data capable of supporting public policy managers in decision-making about strategies for the conservation of ecosystem services (ES), including hydrological ecosystem services (SEH), this work proposes to carry out a systematic mapping of methodological paths to fill such knowledge gaps.

This study therefore aims to i) carry out a systematic mapping of scientific literature focused on the quantification of ES in terrestrial and freshwater environments, aggregating the services studied under the conceptual framework of Nature's Contributions to People (NCP) (Díaz et al., 2018)and including general bibliometric analyses, and ii) carry out an inventory of estimation methodologies and ES indicators, as well as provide an interactive consultation base for users interested in developing ES quantification research, considering the urgency of expanding local, regional and global strategies to address changes in the hydrological cycle resulting from climate change and changes in land use regimes.

2 THEORETICAL FRAMEWORK

ES are defined as the benefits that human populations obtain, directly or indirectly, from ecosystem functions (Costanza et al., 1997), while the more comprehensive concept of NCP includes the positive or negative contributions of organisms, ecosystems, and associated ecological and evolutionary processes to the quality of human life (Díaz et al., 2018).

Considering that changes in land use resulting from human activities are closely related to changes in the provision and flow of ES/NCP, threatening the well-being of societies (Hasan et al., 2020; Song et al., 2015)and responding, additionally, to the worsening of climate change (IPCC, 2023), several efforts have been made to expand knowledge about sources, sinks, ES flows and interactions between multiple services.

Within the scope of the Economic-Environmental Accounting System - Ecosystem Accounting (SEEA-EA), an integrated statistical framework for organizing spatially explicit information on ecosystems and changes in the extent and state of ES (United Nations et al., 2021), a correspondence table was produced between different classifications and typologies of ES widely used today (Common International Classification of Ecosystem Services-CICES, National Ecosystem Services Classification System - NESCS+, Intergovernmental and Science Platform for Biodiversity and Ecosystem Services - Nature's Contributions to People-IPBES, Millenium Ecosystem Assessment-MEA, The Economics of Ecosystems and Biodiversity-TEBB). This effort has enabled the consolidation of scientific information on the provision and flow of ES/NCP generated in different regions and scales, under different conceptual frameworks and classification systems.

Despite previous investigations on methodologies and models available for quantifying ES, the scale of review and the research questions chosen vary and rarely include the recording of ES indicators and units of measurement. In a study on the global use of ES models, the adoption of Integrated Valuation of Ecosystem Services & Tradeoffs (InVEST) tools by different countries was evaluated for a two-year period, but without recording the locations studied or indicators (Posner et al., 2016). Other reviews focused on the use of Soil & Water Assessment Tool (SWAT), with recording of information on models and ES studied, countries, contexts of applicability of the models and other bibliometric analyses (Francesconi et al., 2016; Zhao et al., 2024).

Turner et al. (2015)identified and discussed available data and methods to determine land degradation and assess the sustainability of alternative management practices, consolidating a framework of ES models with information on their nature and applicability and also evaluating the distribution of models in terms of aggregation scale and ease of understanding. In a review of a similar nature, limited to the Asian continent, Shoyama et al. (2017)they recorded information on study regions, types of ecosystems, ES categories, applied approaches, types of model, among others, with the quantification, but without specification, of biophysical indicators of ES.

Ochoa & Urbina-Cardona (2017), in turn, mapped tools for spatial modeling of ES, recording countries, types of study areas, spatial scale, ES studied, software and tools applied. They have already Baustert et al. (2018)paid attention to the use of uncertainty analyses, recording ES models used, while Agudelo et al. (2020)they dedicated themselves to reviewing articles from the perspective of modeling interactions between multiple ES and techniques used to analyze such interactions.

The emphasis of this paper is on EHS, which encompass the benefits to people produced by the effects of terrestrial ecosystems on freshwater, and are organized into the categories of improving water supply for extractive purposes, improving water flow provision, mitigating water damage, providing water-related cultural ES, and maintaining aquatic habitats that produce services (Brauman et al., 2007). Jobbágy et al. (2022)defined EHS in a similar way, differentiating water provision, flow regulation, and water quality services provided by aquatic and terrestrial ecosystems, and separating cultural ES provided by aquatic ecosystems.

Terrestrial ecosystems move and modify water flows, and it is crucial for the scenario of SEH studies and water resource management to consider key attributes of each service related to quantity, quality, location, periodicity and water flow (Brauman, 2015; Brauman et al., 2007). To this end, in addition to the justified choice of certain methodologies for quantifying and spatializing SEH over others - which must involve prior understanding of the potential and limitations of each model, as well as the availability of data for the study area, in spatial and temporal resolution appropriate to the research objectives - it is necessary to start filling the gap of the lack of minimum standardization of SEH indicators, which is why this work was proposed.

3 METHODOLOGY

Literature mapping was conducted in a systematic and replicable manner (James et al., 2016; Pullin et al., 2018), incorporating two levels of detail: i) reading, abstract selection and general bibliographic mapping, and ii) reading of full texts and systematic mapping of estimation methodologies and SEH indicators. The search covered the last ten years (2014 to March 2024) and the Web of Science, Scopus and Science Direct databases were consulted. The search key used was similar for each database (Table 1).

Table 1

Databases, search keys and number of articles returned per search.

Database	***Search key***	**Number of articles**
Scielo Citation Index (Web of Science)	TS = (Ecosystem services OR Nature's Contributions to People) AND (estimate* OR model*) n = 262	262
Scopus	TS = (Ecosystem services OR Nature's Contributions to People) AND (estimate* OR model*)	211
Science Direct	TI= (Ecosystem services OR Nature's Contributions to People) AND (estimate* OR model*)	281
Total		**754**

The search results files from each database were gathered in EndNote Web and, after eliminating duplications, the total number of articles was reduced to n=743. The file containing bibliographic information and abstracts was exported in Research Information Systems (RIS) format and inserted into a project on the SysRev platform for the reading and abstract selection stage. In this stage, level 1 inclusion criteria were applied, allowing, at the end, the export of a raw results spreadsheet, with identification numbers assigned to each article.

Review articles and proposals for conceptual frameworks for ES analysis were excluded from the mapping, as well as monetary valuation works, except those that included quantification steps for biophysical indicators.

Subsequently, the papers whose abstracts were included in the first stage were downloaded. The articles were inserted into a specific collection in the Mendeley Reference Manager software for complete reading and completion of a spreadsheet containing the level 2 detail fields, that is, focusing on the methodologies, models, indicators and units of measurement of SEH, software and tools used and approximate geolocation of the study areas. In addition to these, other information was recorded regarding the presence or absence of SE maps, SE assessments in different scenarios, use of validation methodologies, uncertainty and/or accuracy analyses, spatial autocorrelation and sensitivity analyses (Table 2).

Table 2

Inclusion criteria for abstracts and analysis of the articles selected for the literature mapping .

Characteristics evaluated	Description	Inclusion criteria - level 1 (abstracts)	Detailed criteria - level 2 (full articles)
Spatial distribution of study areas	Information on continents, countries, regions studied	All continents and countries	Study area, geographic reference coordinates searched on Google Maps
Type of study	Applied research, literature reviews, public policies	Applied research	-
Spatial scale	Local, regional, global	All spatial scales	Watershed, protected area, agricultural area, administrative region, forest management area, lake, mountain range, green urban infrastructure, country, global
Type of ecosystem	Terrestrial, aquatic, marine, other	Only articles covering terrestrial ecosystems, wetlands or aquatic ecosystems	-
Type of ES estimation metric	Biophysical metrics, human perception metrics, monetary valuations	Articles with at least one biophysical or human perception metric	-
Nature's Contributions to People	Information on the NCP studied	All the NCPs were included, except NCP 5, which is specific to marine environments	Only HES-related NCP
ES classes	Information on the ES category according to the Millennium Ecosystem Assessment (MEA)	All classes were included	MEA classes of ES included for each quantified HES
HES	Review of the nomenclature of each HES based on the ES Reference List Crosswalk to Selected ES Classifications and Typologies table (SEEA EA)	-	The CICES classification was adopted as the standard for systematizing the quantified HES
HES indicators	Identification of the indicators used to estimate HES	-	Only biophysical and human perception indicators for HES
Units of measurement	Identification of measurement units for the indicators used to estimate HES	-	Units of measurement for each HES indicator
Models and methodologies	Identification of models and/or methodologies used to estimate HES	-	For the same HES evaluated, all the models and/or methodologies adopted were recorded.

Software and tools	Identification of software and/or tools used to estimate HES	-	For the same HES evaluated, all the software and/or tools used were recorded.
Generation of HES maps	Identification of studies with spatially explicit presentation of HES estimation results	-	Presence or absence information for each HES study
Scenario generation	Identification of HES estimation studies in different scenarios (climate change, time projections, public policies, etc.)	-	Presence or absence information for each HES study
Use of methodologies to validate results	Identification of HES estimation studies that used methodologies to validate results	-	Presence or absence information for each HES study
Use of uncertainty or accuracy assessment methodologies	Identification of HES estimation studies that used methodologies to estimate the level of uncertainty and/or accuracy of the results	-	Presence or absence information for each HES study
Use of methodologies to assess spatial dependence	Identification of HES estimation studies that used spatial autocorrelation techniques	-	Presence or absence information for each HES study
Sensitivity assessments	Identification of HES estimation studies that used different data inputs to test the sensitivity of models	-	Presence or absence information for each HES study

A bibliometric analysis of co-occurrence of authors and keywords was performed using the VOSviewer software for the complete set of articles and for the SEH article collection, with two co-occurrences assigned as the minimum limit. In the scientific landscape maps created in this program, the items correspond to the objects of interest (in this case, authors and keywords), the links denote the existence of a relationship between items, and each link has a strength with a positive numerical value assigned (the higher the value, the stronger the link) (Jan van Eck & Waltman, 2018).

Once the information presented in Table 2 had been recorded, the resulting spreadsheets were cleaned up and three dynamic web panels for viewing the results were created using the Google Looker Studio tool. Panels 1 and 3 allow the application of filters for cross-viewing specific information, according to the user's interest, returning the list of resulting publications at the end of the graphical visualizations. The analyses of co-occurrence of authors and keywords are static in relation to the other data, as they are characterized as links incorporated from VOSviewer to Looker Studio. It is possible to click on specific clusters of keywords to check relationships with other groups.

The general results of the review were aggregated to the first panel. The spatialization of co-occurrence of keywords and the graphs of publication counts by year, region, SE class (regulation, provision, support, culture), NCP, types of SE estimation metrics, scientific journals and spatial scale of study areas (local, regional or global) were included. It is worth noting that the registration of NCP and SE classes was made, for this set of articles, based on the reading of the abstracts, which may generate discrepancies in relation to the results for the articles in the SEH set.

The spatializations of co-occurrence of authors were added to the second panel, for the two levels of research detail, in addition to information about the institutions to which they are linked.

The third panel, specific to SEH, also included the spatialization of keyword co-occurrence. Point and heat maps were generated for the spatial distribution of the study areas, with the sizes of the reference geographic coordinate points weighted by the number of SEH indicators in each publication. This panel allows filtering of studies by NCPs, SEH, indicators, year of publication, country, study scale, and other information presented in Table 2. Graphs containing the mapped SEH indicators were created, with the possibility of interactive filtering of different software, tools, and analyses used. The final table returns the references of the studies and presents details of the measurement units of each indicator, corresponding metric types, models, and methodologies adopted.

The aim was to reduce the redundancy of HES indicators by standardizing indicator nomenclature, such as registering the indicators “water provision”, “water yield” and “water supply” as “water supply”, or “erosion control” and “soil conservation” as “soil conservation”, as long as they are semantically equivalent.

The steps of the systematic mapping protocol adopted in this work were summarized in Figure Web - Systematic mapping protocol .

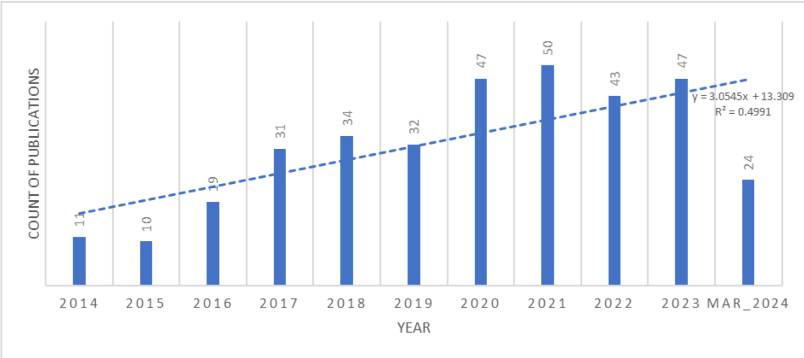
4 RESULTS AND DISCUSSIONS

4.1 GENERAL RESULTS OF THE REVIEW

The research resulted in 196 articles published in 88 scientific journals, with an average of 31 articles/year and an increasing trend in the number of publications per year throughout the period analyzed (Figure 1).

Figure 1

Number of articles published per year .



There was a tendency for the volume of publications to be concentrated in a few journals, with 42% of the articles published in Ecological Indicators (24), Ecosystem Services (24), Science of the Total Environment (21), Environmental Modelling & Software (9), Ecological Modelling (6), Applied Geography (5), Journal of Environmental Management (5) and Bosque (5), following Bradford's law regarding the concentration of scientific production on specific topics in a few journals (Guedes & Borschiver, 2005)(Web Panel 1).

The research was conducted, massively, on a local scale (80%), and predominantly in the continents of Europe (29.5%), Asia (26%) and South America (23%). In all years, the most studied ES classes were those of regulation and provision. The most studied NCP were NCP 4 (climate regulation) and NCP 6 (regulation of the quantity of freshwater in space and time), with a predominance of the use of biophysical metrics (Web Panel 1).

In the analysis of co-occurrence of keywords, 8 clusters were formed that suggest changes in land use as an important mobilizing factor for several lines of studies on ES quantification. In five clusters, it was possible to verify the mention of ESH directly (“water supply”, “nutrient retention”, “sediment retention”, “water”, “water flow regulation”, “hydrological ecosystem services”) or indirectly (“SWAT model”) (Table 3). A connection was observed between clusters 4 and 2, with a link between studies on changes in land use and climate change.

Table 3

Keyword co-occurrence clusters formed for the complete set of articles analyzed (n=196), with the most frequent words highlighted in bold.

Cluster	Number of keywords	Keywords
1	10	ARIES, biodiversity, carbon, carbon sequestration, **InVEST models**, Land-use Capability Indicator (LUCI), nutrient retention, scenario analysis, sediment retention, water supply
2	9	Climate change, ecosystem accounting, environmental services, FLUS model, Maxent software, model comparison, **SWAT model**, uncertainty, validation
3	7	Big data, **cultural ecosystem services**, recreation, social value, social-ecological systems, SOLVES model, spatial analysis
4	6	Human well-being, **land use change**, natural capital, nature's contributions to people, sustainable development, water
5	5	**Carbon storage**, environmental justice, soil organic carbon, urban ecology, water flow regulation
6	5	Green infrastructure, **modeling**, quantification, urban planning, valuation
7	4	Hydrological ecosystem services, land cover, **mapping**, spatial modeling
8	3	Biomass, **ecosystem services**, integrated modeling

Regarding authors and research networks, using the co-occurrence criterion, three clusters of research networks were formed, covering institutes in the United Kingdom, United States, Spain and the Netherlands (Web Panel 2).

4.2 HYDROLOGICAL ECOSYSTEM SERVICES

The research resulted in 103 articles published in 43 journals, 56% of which were published in Ecological Indicators (16), Ecosystem Services (15), Science of the Total Environment (11), Environmental Modelling & Software (6), Ecological Modelling (5) and Journal of Environmental Management (5) (Web Panel 1).

In addition to the research networks verified for the complete set of papers, which were repeated for the set of articles related to SEH (reorganized into only 2 clusters), three new isolated clusters were formed, highlighting research institutes in France and China (Web Panel 2).

In the keyword co-occurrence landscape, 8 clusters were formed, suggesting a certain compartmentalization of SEH studies, modulated by the choice of one of the most well-known SEH modeling tools. A specific cluster was formed for model comparison efforts and uncertainty assessments , with connections to clusters 1 (InVEST) and 6 (SWAT), suggesting that most publications that compared SEH quantification results by different models did so for InVEST and SWAT, which is verified in Cong et al. (2020)and in Decsi et al. (2022)for indicators of water quality, erosion control, water supply and/or flood control. The keywords related to climate and land use changes were grouped in the same cluster and showed a relationship with cluster 4, demonstrating a relationship between SEH and climate change studies (Table 4, Web Panel 3).

Table 4

Keyword co-occurrence clusters formed for the set of articles dealing with HES (n=103), with the most frequent words highlighted in bold.

Cluster	Number of keywords	Keywords
1	6	Carbon sequestration**, InVEST models**, Land-use Capability Indicator (LUCI), nutrient retention, restoration, sediment retention
2	5	Biodiversity, carbon, validation, water security, **water supply**
3	4	Ecological restoration, **ecosystem services**, freshwater provisioning, sustainability
4	4	ARIES, human well-being, **natural capital**, scenario analysis
5	4	**Land cover**, mapping, nature’s contributions to people, spatial analysis
6	4	Hydrological ecosystem services, **SWAT model**, water flow regulation, watershed management
7	3	Climate change, FLUS model, **land use change**
8	2	Model comparison, **uncertainty**

Considering the geolocation of the study areas, the bibliographic production, in quantity and also in territorial representation, has been significant in China (n=27). In terms of spatial scale, most of the research was applied to river basins (n=42), corroborating a previous review (Ochoa & Urbina-Cardona, 2017), as well as to administrative regions, such as municipalities and provinces (n=31), followed by protected areas (n=13) (Web Panel 3).

Seventy-nine SEH indicators were mapped, mostly estimated from biophysical parameters and predominantly representative of NCP 6 (regulation of freshwater quantity in space and time) (n=74, 29 indicators), NCP 7 (regulation of freshwater quality) (n=35, 18 indicators), NCP 8 (formation, protection and decontamination of soils and sediments) (n=51, 8 indicators) and NCP 9 (regulation of threats and extreme events) (n=20, 9 indicators) (Web Panel 3).

It is noteworthy that, among the articles that estimated SEH related to water supply and hydrological flow regulation (n=73), only 43% adopted the river basin scale. The production of articles that addressed NCP 9, related to SEH for flood control (n=18, with 8 mapped indicators) and attenuation of mass movements (n=2, with 1 indicator), such as landslides, was very incipient when observed in the individual context of the countries.

For Brazil, despite the increase in social and environmental disasters caused by storms, only one publication was found that includes a local-scale flood control indicator for a river basin in the southeast of the country (Gianuca et al., 2024). Nevertheless, the Sendai Framework for Disaster Risk Reduction 2015-2030 recommends that all countries adopt water as a central element of their disaster risk reduction strategies, with the aim of reducing the occurrence and severity of water-related disasters (United Nations Office for Disaster Risk Reduction, 2015).

Regarding the use of models and tools, the InVEST (n=35) and SWAT (n=12) models were most frequently used, although methodologies based on human perceptions also deserve to be highlighted (n=12), especially those supported by probability matrices determined by experts and which incorporate measures of uncertainty and/or accuracy.(Choquet et al., 2021; Maldonado et al., 2018; Malekmohammadi & Jahanishakib, 2017). Roche & Campagne (2019), for example, found a high correlation between SEH indicators estimated by expert-based scores and by biophysical parameters. Additionally, publications that used Bayesian networks were identified, based on dependency relationships between probabilities of change in the state and SEH flow (Crossman & Pollino, 2018; Forio et al., 2020; Peng et al., 2022).

Approximately 64% of the articles systematized results in SEH maps (n=68) and 43% included analyses of different scenarios (n=45). Studies that included model validation (n=36) and uncertainty and/or accuracy analyses (n=35) represented, respectively, 34.6% and 33.7% of the total. Method sensitivity tests (n=26) and spatial autocorrelation analyses (n=15) occurred in a smaller number of studies (Web Panel 3).

Few publications (n=4) included, simultaneously, the generation of maps, scenarios, model validation techniques, uncertainty and/or accuracy measures and sensitivity analyses (Balbi et al., 2015; Jackson et al., 2017; Ma et al., 2024; van Soesbergen & Mulligan, 2018). Only 3 included maps, model validation techniques, uncertainty and/or accuracy measures, sensitivity analyses and spatial autocorrelation simultaneously (Cong et al., 2020; Gwal et al., 2023; Willcock et al., 2020). In this sense, Van Soesbergen & Mulligan (2018)they highlighted how much the variability of different precipitation data sets can affect the estimation of SEH, finding a difference, for the runoff indicator, of 99% in the monthly estimate and of 60% for the dry season as a whole, for a protected area in eastern Madagascar.

The results of this work indicate that, although there is already a considerable diversity of methodologies, models and tools available for estimating SEH, which are extremely important for the development of adaptation strategies to changes in the hydrological cycle that result from complex interactions between the impacts of population growth, changes in land use unaccompanied by adequate land use planning policies and climate change, the diversity of indicators is low for most SEH, as is the availability of studies produced in the individual context of nations.

Another point worth noting is the lack of standardization, at various levels, of the nomenclature of SEH and measured indicators, aggravated by the large number of frameworks proposed for SE studies, making it difficult to systematize information for larger scales. Several studies do not clearly define which indicators are measured or their measurement units. For this reason, it is recommended that efforts be made in research of this nature to mention the SE classification adopted, to differentiate between SEH, indicators and measurement units studied and to provide a conceptual description of indicators.

It is proposed that future work seek to centralize the object of study on indicators of ecosystem functions, rather than on the chosen models. The spatialization of results and the provision of geospatial archives can greatly contribute to the consolidation of information on a country scale, as long as the units of measurement are specified and the methodological description of the work presents transparency.

Finally, it is suggested that nations, academic sectors and civil society increase incentives for the production of information on SEH, aligning methodological and spatial scale choices with data availability and the research object, and paying attention to the importance of analyses of uncertainty, accuracy, spatial dependence and sensitivity, as well as the generation of maps and scenario analysis as tools to support decisions on the protection and management of water resources.

5 CONCLUSION

The results of this research supported a set of interactive panels (Web Panels), through which it is possible to consult indicators that have been used for the quantitative and qualitative study of SEH, as well as methodologies, models, reference works and knowledge gaps within the countries. Despite the increase in bibliographic production on SEH over the last 10 years, there is an urgent need to expand knowledge of the state, flow and interactions between SEH, the evaluation of scenarios as a tool to support decision-making on the management of water resources and terrestrial ecosystems, and the expansion of territorial coverage of the information available in national and regional contexts.

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