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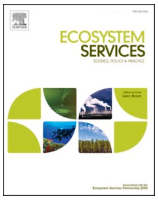

Review Paper

Modeling water regulation ecosystem services: A review in the context of ecosystem accounting

Stoyan Nedkov[a,*], Sylvie Campagne[b,c], Bilyana Borisova[d], Petr Krpec[e], Hristina Prodanova[a], Ioannis P. Kokkoris[f], Desislava Hristova[a], Solen Le Clec'h[g], Fernando Santos-Martin[h], Benjamin Burkhard[b], Eleni S. Bekri[i], Vanya Stoycheva[a], Adrián G. Bruzón[h], Panayotis Dimopoulos[f]

[a] National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria
[b] Institute of Physical Geography & Landscape Ecology Leibniz Universität Hannover, 30167 Hannover, Germany
[c] Sorbonne Université, CNRS, Station Biologique de Roscoff, UMR7144, Adaptation et Diversité en Milieu Marin, Place Georges Teissier, F-29680 Roscoff, France
[d] Sofia University St. Kliment Ohridski, Faculty of Geology and Geography, Landscape Ecology Department, Bulgaria
[e] The Czech Academy of Sciences, Global Change Research Institute, Prague, Czech Republic
[f] University of Patras, Department of Biology, Division of Plant Biology, Laboratory of Botany, University Campus, 26504 Rio, Patras, Greece
[g] Environmental Systems Analysis Group, Wageningen University and Research, The Netherlands
[h] Department of Chemical and Environmental Technology, ESCET, Rey Juan Carlos University, C/Tulipán s/n, Móstoles, 28933 Madrid, Spain
[i] University of Patras, Department of Civil Engineering, Environmental Engineering Laboratory, University Campus, 26504 Rio, Patras, Greece

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ABSTRACT

Natural Capital Accounting (NCA) has evolved rapidly in recent years through substantial efforts of both international organizations and the scientific community. Water regulation ecosystem services (ES) are key elements of regulating services in ecosystem accounting, with most relevant studies strongly relying on models for ES quantification up to now. In this paper, we provide a review of modeling efforts for water regulation ES based on 148 scientific papers, properly systematized, analyzed and interpreted by using a detailed and structured original template. We examined emerging trends and gaps in model applications and the readiness to integrate them into the NCA and SEEA-EA frameworks. We propose a classification scheme which organizes the 92 different models and modeling approaches identified in the review process into eight model categories so that this scheme can be efficiently used in the water ES assessment of and for further integration into the accounting framework. Among the models, the hydrologic model SWAT and the modeling tool InVEST are by far the most popular. The results of the review revealed differences between the general ES literature and the accounting-related papers. Moreover, our analysis sets the basis for useful recommendations of which model categories are the most appropriate for the water regulation ES, included in the SEEA-EA reference list. Based on the number of relevant papers, the reliability and the confidence level of the recommendations for the use of models have been incorporated in our analysis. We highlight as model category with the highest confidence the ones relative to quantification water flow and flood control service aiming at ES accounting. Models for erosion control ES can only be recommended with a lower confidence, while for water purification the results lack clear evidence for using a particular group of models. Based on the research findings we identified the main research priorities on model integration in the accounting of water regulation ES: 1) further development of guidelines for the use of models in ecosystem accounting; 2) analyses of the spatial aspects of the model towards a clear distinction between ecosystem service supply and use; and 3) development of integrated modeling approaches for water regulation ES accounting.

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* Corresponding author at: Akad. G. Bonchev str. Bl.3, 1113 Sofia, Bulgaria.
E-mail address: snedkov@abv.bg (S. Nedkov).

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1. Introduction

Natural capital accounting (NCA) has evolved rapidly in recent years through substantial efforts of both international organizations and the scientific community (Turner et al., 2019; Vačkářů and Grammatikopoulou, 2019; Obst, 2015). NCA can integrate biophysical and economic information on the changes in the stock of natural capital and the value of ecosystem services (ES) to regularly provide information to decision-makers (Vardon et al., 2019). In March 2021, the United Nations Statistical Commission adopted the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA–EA). The SEEA–EA is a result of a 3-year revision process that was launched in March 2018 under the responsibility and direction of the United Nations Committee of Experts on Environmental-Economic Accounting and in particular the SEEA–EA Technical Committee. The revision process was focused on advancing four priority research issues: spatial areas, ecosystem condition, ecosystem services and valuation. Water flow regulation ES and biophysical modeling are among the most important topics in the individual ES part of the revision. Although there has been some progress in the accounting of water-related regulating ES, further development in this area is needed (Vardon, 2014; Vardon et al., 2019). The revision of water flow regulation ES underlines the need for the application of modeling approaches (Crossman et al., 2019).

Water regulation, considered one key regulating ES in ecosystem accounting, includes several ES, such as water retention and storm and high-water protection (including flood control on rivers and coasts). These water regulation services are closely related to other regulating ES, such as erosion and sedimentation control and water purification. Characterizing and assessing these water regulation ES is challenging for three main reasons. First, these ES can be regarded as both final and intermediate services (Boyd and Banzaf, 2007), i.e., it is usually difficult to distinguish between ES flow and ES potential (or ecosystem capacity to provide ES according to the SEEA–EA terminology). For this reason, water regulating services have in most cases been incorporated into other water-related services and not treated as individual, separated ES. For instance, water flow regulation and water filtration that are not provided by water per se but by other ecosystem components, such as vegetation and climate, are embedded in water provisioning services (Vardon, 2014). Therefore, there is a great need to explore the more general "water-related ecosystem services" literature and to glean the water regulating services, which are considered intermediate ecosystem services. Second, both assessments and accounts of water regulation services need various data usually not available through either direct or indirect measurements. To overcome this difficulty, modeling approaches of water regulation are used to provide data for different aspects of the water cycle that cannot easily be extracted through direct measurements (Vigerstol and Aukema, 2011). Moreover, modeling water regulation ES is often data intensive, analytically complex and generally requires the use of hydrological models (UN et al., 2017). Within this framework, this paper includes and analyses the general ES category of water-related ES and focuses on water regulating services (see Table 1, where the various relative terms are explained). Such a study is important to identify current research gaps and recommend key directions for future research on the implementation of models and modeling approaches for the needs of ecosystem accounting and further development of the SEEA–EA.

Water issues have been an integral part of all frameworks since the first studies on environmental accounting. One of the first attempts was made by the Australian Bureau of Statistics through the assembly of existing data on the value of water and volume of water used so that they could be integrated with other information and, in particular, information from the System of National Accounts (Vardon et al., 2007). An accounting procedure for analyzing water use patterns and trade-offs between users to account for groundwater and surface water components was developed by Peranginangina et al. (2004). Onda et al. (2012) developed an accounting system for microbial water quality and sanitary risk using monitoring data available at a national level in several countries. Water Accounting Plus (WA +) is a framework that was designed to provide explicit spatial information on water depletion and net withdrawal processes in complex river basins (Karimi et al., 2013). The role of water accounting in resolving economic, social, and environmental issues at the individual, organizational, industrial, national and international levels was discussed in several chapters of a book edited by Godfrey and Chalmers (2012). However, the first work that summarized the conceptual and methodological material related to water in the context of the development and application of the SEEA–EEA was undertaken as part of a series of technical notes, developed as an input to the SEEA–EEA Technical Guidance (Vardon, 2014). It addressed four ES accounts: water provisioning, water flow regulation, water filtration, and flood protection. There have been a few attempts to test water-related ecosystem accounts in case studies from local to continental scales (Duku et al., 2015; La Note et al., 2017; Lai et al., 2018). The analyses on indicator applicability in Finland showed that indicators are appropriate to contribute to extent and condition accounts, but for ES there is no regular update, which is an important limitation (Lai et al., 2018). The studies by Monblansch et al. (2017) on modeling the freshwater provisioning ES and by Menendes et al. (2019) on the effects of using high-quality data models in valuing the flood protection ES of mangroves provided some clues to ecosystem accounting. Furthermore, water-related ES modeling and its links to ecosystem accounting were examined in the more complex studies of Tammi et al. (2016) and Vogl et al. (2016).

Table 1
Basic terminology about ES and water used in this paper.

Terms	Meaning	Use in the paper
Water regulation ES	Regulation ES related to water function which correspond to 7 CICES classes in division Regulating and maintenance services	The main focus of the paper in relation to ES
Water-related ES	All ES obtained from ecosystems reliant on water, including both provisioning and regulating	Used in the literature search to identify all models applied for water modeling in relation to ES. The aim is to cover all possible models that could be used for water regulation ES
Water-related ecosystem functions	Behind the supply of ES are a variety of other (not directly used) ecosystem functions, which support the preservation of essential resources	Used for the analyses of the data derived during the papers review

There is a great variety of models and modeling approaches that address water-related ES and consider water regulation. Each approach has its own specifications, advantages and disadvantages, field of application and limitations, as well as specific data requirements. To date, their applications in various aspects of ES assessments have been studied in several research articles. Lüke and Hack (2017) provided a comparison of three models, SWAT (soil and water assessment tool), InVEST (integrated valuation of ecosystem services and tradeoffs) and RIOS (resource investment optimization system), to incorporate hydrological ES in decision-making processes. Vigerstol and Aukema (2011) provided a comparison of tools for modeling freshwater ES, which included widely used hydrological models such as SWAT and VIC (variable infiltration capacity) as well as tools specifically designed for ES such as InVEST and ARIES (artificial intelligence for environment and sustainability). The application of different GIS-based modeling tools has been applied to flood regulation ES mapping and assessment (Nedkov and Burkhard, 2012; Farrugia et al., 2013; Strurk et al., 2014; Boyanova et al., 2016; Shen et al., 2019). Erosion control ES provided by different ecosystem types have been mapped and assessed in several case studies (Bangash et al., 2013; Kauffman et al., 2013; Guerra et al., 2014;

Khan et al., 2019). Water-related ES have been studied on different scales and aspects ranging from service provisioning to economic valuation (Schmalz et al., 2015; Schmalz et al., 2016; Gao et al., 2017; Luke and Hack, 2018; Pan and Choi, 2019; Sahle et al., 2019; Kokkoris et al., 2019).

Despite growing attention and more studies using water-regulation models to assess and/or map water-related ES and to capture them in the SEEA-EA, three main knowledge gaps still exist. First, there is not enough information on the use of models for water-related ES, organized in a systematic way for formulating specific recommendations of the most appropriate models for the various ES. Furthermore, there are some discrepancies between terms used to define water regulation ES in CICES (common international classification of ecosystem services; Haines-Young and Potschin-Young, 2018), the SEEA–EA reference list and various literature sources. Second, a classification of water-related ES modeling methods is lacking and could satisfy the needs of both ES assessment and ecosystem accounting. Discrete classifications exist for biophysical ES models (Vihervaara et al., 2019), hydrological and hydraulic models (Sindh and Frevert, 2006; Gosain et al., 2009; Jajarmizadeh et al., 2012) and water quality models (Grossmann, 2012; La Notte et al., 2012, 2017). Other than these, no wider classification covering the great variety of models and modeling approaches applicable to ecosystem accounting is available. This gap includes some approaches that do not fit classical modeling understanding (Simonit and Perrings, 2011) but have the potential for accounting purposes. Third, while the use of models to quantify water regulation ES is relatively well documented, the use of their outputs for physical ES flow accounts is often fuzzy and unclear. Therefore, it is necessary to explore the relationships between the current quantification of ES by using the models and the respective ES accounting in compliance with SEEA–EA.

This paper explores the readiness to integrate modeling approaches in water regulation into the NCA and SEEA–EA frameworks. This is conducted by reviewing advances in the current scientific literature on water-related ES modeling with a focus on water regulation. More specifically, we aim to i) identify and systematize the studies on water regulation modeling and analyze the ES included in these studies; ii) systematize and classify the water regulation models and modeling approaches used for ES assessment and mapping; and iii) define the relationship of modeling efforts to quantify ESs and the flow regulation service accounting in SEEA–EA.

2. Materials and methods

A systematic literature review for relevant papers was conducted in two main stages: 1) a literature search and 2) review of relevant papers following the flow diagram presented in Fig. 1.

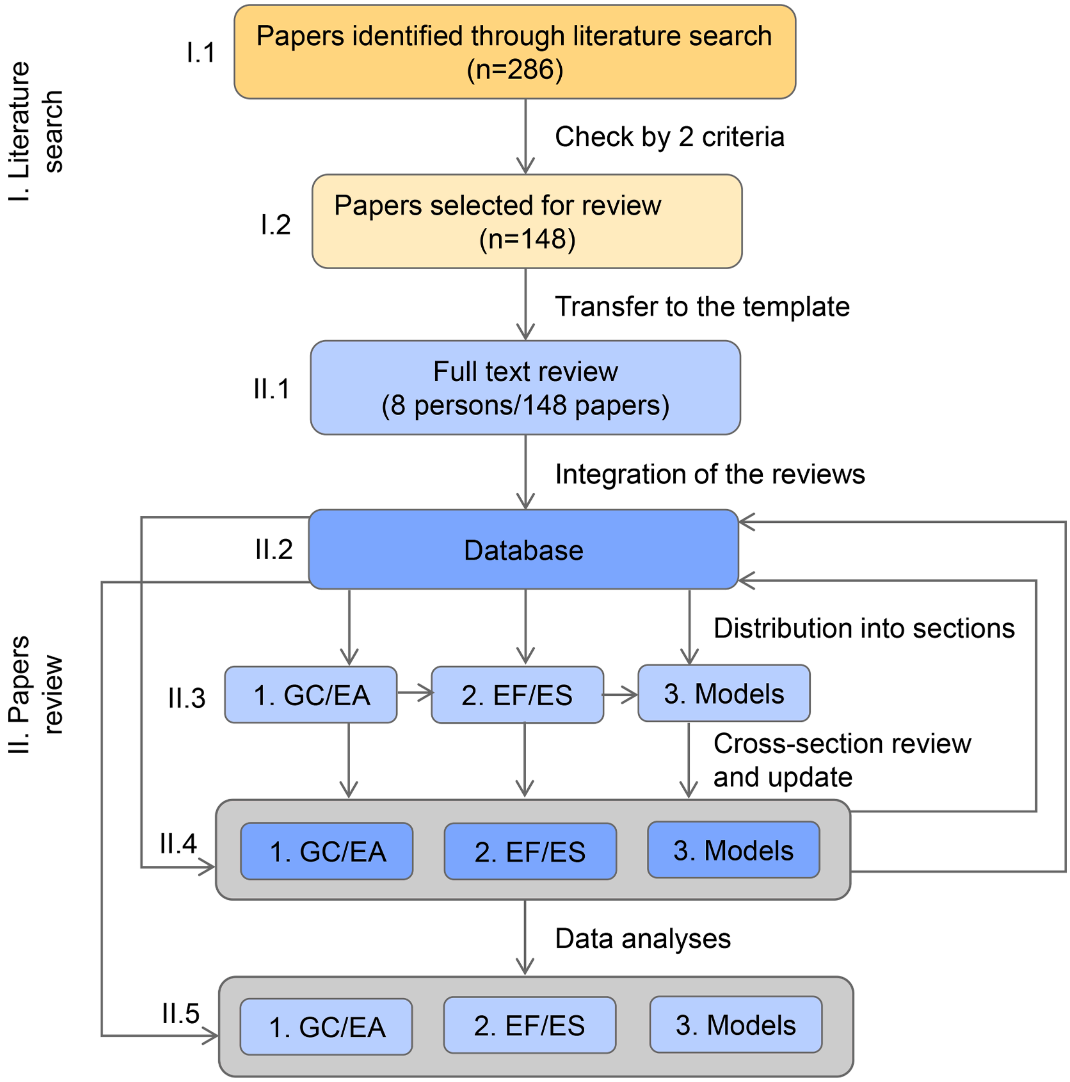

Fig. 1. Flow diagram of the literature search and papers review. GC – general characteristic; EA – ecosystem accounting; EF – ecosystem functions; ES – ecosystem services.

2.1. Literature search

We first aimed, through a systematic review, to find all available publications that addressed the goals of the study, operationalized through search terms (Siddaway et al., 2019). The literature review was conducted in two steps. In the first step, terms related to modeling water-related ES were used to search the Web of Science and Scopus database records from 1990 to February 2020 (Figs. 1 - I.1.) The search procedure was developed on the basis of analyses of previous studies (Martinez-Harms et al., 2015; Luederitz et al., 2015; Ezzine-de-Blas et al., 2016; Yang et al., 2018; Perevochtchikova et al., 2019; Cheng et al., 2019). We developed a search string following the procedure presented by Ochoa and Urbina-Cardoba (2017). The search string was (ecosystem services OR water regulation OR water ecosystem services) AND (water provision OR water purification OR flood regulation OR erosion regulation) AND (model OR modeling OR mapping OR assessment OR accounting). The initial search resulted in 286 papers. In the second step, each of these papers was checked to identify those that met the following criteria: i) papers using modeling approaches; and ii) the approach was applied to water-related functions of ecosystems or water-related ES. The papers that passed both criteria were selected for further analyses (Figs. 1 - I.2.). Thus, the final number of papers was reduced to 148 (Appendix 1).

2.2. Structure of the review process

2.2.1. Review template – Concept and structure

To systematize and characterize the content of the reviewed papers, a special database with a standard nomenclature was constructed following Ochoa and Urbina-Cardoba (2017) and Perevochtchikova et al. (2019). The information from the selected 148 papers was extracted by several members of the research team who reviewed the full text of each individual paper. To ensure a uniform and comparable review process and the development of the database, a template in the form of a structured MS Excel sheet was developed. It was designed to fulfill three main objectives of the review: i) to identify models for water regulation; ii) to identify water regulation ES that can be assessed by modeling; and iii) to define the main characteristics of the models in relation to ecosystem accounting. When possible, the variables in the table were entered using a binary numerical system; otherwise, inputs were made in the form of text. The binary system is the most appropriate in this case, as it allows easy calculation and proper data analyses.

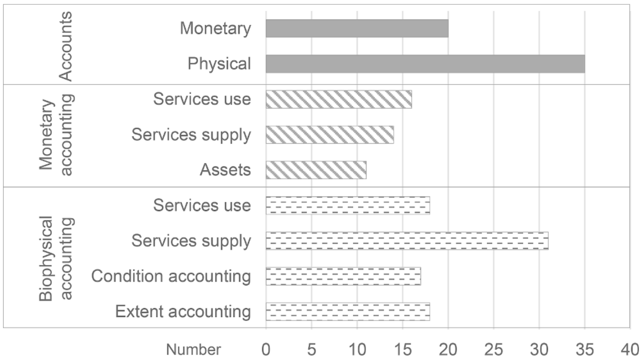

Fig. 3. Distribution of papers related to ecosystem accounting.

The template was divided into two parts, i.e., the main and modeling parts. The main part contained three sections: (1) general characteristics of the publication and ecosystem accounting; (2) ecosystem functions and services; and (3) models for water regulation. The information of each paper in the main part was stored in a single row to facilitate the statistical analysis and classification process. The first section on the

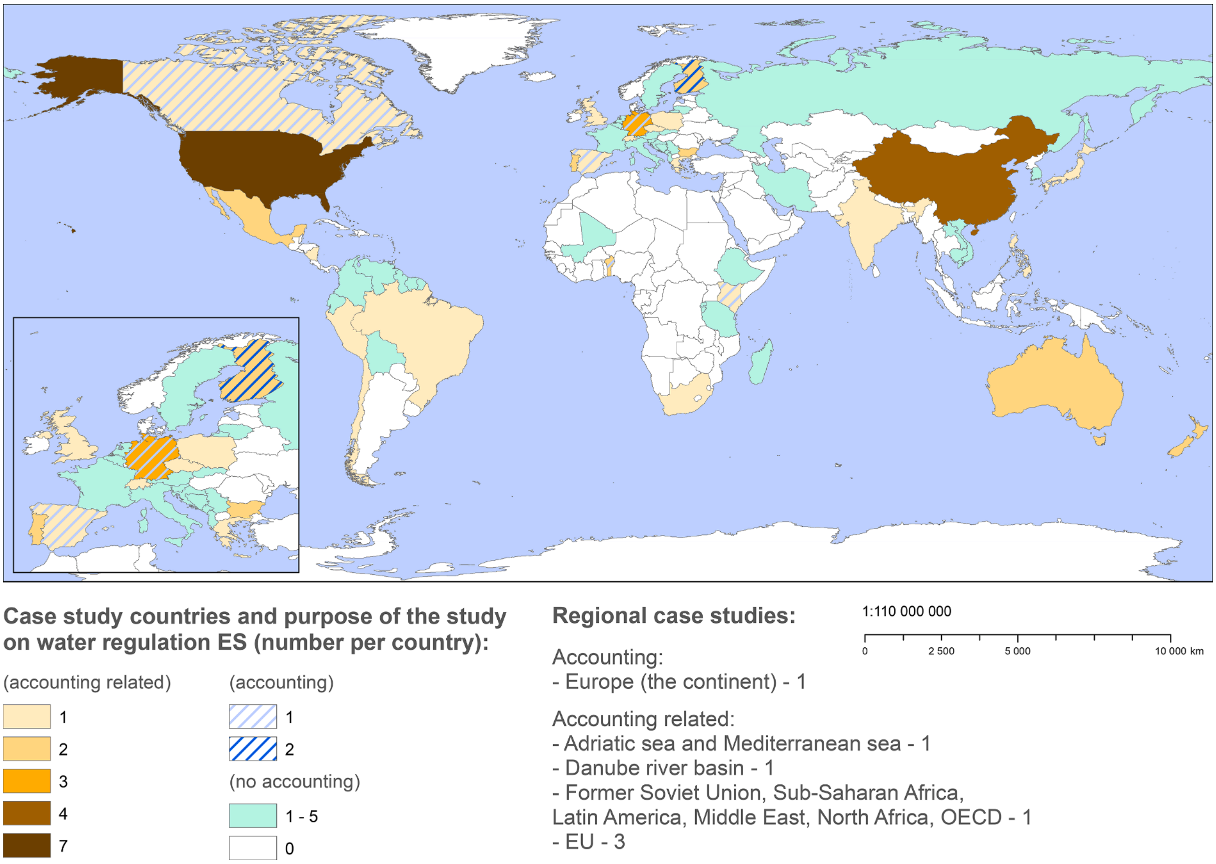

Fig. 2. Spatial distribution of the case studies on water regulation ES by countries.

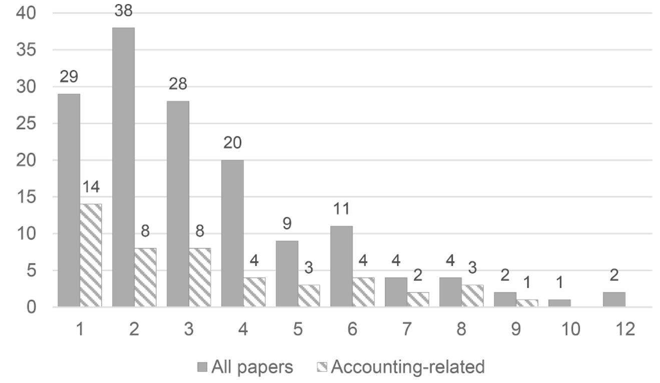

Fig. 4. Distribution of papers according to the number of water-related ES studied in a paper (based on CICES 5.1 classes).

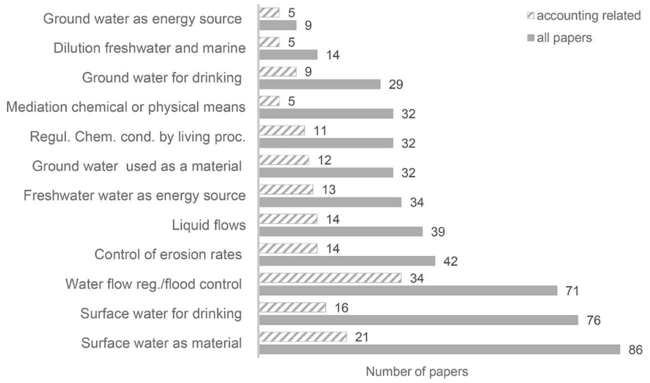

Fig. 5. Distribution of papers into water-related ES (based on CICES 5.1 classes).

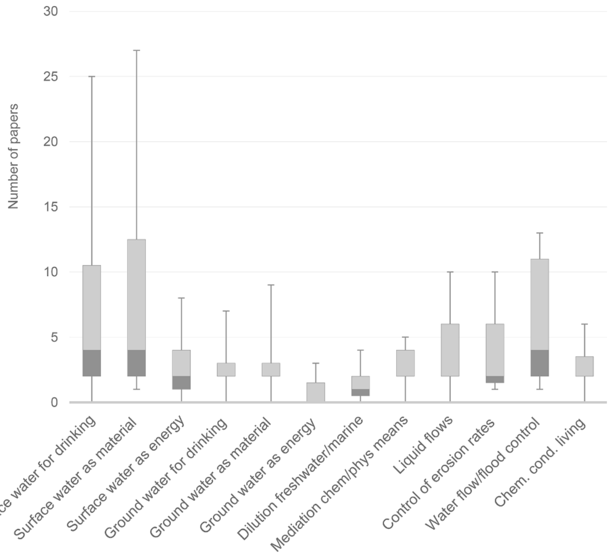

Fig. 6. Distribution of the water-related ES according to the number of services studied in a paper (based on CICES 5.1 classes).

general characteristics of publications contained (i) bibliographic data of the publication (authors, journal, year, and DOI), (ii) data about the case study, (iii) purpose and (iv) dimensions of the study (biophysical, social or monetary). The other part of the section focused on collecting information relevant to ecosystem accounting based on the main elements presented in SEEA–EA, i.e., ecosystem extent, condition, ES supply and use accounts.

The second section, on ecosystem functions and services, gathered information about the water-related functions and services studied in the papers. The water-related ES were identified based on the CICES classification (common international classification of ecosystem services) Version 5.1 (Haines-Young and Potschin, 2018). The CICES classification fits into the broader framework of ecosystem accounting by providing a structure for classifying flows defined as ecosystem services (UN et al., 2014). As some models can be used for both regulating and provisioning ES, we also included provisioning ES although they are not within the scope of this study. Thus, the template captured all water-related ES corresponding to 12 CICES classes (see Appendix 2). The analyses on the use of models were made for the whole range of water-related services, and the interconnections to the ecosystem accounting are focused on water regulation services.

The third section contained general information for the models identified in the publications. The information of each paper in the main part was stored in a single row, which facilitated the data analyses.

The modeling part of the template collected specific and detailed information about the models potentially useful for accounting purposes. As some papers included multiple models, each row corresponds to a single model identified in a paper. The modeling part was divided into three subsections: (1) reference and classification information (publication ID, number of models, and name); (2) specific information about the models, such as software, availability, compatibility, and spatial and temporal scale; and (3) model requirements, concerning input data, accuracy, computing capacity, time consumption, expertise, etc.

2.2.2. *Main steps of the paper review*

The review process was conducted in five steps: 1) review of each paper by one of the team members; 2) extraction of information into a database and initial verification; 3) assignment of the different sections to the team members (see Section 2.2.1) and data verification; 4) cross-section review and update; and 5) data analyses.

During the first step, each paper was reviewed, and the information was recorded in the template, following the rules explained in the previous subsection. Eight people conducted the review, producing eight datasheets. In the second step, the datasheets were integrated into a common database (Fig. 1 - II.2). As the review was performed by different persons, other members of the team verified the data and corrected some discrepancies, gaps or errors by reviewing a few randomly selected papers for a second time and cross-checking the analytical results. The initial verification included a check of gaps, standardization of the records, and verification and analyses of the columns with fewer records (those with less than 10% completed fields were omitted from further analyses). In the third step, further verification was conducted for each section, leading to some updates or even to a restructuring in some sections. For instance, the great variety of models and modeling approaches (some of them not clearly specified) led to the incorporation of new columns in the template. In the fourth step, we synchronized the edits and updates between the different sections of the database (Fig. 1 - II.4). The final step analyzed the information as explained in detail in the next subsection.

2.3. *Data analyses*

2.3.1. *General characteristics of the publications and their relation to ecosystem accounting*

This analysis aimed to describe the pools of papers at a meta level in terms of literature sources, year and place of publication, and purpose and dimensions of the studies. The time and spatial frame of the publications were analyzed for the whole set of papers and separately for the papers related to or focused on accounting. The purpose of the publications was analyzed based on three categories of purposes with subcategories: (i) implementation with decision/policy development, land use planning and management options; (ii) method/tool development with paper review, tool explanation/upgrading and methodological investigation; and (iii) data development with accounting, valuation, mapping and assessment. To identify the dimension of the study presented in each paper, we assigned each publication to one or more of the following general dimensions: (i) biophysical, (ii) social and (iii) economic.

The review focused on models and modeling approaches applied to water regulation ES mapping and assessment. The relation to ecosystem accounting was, thus, not the main criterion for the selection of the papers, but instead we aimed to establish a solid background for the integration of the models into the accounting framework through an analysis of the existing or potential accounting components of the selected papers. The papers were distributed among three groups according to their relation to ecosystem accounting: (i) papers with accounting in their purpose, as identified during the first review step; and (ii) papers mentioning accounting in a particular context, such as possible application, policy and decision-making in relation to the methods, as analyzed in the final datasheet. The search was conducted using keywords of different terms related to ecosystem accounting, i.e., ecosystem accounting, environmental accounting, account, accounting, SEEA, SEEA–EA, green accounting, ecological footprint, NAMEA (national accounting matrix including environmental accounts), MFA (material flow accounting), and AAS (agroforestry accounting system); and (iii) papers not directly related to ecosystem accounting. The analyses relating to accounting were conducted using the data from the first and second groups, for a total of 47 papers. The analytical process followed the SEEA–EA accounting framework. First, the information from the papers was distributed among biophysical and monetary accounts. Then, the data about biophysical accounting were subdivided into extent, condition, service supply, and service use, while the monetary account data were divided into assets, service supply, and service use, following the accounting scheme in SEEA–EEA (UN et al., 2014). The relatively low number of papers focused on accounting could be explained by the fact that much of the work conducted on ES accounting has not been published in scientific journals and probably resides in the “gray literature” published by governments or international agencies that are not in scope of this review.

2.3.2. Ecosystem functions and services

Twelve water-related ES were included in the initial review template (see Section 2.2.1). In the first draft of the revised SEEA–EA (UN et al., 2021), a reference list of selected ES was published. The classification and formulation of ES in this list differ from the CICES 5.1 classes used in our template. Therefore, we reclassified the twelve CICES individual ES in the template to match the SEEA–EA reference list, i.e., four individual services. Six provisioning ES from the template correspond to the water supply category from the reference list; therefore, they were merged into a single service. Three regulating services (regulation of chemical condition, dilution of freshwater, and mediation of chemical or physical means) correspond to water purification ESs from the reference list. The correspondence between water flow-related ES is more complicated, but for the needs of the current analyses, two ES from the template (regulation of liquid flows and hydrological cycle) were merged to link the water flow regulation and flood control. The only ES that had a one-to-one correspondence was soil erosion control. All analyses were performed for both CICES services (12) and the SEEA–EA reference list (4).

2.3.3. Models for water regulation

The model part of the review is the most important and the most comprehensive in terms of the variety of data and methods. During the initial verification of the database conducted at the second step of the review process (see Section 2.2.2), three problems were related to the great variety of models (and modeling approaches), and the ambiguity of the terminology was identified. First, some methods were incorrectly named models. For instance, statistical software, such as MATLAB, R and SPSS (Xu et al., 2017; Cheng et al., 2017), which are used for data processing but not modeling, was removed from our analyses. Second, several approaches did not fit the classical modeling understanding (such as Simonit and Perrings, 2011; Barth and Doell, 2016; Šatalová & Kenderessy 2017), and some non-water models were used in combination with hydrological models (such as Postumuss et al., 2010; Sample et al., 2016). As our aim was to provide an overview of efforts in modeling water regulation ESs that can be used for ecosystem accounting, we kept them in the review and took a broader understanding of models and modeling. The next issue was the classification of the models. The biophysical modeling methods for ES mapping and assessment come from ecology or other Earth science-related fields, such as hydrology, climatology or soil science, and can be classified into nine classes (Vihervaara et al., 2019). The models for water regulation come mainly from the process-based class (predominantly hydrological models), but there are also appropriate options in the integrated modeling frameworks (such as InVEST and ARIES). Hydrological models are classified into deterministic and stochastic models (Shaw, 1983), physical and abstract models (Chow et al., 1988), or more detailed classification schemes (Sindh and Frevert, 2006; Gosain et al., 2009; Jajarmizadeh et al., 2012), but they do not cover hydraulic models that can be used for the assessment of wetland functions for flood regulation ES supply (Vinten et al., 2019). Some water-quality models, such as the GREEN model (La Notte et al., 2012; 2017) and MONERIS (Grossmann (2012), are used for water purification ES assessments. Furthermore, the abovementioned approaches, which did not fit the classical modeling understanding and non-water models, could not be listed into any of the existing schemes. Therefore, we developed our own classification scheme. Finally, the data were analyzed based on the use of models (single or multiple), the type of model according to the classification, and the use of the most common models.

3. Results

The analysis of the papers was performed at two levels: (i) the entire database (148 papers) and (ii) the pool of papers directly related to ecosystem accounting (47 papers). The results at the first level are valid for all modeling efforts used in water-related ES studies and give a broad overview of the published research in this field. They provide a useful synopsis of the application of models and modeling approaches in ES research and can support the development of general guidelines for water regulation ES accounting. The results at the second level provide a more concrete understanding of the use of models in water-related ES accounting and offer background information for specific guidelines.

3.1. Characteristics of the publications

3.1.1. General characterization of the publications

The 148 publications on water regulation ES modeling covered the time period from 2000 to 2019. The number of papers per year grew gradually but unevenly from 1 in 2000 to 27 in 2019. The trend line (linear regression) for all papers indicated a steady increase during the whole period. The majority of the papers (87%) were published after 2011, after which there was a rapid increase from 3–5 per year to 15–17 per year. Ten papers focused on ecosystem accounting, with no clear temporal trend (see Appendix 3), mainly due to their limited number. Most of these were published after 2014, most likely due to the effect of SEE-EEA. The accounting-related papers numbered 37, and their trend followed the growth of the total number, although the trend line was smoother.

The papers were published in 62 different scientific journals, but only 13 journals had more than two papers. The highest number of papers was published in *Science of the Total Environment* (15), *Ecological Economics* (12) and *Ecosystem Services* (10). For the rest, from 3 to 9 papers were published in ten (10) journals and 2 papers in total were identified in ten (10) journals, while one paper was found in 39 journals (for more details, see Supplementary Materials).

The 148 papers comprised 60 unique case studies at the country level and only 11 at the regional scale (Fig. 2), revealing a gap at local and regional scales. Fig. 2 shows a large disproportion in ES studies across the world, with no studies for Antarctica, few in Africa, and the highest numbers in North America, Europe and Asia. Most case studies at the country level were found in the USA (27), followed by China (14), Germany and Spain (12), Kenya and the UK (8), and Mexico (6). All other countries had 1 to 5 case studies each.

In only 7 countries, the performed studies aimed at ES accounting (i.e., Canada, Spain, Germany, Finland, Benin, Kenya and the Philippines), and in 26 countries, the relevant studies were indirectly related to accounting. The regional case studies demonstrate a great variability in spatial extent scale ranging from river basins and sea coasts to political and economic unions, such as the Danube River Basin, Mediterranean Sea, European Union, former Soviet Union or Latin America. Only one case study addressed Europe as a continent, and two studies had a global perspective.

The majority of the reviewed papers (136) had multiple purposes (more than one purpose assessed). The dominant purpose was data development (94% aiming at assessment, mapping, valuation or accounting) or assessment (82%).

Biophysical assessments prevailed, followed by economic assessments, while assessments on the social dimension were the least studied. More precisely, one-fifth of the papers (30 papers) addressed biophysical and economic dimensions, 17% (25 papers) addressed all three dimensions (biophysical, economic and social) and 10% (15 papers) addressed biophysical and social dimensions. Ninety-seven percent of the considered papers (143 papers out of 145) addressed biophysical assessments, among which almost half of them (73 papers) exclusively addressed biophysical assessments. Almost one-third of the papers (40 papers) addressed social assessments and 39% (57 papers) addressed economic assessments, among which only 1% (2 papers) exclusively addressed the economic dimension. It is of note that no paper exclusively addressed social assessments.

3.1.2. Publications related to ecosystem accounting

The paper analysis in relation to ecosystem accounting aimed to reveal how existing studies on the modeling of water-related ES fit the SEEA–EA framework. Only one out of ten papers had accounting as a single purpose (Lai et al., 2018). Two papers (Duku et al., 2015; La Notte et al., 2017) had accounting as a primary purpose, whereas the remaining seven papers had different primary purposes but also included accounting in their study aims. In less than one-fourth (37 papers out of 145 papers) of the reviewed papers, "accounting" was mentioned in the text in a particular context; for instance, as a possible application, policy and decision-making or in relation to the methods. For this reason, these papers were also included in the present analysis (10 + 37 = 47 papers in total).

The predominant number of papers were related to biophysical accounting, while monetary accounting was less studied (Fig. 3), revealing a large gap in terms of valuation. Most papers were related to one of the core accounts, and less than one-fourth had a relation to both physical and monetary accounts.

3.2. Water-related ecosystem services and functions with respect to water modeling and ecosystem accounting

The number of ES studied in a paper varied between one and twelve (Fig. 4). The majority of papers studied between one and four ES. Studies with more than six ESs were quite rare, and most of them covered a broader range of ES, outside water-related ES. After summing up the individual ES studied in all reviewed papers using some kind of modeling, the total number of ES identified in the papers increased to 492, and they were used as the main entries for the analyses below.

The number of papers was distributed quite unevenly among the different relevant ES (Fig. 5). Three ES (surface water used as material, surface water used for drinking and water flow regulation/flood control) were studied in approximately half of the reviewed papers (48%–58%). They were not as highly represented in the accounting-related papers except for water flow regulation/flood control service, which was even better represented in this group (72%). This ES could also be identified as the one that was most often studied in the single service papers (13 of 29 papers) (Fig. 4). A second group of seven ES was relatively well represented (between 29 and 39 papers; see Fig. 5). They were studied in approximately a quarter of the papers (20–28%). Two ES (dilution by freshwater/marine ecosystems and ground water as an energy source) were studied in a few papers, mostly in combination with other services. The services in accounting-related papers could also be divided into three groups. The group with the most papers contained only one service (flood control with 34 papers), the second group contained the majority of services (11–21 papers), and the third group contained fewer than nine papers.

Fig. 6 shows how the abovementioned 492 entries were distributed between the ES based on the number of papers that were studied in and how these numbers were distributed when the entries were grouped into modeled ES. The overall pattern of the box plots (shape, position and range) allowed us to analyze the distributional characteristics of each particular service in terms of related papers. The box plots with clearly formed 25th and 75th percentiles and a high extent in them indicated a good basis for analysis with a high number of modeling cases and a good relation between the models used in the papers. This was the case for three services, i.e., surface water for drinking, surface water as material, and flood control. Therefore, the analysis of the papers for these services could have a higher level of confidence in regard to the models used. The second group of three services, i.e., surface water as energy, dilution of fresh and marine water, and control of erosion rates, had clearly formed percentiles with a low extent, indicating a good relation between the studied services and the models used to assess them, but with a lower number of modeling cases. The services with only a 75th percentile and a low extent indicated a moderate relation with a low number of cases. Finally, two services had only a 75th percentile with a limited extent, i.e., ground water for drinking and ground water as material, which indicated a high uncertainty of the results. These ES were not the services with the lowest number of papers (Fig. 5), as might have been expected.

The distance between the extremes (min and max) and the percentile part of the box plots indicated the homogeneity of the results that could serve as additional criteria for the confidence of the results. The lowest distance (0.2) was flood control, which indicated high homogeneity and high confidence. The other services had a moderate (0.9–1.3) to high (1.4–1.7) distance. The services with very high distances (4.1–6.2) and high uncertainties were again ground water for drinking and ground water as material.

The distribution of papers between the water-related ES classified according to the SEEA–EA reference list showed a similar pattern with some differences. Water supply was the most studied ES among all papers (in 66%), as it combined six CICES classes, including two highly studied CICES services (surface water for drinking and surface water as material). Water supply was studied predominantly in single service papers.

The water flow regulation and flood control services were the most studied in the accounting-related papers (in 74%, Fig. 7), both in single service papers and in combination with the other three (papers with two, three and four services). The water purification ES, which combined three CICES classes, normally increased the number of studies, which could make the analyses about the use of models for this service slightly more reliable.

The analyses of water-related ecosystem functions could complement the analyses of ES and the use of models (Fig. 8). Water yield was the function that was studied the most, but its relative share in accounting-related studies was slightly lower. These results matched the

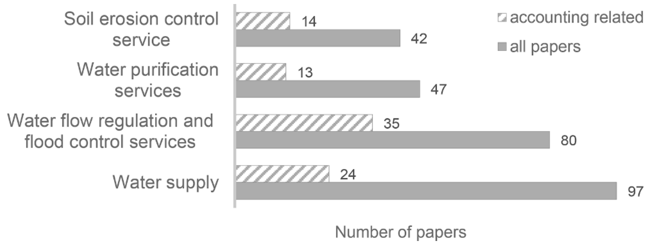

Fig. 7. Distribution of papers into water-related ES (based on SEEA-EA reference list). Soil erosion control corresponds to the Control of erosion rates in Fig. 5, as both CICES and SEEA-EA reference lists include this exact same ES.

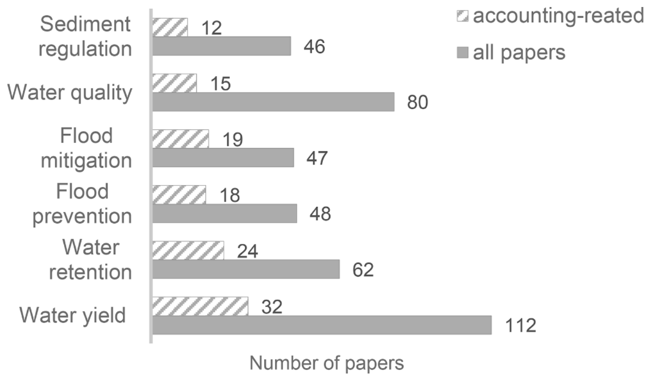

Fig. 8. Distribution of papers into different water-related ecosystem functions.

results on water supply ES. They could be attributed to the increased availability of hydrological models and the high experience in hydrological modeling. Water quality was the second most studied function in all papers (80 papers) but was studied in only 15 accounting-related papers. This function could be associated with the water purification ES from the SEEA reference list and the corresponding three CICES classes. Water retention, flood mitigation and flood prevention were almost equally distributed between the reviewed papers. Their function could be associated with water flow regulation and flood control services from the SEEA–EA reverence list. These functions could also be linked to the baseline flow maintenance, peak flow mitigation, and river flood mitigation services formulated at the second level of the SEEA–EA reference list. The results regarding the sediment regulation function fully correspond to the erosion regulation ES both in the CICES and SEEA–EA reference lists.

3.3. *Water regulation modeling*

3.3.1. *Classification of models and modeling approaches*

We identified more than 200 individual models and modeling approaches that we systematized based on the existing classifications (see 2.3.4). We relied on eight model categories specific to water-related ES: (1) hydrological models; (2) hydraulic models; (3) integrated modeling frameworks; (4) other water-based models (methods that better fit the classical model understanding but did not fit the above categories); (5) GIS tools (use of tools that are an integral part of the commonly used GIS software such as ArcGIS and GRASS); (6) water modeling approaches (using equations to calculate particular water parameters and not fitting the classical model understanding); (7) conceptual or expert-based approaches; and (8) other models and modeling approaches (non-water models used in combination with hydrological or other water-based models to assess particular service or management practices).

Table 2 presents the distribution of all papers among the model categories. While hydrological models prevail and were used in two-thirds of the papers, various other modeling approaches were used to study water-related ES. The integrated modeling frameworks were the second most frequently used category (40 of all papers; 27%). The non-water models and approaches (Category 8) were also well represented in the reviewed papers (13% of the papers). The water-based models, which differ from the classical hydrological and hydraulic models, were used in only one tenth of the papers (16 papers; 11%). The other model categories were less frequently used and did not exceed 10% of the papers.

Table 2
Number (n) of papers per model category (*the percentages exceed 100 because there are papers using multiple models).

Model category	All papers		Accounting rel.		n models
	n	%*	n	%*	
1. Hydrologic models	99	67%	27	57%	31
2. Hydraulic models	3	2%	1	2%	3
3. Integrated modeling frameworks	42	28%	9	19%	6
4. Other water-based models	13	9%	5	11%	12
5. GIS tools	7	5%	3	6%	7
6. Water modeling approaches	8	5%	1	2%	8
7. Conceptual or expert-based approaches	10	7%	4	9%	8
8. Other models and modeling approaches	18	12%	13	28%	17

The distribution of modeling approaches among the accounting-related papers had a similar pattern. Hydrological models were slightly less predominant, while the other non-water models (Category 8) had a higher percentage (28%, which is almost double), making them the second most frequently used. Their increase led to a relative decrease in integrated modeling frameworks (17%; Table 2).

The analysis of the hydrological models revealed that SWAT was by far the most frequently used model (55% of the papers) in this category and in one-third (37%) of all papers. It covered the whole range of ES with the highest use for surface water for drinking (34 papers) and surface water as material (33 papers). KINEROS (kinematic runoff and erosion model) was the second most used model (four papers); HSPF (hydrological simulation program – FORTRAN) and SWIM (soil and water integrated model) followed, with three papers each. Eight hydrological models were used in two papers, and the other 20 hydrological models were used in only one paper. Hydrological models were mainly used to simulate water budgets at the scale of the river basin. Especially in event-based modeling (time step from minutes to hours), the main simulated process was the transformation of precipitation into runoff. This type of modeling could provide an estimate of the mitigation of high runoff by canopy interception volume, soil infiltration rate or surface roughness retardation in high precipitation events.

INVEST was the most popular tool from the integrated modeling frameworks (32 papers, including 76% of this category). ARIES was used in five papers, LUCI (land utilization capacity indicator) was used in two papers, and ESTIMAP (ecosystem services mapping tool) was used in only one paper. The high share of this category was closely related to model integration, which has often been discussed in recent years. In the majority of the reviewed papers (122; 82%), a single model or modeling approach was used. Among the 26 papers (18%) in which multiple models were applied, two models were used in 13 papers, three different models were used in eight papers, and four and five models were applied in two papers. A single model was used in 79% of the accounting-related papers (37 papers), and multiple models were used in 21% (10 papers). SWAT was used in 40 single model papers, which was a slightly lower share (72%) than the respective percentage of all papers. SWAT was also used in integrated modeling approaches.

The distribution of the most commonly used models and model categories according to the number of ES estimated in a paper shows a pattern quite similar to the general distribution (see Fig. 4), especially for hydrological models (including SWAT). A particular difference was found for the integrated modeling frameworks, which were more often studied in papers with one ES and a secondary peak in papers with six ES. However, this is not enough to make a particular conclusion for the use of models based on the number of services per paper.

3.3.2. Relationship between models and water-related ES accounting

The analyses of the relationships between modeling categories and ES revealed which models were used to quantify respective services. Some ES, such as flood control, surface water for drinking, and surface water as material, were studied by models from all eight categories, while the others were not included in one or more of the categories (Table 3). The most specific ES was groundwater as an energy source, which was analyzed by methods from only four categories (Table 3). The use of the hydrological models for ES studies varied from 55% (groundwater for drinking and material) to 25% (regulation of chemical conditions by living processes and mediation of chemical or physical means). The integrated modeling framework was the most used model category in studies of freshwater as an energy source and mediation of chemical and physical means, while this method was seldom used in studies on flood control and dilution of freshwater and marine water. The use of other water-based models (Category 4) ranged from approximately 20% in dilution by freshwater/marine water ecosystems to 2% in the control of erosion rates and 0% in groundwater as an energy source. The other models and modeling approaches (Category 8) also varied in wide ranges from 28% in groundwater as an energy source to 5% in the mediation of chemical and physical means.

The use of models in accounting-related papers showed some differences in comparison to the general distribution (Table 3). The hydrological models were the most used method for the control of erosion rates and for the regulation of chemical conditions, and their percentage was twice as high as for all other papers. The use of the other water-based models for dilution by freshwater/marine water ecosystems was even more pronounced, reaching approximately 35%. For surface water for drinking and material services, the use of models from Category 8 was much higher in comparison to the hydrological models. The use of integrated modeling frameworks in accounting-related papers was lower and was more pronounced in the regulation of chemical conditions (from 25% to 7%) and regulation of liquid flows (from 20% to 7%).

The distribution of the models and modeling approaches among the ES classified according to the SEEA–EA reference list of key ES showed that only one model category, namely, the hydraulic model, was not represented in all four services. This model category was used only for water supply and flood control (Table 3). Hydrological models were the predominant method for these two services, while the integrated modeling frameworks seemed to be the most often used tool for water purification and soil erosion control. The other categories had a similar distribution among the services. For the accounting-related papers, the hydrological models maintained the same share, but their use was lower for water supply and much higher for soil erosion control.

An analysis of all papers showed that the use of the different model categories was almost evenly distributed between the ecosystem functions. The accounting-related papers showed pronounced differences between the addressed ecosystem functions (Table 3). When looking at all papers, hydrological models comprised approximately 50% of the use in all functions, slightly higher for flood prevention and lower for water retention. The hydraulic models were used only for flood prevention and mitigation. The integrated modeling frameworks were more frequently used for water retention and sediment regulation and less for water quality functions. The water modeling approaches were used predominantly for water quality and not at all in sediment regulation studies. For accounting-related papers, the use of hydrological models increased to 65% for flood prevention and mitigation studies and decreased to 40% for water quality and water yield. The other water-based models (Category 4) were used predominantly for water quality studies, while GIS tools were applied only to water yield and water retention assessments. Water modeling approaches (Category 6) were applied only to water quality and water yield studies.

Table 3

Relation between ES (according to CICES and SEEA-EA), ecosystem functions and model categories (numbers are given in Table 1) for all papers and accounting-related papers.

Ecosystem functions and services	Model categories															
	All papers								Accounting-related papers							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
CICES 5.1 classes																
Surface water as material	61	1	28	6	3	6	5	12	12	0	5	1	1	0	3	9
Surface water for drinking	56	1	29	6	3	4	3	10	11	0	4	1	1	1	2	6
Water flow/flood control	44	2	15	6	5	2	8	7	20	1	5	3	2	1	3	5
Control of erosion rates	21	0	16	1	1	1	4	6	9	0	2	0	0	0	2	3
Liquid flows	20	0	10	4	3	2	4	7	8	1	2	1	1	1	2	4
Freshwater as energy	16	0	20	2	2	2	2	4	7	0	4	1	0	1	2	2
Ground water material	28	1	10	5	0	1	2	5	10	0	3	1	0	0	1	3
Chem. cond. living	10	0	12	5	2	2	5	5	6	0	1	3	0	0	2	3
Mediation chem/phys means	11	0	18	3	1	2	5	2	2	0	2	1	0	0	2	1
Ground water for drinking	30	1	12	5	0	0	1	5	8	0	3	1	0	0	1	3
Dilution freshwater/marine	4	0	3	3	0	0	2	3	1	0	1	2	0	0	1	1
Ground water energy	5	0	2	0	0	0	1	3	4	0	2	0	0	0	1	2
SEEA-EE reference list of key ES																
Water supply	71	1	33	6	4	7	5	13	14	0	5	1	1	1	3	9
Water flow/flood control	48	2	18	6	6	3	8	8	21	1	5	3	2	1	3	5
Water purification	22	0	21	7	2	3	8	5	8	0	3	4	0	0	3	3
Soil erosion control	21	0	16	1	1	1	4	6	9	0	2	0	0	0	2	3
Ecosystem functions																
Water yield	82	1	37	11	6	4	7	11	19	0	7	3	3	1	3	8
Water retention	37	0	23	5	5	3	4	5	15	0	5	1	2	0	2	3
Flood prevention	34	1	15	4	2	1	4	4	15	0	3	1	0	0	1	3
Flood mitigation	33	2	18	3	3	1	4	5	15	1	3	0	0	0	1	3
Water quality	61	0	23	12	2	6	7	6	10	0	3	4	0	1	2	2
Sediment regulation	32	0	20	4	2	0	4	5	10	0	3	1	0	0	1	3

4. Discussion

4.1. Water-related ES and ecosystem accounting

The systematization of the studies on water regulation modeling and the analyses of ES included in these studies enabled the separation of ES into four categories based on the number of relevant papers (all and accounting-related) and the analyses of their distribution (Fig. 6). The first category has only one service (flood control) with the best performance in all criteria (see 3.2) and a high confidence in regard to the recommendations of model use. The second contains four services: two services, studied in a high number of papers (surface water for drinking and surface water as material), and two services (surface water as energy source and control of erosion rates) with a good relationship between the studied services and the models used to assess them. The confidence for their recommendation could be defined as moderate. The third category contains five services, modeled in a few studies, with weak correlations that have a low confidence in regard to the recommendations. The fourth contains two services (groundwater for drinking and groundwater as an energy source), which have been studied in very few papers with a low confidence level. This analysis did not lead to any recommendations on which model to use in ecosystem accounting.

From the perspective of the SEEA–EA reference list (UN et al., 2021), the accounting of water flow regulation and flood control services could rely on the most developed modeling approaches as identified by the abovementioned results on flood control and the well-presented ecosystem functions (flood mitigation, flood prevention, and water retention) in the studied papers. Further studies in this respect are needed to reveal how these modeling approaches are linked to the ESs at the second level of the SEEA–EA reference list. Both water flow and flood control are indeed divided into several more specific services. For instance, models should distinguish coastal protection and river flood mitigation services (Crossman et al., 2019). The results regarding the soil erosion control service are the most homogeneous, as this service corresponds to just one CICES class and one ecosystem function. Therefore, it can be considered the second best performed in the studied papers, and the confidence in regard to the recommendations is moderate. The modeling of water purification could rely on experience and data from a relatively high number of studies, both as ES and ecosystem functions. However, the level of confidence in these data is relatively low, and the diversity of ESs in the CICES matching “water purification” adds to the complexity. Water supply incorporates the highest number and variety of CICES classes. The recommendation for these ES varies from moderate to very low confidence.

Vardon (2014) recommended developing SEEA in a direction that is conducive to explicitly account for regulation as an intermediate ES. The surveyed data show that water flow regulation and flood control services are more often coherent subtopics in water quantity research and less prominent in publications with research questions directly focused on the flood prevention/mitigation function and related final services. Our data confirm the findings of the SEEA–EA (2021) standard “hydrological modeling”, which is commonly used to underpin the measurement of a range of regulation ecosystem services, including flood prevention and mitigation and water retention. The water quality function and the ‘surface water used for drinking’ service are regularly featured in research papers but still remain ‘on the backburner’ in accounting-related publications. Water quality has a direct effect on an ecosystem and on the activity of regulatory processes and can be considered once again as a final service, but this time also as a qualitative result of inter- and intra-systemic interactions. However, the evaluation of this function hardly meets the accounting requirements for clarity and simplicity of a procedure.

We also revealed the contribution of modeling to explicitly account for water regulation, as an intermediate ES. Modeling has the potential to significantly support our understanding of spatially explicit processes, but such potential must be confirmed by additional verification based on environmental monitoring data. Thus, our findings confirm the statement in the technical recommendations in support of SEEA (UN et al., 2017) that water retention, water purification, and erosion control “can be both final and intermediate” ES.

4.2. Water regulation modeling and ecosystem accounting

The models and modeling approaches used for water regulation ES assessment go far beyond the conventional hydrological and hydraulic models. The proposed classification enables us to distinguish eight model categories that should be considered for water regulation ecosystem accounting. The next step of this work will be to explore the application of models from each category to the ESs from the SEEA reference list and to structure and rationalize them into guidelines following, for instance, the decision tree approach proposed by Harrison et al. (2018).

The hydrological models provide the best options for modeling water regulation accounting, and the SWAT model is the leader in this group, covering all aspects of water-related ESs. Water regulation appears to be the most suitable for the control of erosion rates and floods. Its approach of continuous modeling (time step from days to years) involves multiple processes, such as evapotranspiration, water uptake by plants, or snowmelt. This approach can estimate other ecosystem functions and related services, such as climate regulation by evapotranspiration, maintaining the flow of a river for water supply, or reducing nutrient pollution. Such a usage was elaborated by Logsdon and Chaubey (2013).

Hydraulic models can provide an estimate of the influence of the geomorphology of river channels and the occurrence of floodplain vegetation on the attenuation of flood waves and the reduction of property damage. For instance, they can capture and estimate the effect of mangroves on coastal flood damage protection (Menéndez et al., 2019) and wetland effectiveness in water purification (Trepel, 2010). However, the potential of hydraulic models for ES assessment and further ES accounting is still far from being used effectively. The importance of natural and seminatural land cover in riparian zones is mentioned by Vallecillo et al. (2020) as one of the main elements of flood control potential (or capacity in SEEA-EA terms) accounting. The application of hydraulic models will allow users to quantify the capacity of these zones more precisely.

The integrated modeling frameworks provide simple and low data-intensive tools that require less expertise in comparison to complex hydrological models (Vigerstol and Aukema, 2011). The most popular approaches are the InVEST toolkit modules for estimating water yield. Integrated frameworks can be considered static from a time perspective and provide only general outputs with long-term average values. In comparison to hydrological models, they provide different output values but generally also capture the pattern of hot and cold spots in a watershed, as shown by Cong et al. (2020). The integrated modeling frameworks are the second most used group of models when considering all papers, but the use of this group is less important in accounting-related papers. These results contradict current tendencies in the technological development in these tools toward more specific ES assessment and accounting applications. For instance, the ARIES modeling platform allows for data and model integration to produce accounts (Capriolo et al., 2020) and provides a tool for natural capital accounting (Zhongming et al., 2021). Keeping in mind that accounting applications are a very recent field, the time frame of our review might not capture this new trend in scientific publications. However, the potential of these tools can be highlighted by the variety of ES (including water regulation services) they cover and their easy-to-use approach.

The analyses in this work were conducted on the basis of the common use of the models in the reviewed literature. However, appropriate integration of models into the SEEA–EA framework necessitates further studies in relation to data availability and capacity to operate with the models, prices for licenses and other expenses, spatial and temporal scale of the models and regional and country specifics. The modeling part of our database contains data that can be used for such analyses and is a matter of further exploration and publication.

4.3. Recommendations and research priorities

The physical ES flow accounts describe the ecosystem services generated by ecosystem assets in volume terms (UN et al., 2021). The quantification of ES flows provided by the models should be used to develop indicators with a focus on the ecological supply side of ecosystem service flows in physical units.

The results of our study, based on the estimated use in the reviewed studies, enable us to recommend the use of the hydrological models for water flow and flood control services (from the SEEA–EA reference list), as these models are the most relevant for the quantification of ES indicators. Specifically, the SWAT model provides the best developed and documented techniques for ES quantification. Many other hydrological models, such as KINEROS, HSPF, and SWIM, could be used, but their applicability needs further research. GIS tools (Category 5) and conceptual- or expert-based approaches (Category 7) seem to be the next preference for these services. The integrated modeling frameworks are still not well represented in the literature concerning flood control. Their rapid development in recent years is promising and could provide appropriate solutions, especially for data- and resource-scarce case studies.

Our results enable us to recommend hydrological models and integrated modeling frameworks as the most relevant quantification means for soil erosion control. The InVEST soil erosion module could be defined as the most developed tool for the quantification of soil erosion regulation services. Conceptual or expert-based approaches (Category 7) and the other modeling approaches (Category 8) also appear suitable. Integrated modeling frameworks are less represented in accounting-related papers, indicating that their application for accounting needs further research.

The results for the water purification service do not allow us to recommend any particular group of models, which is in line with the abovementioned low confidence of the analyzed data for this service. Integrated modeling frameworks were identified as most appropriate for the mediation of chemical means service, which is one of the three constituent CICES classes of water purification from the SEEA–EA reference list. This is mainly due to the water purification module in InVEST, which is used mainly for quantification of this service.

These recommendations are based mainly on the findings of the review about the use of the models within the reviewed papers. We are aware that apart from the use in the existing studies, there should be further criteria, such as data availability and operational capacity, prices for licenses and other expenses, as well as the spatial and temporal scale of the models. Therefore, these recommendations should be considered initial conclusions that need further justification.

One of the main priorities for future research should be the analyses of models with respect to their application requirements and potentials. Some characteristics, such as spatial scale, time-step, input data requirements, accuracy, or computation capacity, are crucial for the application of models and modeling approaches (Lüke and Hack, 2017). Such analyses will allow further development of the recommendations and formulation of guidelines for model applications in ecosystem accounting. Additionally, the planned integration of the database developed for this review into the open-access online repository, ESMERALDA MAES Explorer[1] (Reichel and Klug, 2018), will contribute to the expansion of the online method database for mapping and assessing ESs toward ecosystem accounting.

Further research is also needed to analyze the spatial aspects of the models. The empirical distinction of ES capacity and actual flow (ES supply and use) is indeed a distinguishing feature of ecosystem accounting (Duku et al., 2015). La Notte et al (2017) also note that the definition, in accounting terms, of stocks and flows of ecosystem services is of crucial importance. For the water regulation services, this distinction is even more important as it is usually difficult to distinguish between ES potential (or capacity in NCA terms) and flow (Burkhard and Maes, 2017).

The formulation of some water regulation services in the SEEA-EA reference list differs in some aspects from the CICES 5.1 classes, e.g., flood control, which is divided at the second (subtype) SEEA-EA level into peak flow mitigation, coastal protection, and river flood mitigation services. This difference has implications in terms of modeling. The water purification (water quality regulation) services correspond to three CICES 5.1 classes, each with its own specifics concerning the use of models.

5. Conclusions

The topic of modeling water-related ES is widely used in the scientific literature, which provides a good basis for both ecosystem assessment and accounting. However, specific accounting studies are scarce, which is a gap in ES research that needs to be filled. In agreement with previous studies, we highlighted the variety of approaches for modeling water-related ecosystem services. The approaches vary from traditional hydrological models through specific tools incorporated into integrated modeling frameworks to conceptual approaches with non-water models used in combination with water-based models. The classification proposed in this study arranges this variety into a systematic order, which can be used in the assessment of water regulation ES and for further integration into the accounting framework. The hydrological model SWAT is by far the most popular modeling tool in the assessment of water-related ES. Its applicability is determined by its long history of development and popularity among hydrologists. However, the requirements of data and specific expertise in hydrology limit the number of potential users (Vigerstol and Aukema, 2011). The second most used modeling tool is InVEST, which allows a wide variety of users to apply relatively simple and fast approaches, providing an overview mainly on an annual basis. However, this tool cannot provide reliable results at finer temporal and spatial scales, especially when the modeled ES shows seasonal and spatial variability.

The results from our study provide the basis for recommending the most appropriate categories of models for water regulation ES included in the SEEA–EA reference list. The recommendations for the use of models in the quantification of water flow and flood control services for the needs of ES accounting have a higher confidence than for the other studied services. Models for erosion control ES could be recommended with a lower confidence, while clear evidence about using a particular group of models is lacking for water purification. The main research priorities on the integration of models in the accounting of water regulation ecosystem services are 1) further development of guidelines for the use of models in ecosystem accounting; 2) analyses that disentangle (and integrate) the spatial and temporal aspects of the model toward a clear distinction between ecosystem service supply and use; and 3) development of integrated modeling approaches for water regulation ES accounting.

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.

Data availability

Data will be made available on request.

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[1] https://www.maes-explorer.eu.

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Appendix A. Supplementary data

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