

Accounting for water: A global review and indicators of best practice for improved water governance

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ABSTRACT

Effective water governance requires timely and reliable information, yet water data are often scattered or missing. Water accounting organizes existing data to provide decision-makers with the best possible information. We reviewed 271 water accounts from 139 publications from 78 countries and regions to determine their scope and coverage. Account production increased over time and occurs in countries of low- to high-income, small to large size, and at various water stress levels. The System of Environmental-Economic Accounting was the most used water accounting framework ($n = 73$). Many accounts are “one-off” exercises ($n = 138$). Twenty-seven countries have regular accounts with a time series extending >10 years. Annual accounts were produced mainly by national statistical offices ($n = 14$). The most common types of water accounts produced were for physical (i.e., m^3) water supply and use ($n = 74$) and water assets ($n = 54$), with the level of environmental and economic detail highly variable. Indicators of best practice water accounting are improved engagement between account producers and users for determining users’ needs in terms of the range of accounts, the number of industries and water resources recorded, spatial and temporal coverage, production frequency and timeliness, integration with other environmental and economic data, and the quality and accessibility of water accounts.

1. Introduction

There is increasing competition for water between the economy and the environment (Falkenmark, 1986; d’Odorico et al., 2020). With changing water supplies (Konapala et al., 2020) and climate change increasing the frequency and magnitude of extreme hydrological events (e.g., floods and droughts) and making them less predictable (e.g., Kreibich et al., 2022), much better information is needed for effective water governance (Grafton and Hussey, 2011). This paper reviews water accounts to develop best practice indicators for integrating hydrological information from many data sources with other information on the economy and environment for better water governance.

Multiple water accounting frameworks exist, with the most widely used being the System of Environmental-Economic Accounting¹ (SEEA). This framework was adopted by United Nations (UN) processes as an international statistical standard and is an extension of the System of National Accounts (SNA) (EC et al., 2009). The SEEA offers global benefits because the SNA is used by every country in the world for economic management and policy, with its best-known indicator being the Gross Domestic Product (GDP) (Coyle, 2015).

The SEEA has several water-related components: SEEA Water (UN, 2012a); SEEA Central Framework (UN et al., 2014); SEEA Ecosystem Accounting (UN et al., 2021). Other water accounting frameworks are also in use (Godfrey and Chalmers, 2012), including, for example, Water

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¹ <https://seea.un.org>

Accounting Plus² (WA+). Typically, these other accounting frameworks are aligned with different parts of the SEEA and use similar data sources and methods (Vardon et al., 2012). In addition, corporate water accounting is applied by businesses outside of the water supply industry to inform organizational decisions, and for identifying, for example, their dependence on water (Christ and Burritt, 2018; Ingram et al., 2022).

Two features distinguish SEEA from other water accounting frameworks. It directly links to: (1) water information to the information in the SNA, and; (2) to other the environmental and ecological information in the SEEA Central Framework and SEEA Ecosystem Accounting. These linkages allow for integrated environmental-economic analysis, help bridge the disciplinary divides of socio-economic and bio-physical data analysis, and support multi-disciplinary research and management (e.g., Brandt et al., 2013).

Fig. 1 presents the scope of water accounting. It is a simplified presentation of the stocks and flows of water within and between the hydrological system and the economy. We highlight that water accounts can be produced at any scale: in a country, a river basin, the water supply industry, or for an individual water supplier. Many physical flows have matching monetary flows. Not shown in Fig. 1, but within the scope of water accounting, is the discharge of pollutants, water quality, spending on water resource management and environmental protection, and water-related ecosystem services (e.g., water supply, water purification, and water flow regulation services).

As with any information and decision system, water accounting depends on data availability (UN, 2012a, 2012b) and relies on the expertise of various professions and agencies for their production (Vardon et al., 2018). Water accounts production is a multi-disciplinary endeavor that, typically, includes hydrology, economics, statistics, accounting, and specialized knowledge in key sectors such as energy and agriculture, including research institutions (Bagstad et al., 2021). Thus, when conducted for government decision-making by government agencies, such as in the USA, water accounting involves many agencies (e.g., US Department of Commerce, 2023).

1.1. Water governance and water accounting

Effective water governance requires information for measuring, monitoring, and understanding (Grafton and Hussey, 2011). Four primary objectives of decision-making for water governance are highlighted in Fig. 2. Objective 1 of *providing drinking water and sanitation services* is the governance arrangements that ensure that the population has access to safe drinking water and a means of excreta disposal. Water and sanitation services in urban centers are provided through water supply and sewerage networks and operated by water utilities. Many rural communities and households, especially in low- and middle-income countries, must provide their own water and sewerage services as they are not connected to these networks. Objective 2 of *balancing water supply and demand* is the governance arrangements for water allocation to balance the demands for water by society with the physical availability of water. Water demand and water availability change over time and across locations. Managing this variability without compromising the environment and the needs of future generations is an important public goal. Objective 3 of *maintaining healthy water resources*, is the policies intended to preserve the quality of water resources and the aquatic ecosystems. Objective 4 of *adapting to extreme hydro-meteorological events* is the governance arrangements to mitigate the adverse effects of droughts and floods on people, the economy (e.g., agricultural production), and the environment. This would include adapting to the changes in water supply and demand due to climate change. These objectives are linked to water and other SEEA-based accounts (Table 1).

While water accounting can provide integrated hydrological and

economic information to support water governance, its widespread use in decision-making remains, like environmental accounting, limited in scope and by country (Vardon et al., 2016a, 2016b). This is despite the fact that multiple opportunities have been identified to use water accounting for water management (Meijer et al., 2020), assessing land management trade-offs (Keith et al., 2017), full cost recovery water pricing (Romero et al., 2017), and wildlife management (Vardon et al., 2017).

1.2. Goal and structure of review

Our review builds on previous work, including: Bagstad et al. (2020), Salminen et al. (2018), Smith (2020), Vardon et al. (2016b); and the World Bank (2021). A key value add of our global review is that it covers all water accounting systems and the academic literature, comprehensively examining current practices, and identifying global best practices.

Our goal is to show how water accounting has developed over time and how it could be improved to better inform water governance. Section 2 outlines the main features of water accounting, Section 3 describes current practices (e.g., number and types and accounts produced, institutional arrangements, data sources and methods used for account production), and Section 4 includes our key results and findings. Key insights are highlighted in Section 5, while Section 6 details the learnings from current practices and water accounting best practices for improved water governance.

2. Water accounting

2.1. Types of water accounts

The SEEA describes three general types of accounts. First, there are supply and use tables in physical and monetary terms showing the flows of natural inputs, products, and residuals. Second, asset accounts for individual environmental (including ecosystem) assets in physical and monetary terms, showing the stock of assets at the beginning and the end of each accounting period and the changes in the stock. Third, accounts record transactions about economic activities undertaken for environmental purposes. The SEEA Water identifies 22 different types of standard water accounting tables, 14 supplementary tables, and five indicator tables (Supplementary Information Table S.1).

Physical water asset accounts show stocks of water contained in the inland water resources by asset class (groundwater, soil water, various forms of surface water) and how they change from one period to the next. The physical water asset account is closely aligned with a water balance (Vardon et al., 2012). For theoretical completeness, the water in rivers is included in the asset account, which is the volume at a point in time, for example, the volume calculated by the length, width, and depth of rivers on 1 January. Some water resources are irrelevant to some areas, for example, those without snow, ice, glaciers, or groundwater, or may be considered of little utility, hence not included. This is in line with the "...flexible and modular approach to implementation within national statistical systems which can be aligned with the particular policy context, data availability and statistical capacity of countries" (UN et al., 2014, pp. viii-ix).

Physical flow accounts show the supply and use of water, which can be split by water quality (e.g., potable or non-potable) and desalinated water. Supplementary Information Table S.2 presents an entire SEEA water supply and use table. The flows of wastewater to the sewerage industry are also recorded in physical flow accounts. Conceptually, the physical flow accounts record all flows back to the environment from the economy.

Monetary accounts for water supply and use are aligned with the physical flow accounts. As with the physical flow accounts, different types of water and water-related products can be recorded. Other monetary accounts are part of the SEEA, including the expenditure on the protection and remediation of water resources and financing of

² <https://wateraccounting.un-ihe.org/>

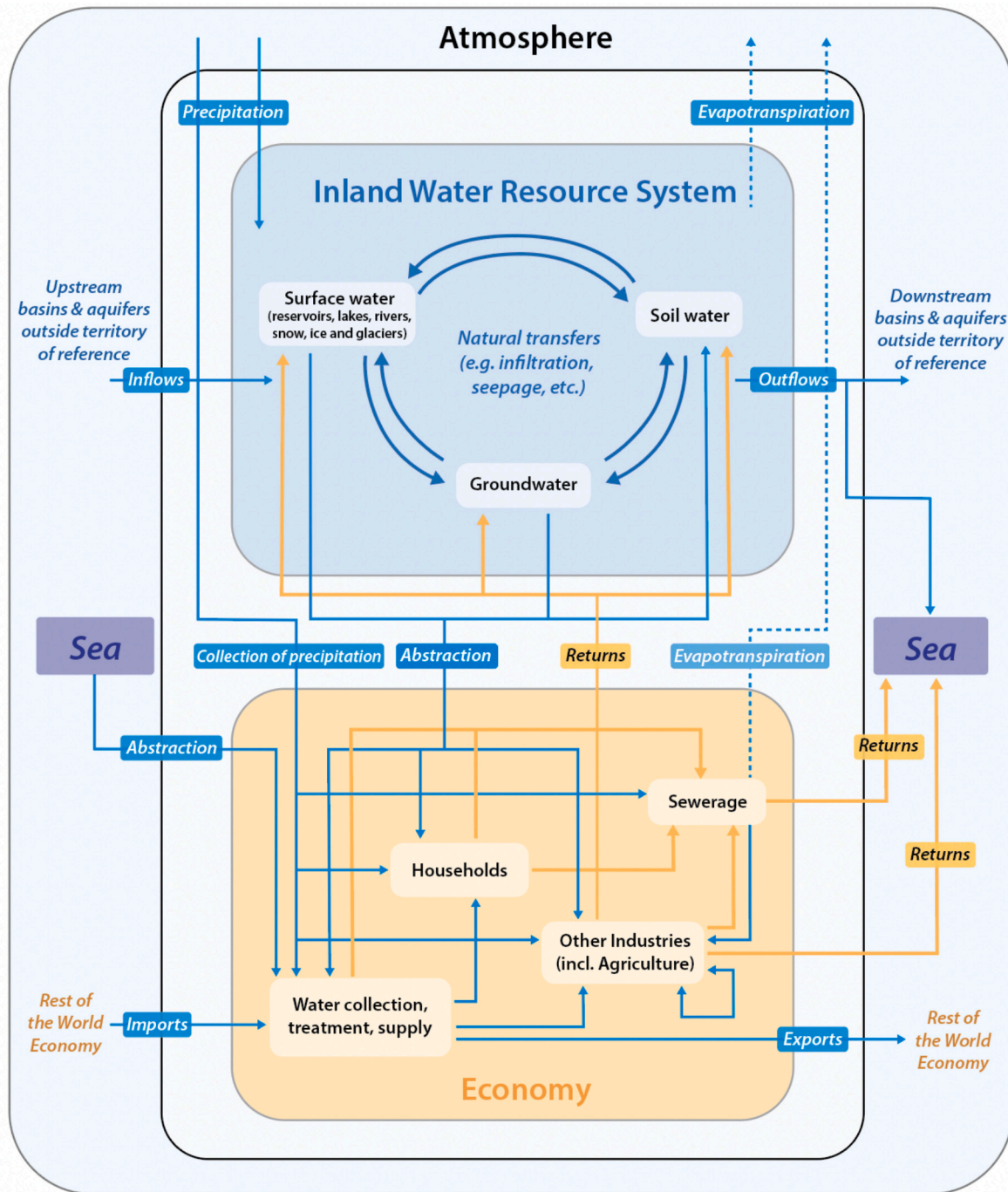


Fig. 1. The scope of water accounting. After SEEA Water (UN, 2012a).

expenditure on the protection and remediation of water resources.

Emission accounts record the volume of water the economy emits, with or without water treatment. This account shows the water flows from different industries and sectors of the economy to the sewerage industry and directly to the environment. Accounts may also include the amount of sewerage sludge and record the pollutants (e.g., N, P, K) added to water by economic activity.

Water quality or condition accounts show water by different quality classes for each type of water resource or show water quality indicators by type of water resource or individual water resources. For example, the Australian Bureau of Statistics (ABS) and Australian Bureau of Meteorology (BoM) (2019) water quality account uses a range of indicators, including pH, conductivity, dissolved oxygen, P and N levels,

for three rivers, four lakes and three catchments. SEEA Ecosystem Accounting also describes ecosystem condition indicators, with water quality being an indicator of overall ecosystem condition (UN et al., 2021).

2.2. Water accounting and 'water budgets'

Water budgets are a tool for quantifying water flows into and out of a hydrological system. They record all water stored and exchanged on the land surface (rivers, lakes), subsurface (aquifer, groundwater), and atmosphere (precipitation, evaporation) (e.g., Healy et al., 2007). A water budget resembles a physical asset account (Vardon et al., 2012).

By linking a water budget to physical supply and use tables, the

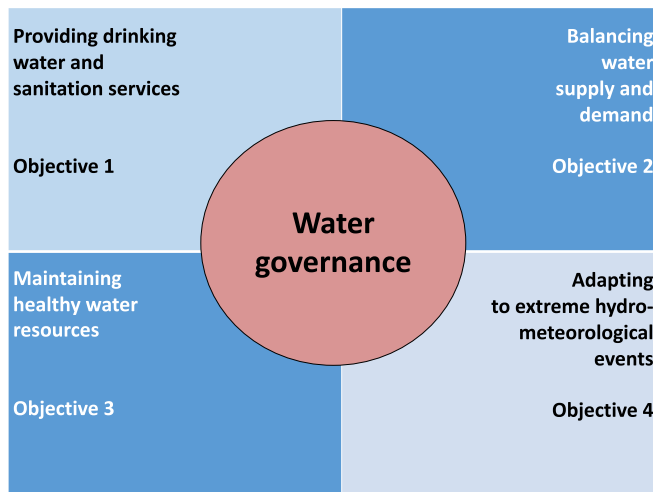


Fig. 2. Four water management and governance objectives. After: UNESCO-WWAP and UNSD, 2011.

Table 1

Links between natural capital accounts and key water policy areas and concepts.

Policy area	Key concept	
	Full cost recovery	Integrated water resource management
1. Providing drinking water and sanitation services	Physical and monetary water supply and use tables SNA accounts (emphasis on the water supply and sewerage industries) Environment protection expenditure accounts Water asset accounts	Physical and monetary water supply and use tables Land cover and land use accounts
2. Managing water supply and demand	Physical and monetary water supply and use tables Water asset accounts Land cover and land use accounts SNA accounts (emphasis on the water supply and sewerage industries)	Land cover and land use accounts Physical and monetary water supply and use tables Water asset accounts
3. Maintaining healthy water resources	Physical and monetary water supply and use tables (emphasis on return flows and operation on sewerage collection and treatment) Land cover and land use accounts Water quality accounts Environment protection expenditure accounts	Land cover and land use accounts Physical and monetary water supply and use tables Water asset accounts
4. Adapting to extreme hydro-meteorological events	Land cover accounts Water asset accounts Environment protection expenditure accounts Ecosystem service accounts (for flood protection and regulation of water flows)	Land cover accounts Water asset accounts Environment protection expenditure accounts Ecosystem service accounts (for flood protection and regulation of water flows)

Source: After Vardon et al. (2018).

amount of water abstracted and returned by human activity can be better understood. This enables water managers to (re)allocate the available water to different users and to better comprehend the impacts on both the hydrological and economic systems of changes in water availability, water use, and expected water demand (e.g., through

increased population or the growth of large water-using industries).

2.3. Ecosystem accounting and water-related ecosystem services

Ecosystem Accounting covers aquatic ecosystems, several water-related ecosystem services, and water quality indicators that contribute to the assessment of ecosystem condition (UN et al., 2021). The Ecosystem Type Reference Classification used in SEEA EA is based on the IUCN Global Ecosystem Topology (GET). Ecosystem types related to water include artificial reservoirs³, lakes, rivers and streams, snow, ice and glaciers and groundwater as well as other water-related ecosystems, such as wetlands. Water-related ecosystem services, include water supply; water purification (retention and breakdown of nutrients and other pollutants, e.g., as provided by the vegetation in water catchments); water flow regulation; river flood mitigation services (this is the riparian vegetation which provides structure and a physical barrier to high water levels). Nursery population habitat (e.g., for harvested fish); recreation-related services (e.g., canoeing on a river); visual amenity (e.g., views of a river or snow, ice, and glaciers); spiritual, artistic, and symbolic services (e.g., the Ganga or Ganges River). SEEA Ecosystem Accounting provides more details on the concepts and structure of the accounts (UN et al., 2021).

2.4. Data sources and methods for water accounting

Water accounts use many data sources and methods. A detailed examination of the data sources and methods used, however, is beyond the scope of this global review. The International Recommendations for Water Statistics (UN, 2012b) provide further details, and since its publication there have been many advances. For example, in the use of remote sensing technologies, hydrological modeling (e.g., Karimi et al., 2013; Pedro-Monzonis et al., 2016; Esen and Hein, 2020; Kind et al., 2020), and an increase in computer power that has resulted in the refinement and development of a range of tools for collecting and analyzing various types of data needed for water accounting (e.g., WA+⁴).

In general, there are two distinct data categories: physical data on the environment (e.g., stocks and flows of water in the environment); and physical and monetary data regarding the water use and economic units (e.g., flows of water between the environment and the economy and flows of water within the economy, and the related financial information). The data sources and methods used to produce the information needed depend on multiple factors, including the institutional arrangements and level of human and financial resources available.

Data on the physical environment are obtained through direct (scientific) observation by agencies responsible for hydrological and meteorological monitoring and research. Data from or about economic units (e.g., businesses and households) are usually collected by two primary means: accessing data collected for administrative purposes (e.g., tax, annual reports, water licensing registers) or by direct survey (e.g., by a national statistical office). In many cases, the original providers of the data and the original sources of the data are the same, namely, the economic units and the records kept by these units. National statistical offices usually conduct surveys, while administrative data may be held by a range of government agencies and some industry associations, and individual companies may produce annual reports with relevant information.

³ Human-created ecosystems, like urban settlements and agricultural landscapes, are all included in the SEEA Ecosystem Accounting typology.

⁴ <https://wateraccounting.un-ihe.org/welcome-water-accounting-plus-0>

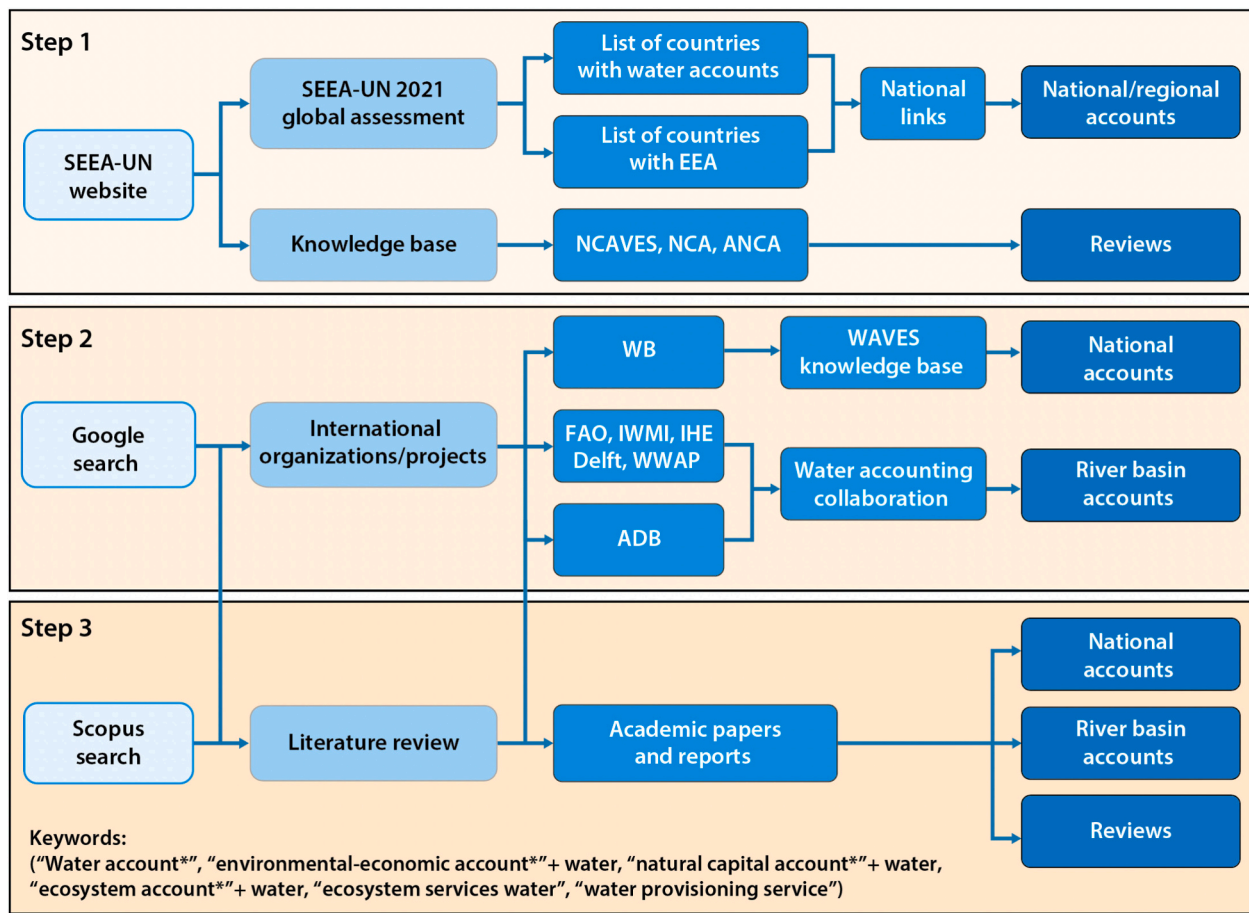


Fig. 3. Search pathways for water account review.

2.5. Uses of water accounts

There are many actual or potential uses of water accounts. To be used, most decision-makers need to know how water accounting is relevant to their needs. Indicators that can be derived from the water accounts play a key role here. This starts with a mapping of their information needs and can be done for the four general water management and governance objectives (Table 1). Example of accounts application to specific topics include water security (Mahdavi et al., 2019), groundwater management (Mazzanti et al., 2014), managing trade-offs in catchments used for water supply (Keith et al., 2017).

2.5.1. Water accounting and the sustainable development goals

Water accounting responds to SDGs, a universal call to action to end poverty, to protect the planet, and to ensure that all people enjoy peace and prosperity. SDG 6 is to “Ensure availability and sustainable management of water and sanitation for all”. The SEEA-based water accounting can support six indicators for SDG 6, including: (1) proportion of wastewater safely treated; (2) proportion of bodies of water with good ambient water quality; (3) change in water-use efficiency over time; (4) level of water stress: freshwater withdrawal as a proportion of available freshwater resources; (5) changes in the extent of water-related ecosystems over time, and; (6) Water- and sanitation-related official development assistance that is part of a government-coordinated spending plan.

Constructing the SDG indicators requires data from several types of water accounts. The Philippines used water accounting to construct two indicators related to SDG 6, namely SDG 6.4.1 Change in Water Use Efficiency (WUE) and SDG 6.4.2 Level of Water Stress (LWS) (PSA, 2020). WUE is defined as the value added of a given major sector divided

by the volume of water used⁵. The Philippines calculated the WUE for three sectors and the nation’s WUE using the SEEA Water physical supply and use tables and the valued added from the SNA (PSA, 2020).

The advantage of SEEA-based indicators is that the water information can be linked to other economic, social, and environmental information, enabling, for example, integrated land and water management (Meijer et al., 2020). In turn, this can be linked to SDGs 8 and 12, respectively, on sustainable economic growth and sustainable consumption and production. Analyses using the data from water accounts can also be used to estimate the cost of providing water to additional households and to forecast future water demands.

2.5.2. Water framework directive of the European Union

The European Water Framework Directive (WFD) is an information framework for water management in the European Union (EU). Member States are required to develop River Basin Management Plans, which include environmental and economic information at the catchment level (Santos et al., 2021; Carvalho et al., 2019). To date, the WFD and a lack of interdisciplinary approaches have yet to result in better water management (Souliotis and Voulvoulis, 2021).

The Netherlands is one of the leading implementers of water accounting and was one of the first nations to meet the needs of the WFD and the demand for integrated environmental-economic information (Schenau and ten Ham, 2005). The Netherlands water accounts provide information at national and river basin scales (Brouwer et al., 2005) on the physical and monetary supply and use of water, wastewater

⁵ <https://www.fao.org/sustainable-development-goals/indicators/641/en/>

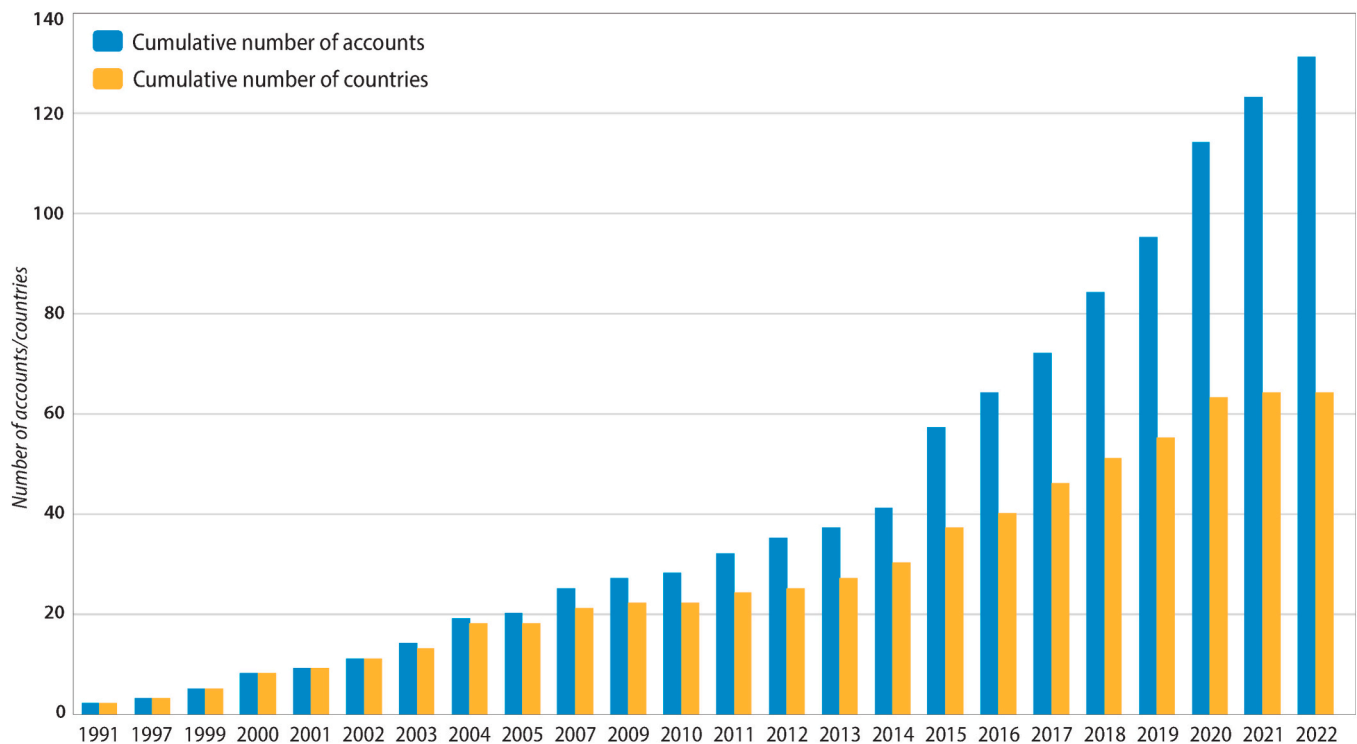


Fig. 4. Cumulative number of water accounting publications and countries producing water accounts, 1991 to 2022. Note: The cumulative number of accounts and countries excludes the nine accounts and four countries where the year of first publication was not identified.

treatment, and economic data on production, value added, and employment (Edens and Graveland, 2014; Van Berkel et al., 2022). Data from the water accounts are used by the Netherlands Ministry of Infrastructure and Water Management for 3-yearly WFD reporting.

Water accounting has been tested at the subnational level for WFD reporting in Spain, Greece, and England. For Spain, Borrego-Marín et al. (2016) and Gutiérrez-Martín et al. (2017) found that the SEEA methodology satisfies the requirements of the WFD, and in particular to estimate cost-recovery for water supply. Gutiérrez-Martín et al. (2017) concluded that using SEEA-based water accounting would increase the comparability of information and knowledge-sharing between regions and countries. For Greece and England, Souliotis and Voulvoulis (2021) determined the value of two ecosystem services and associated these with changes in water condition due to policy instruments. They concluded that water management should consider both current and emerging pressures when designing interventions to manage water resources sustainably, and that ecosystem accounting can assist.

2.5.3. Water accounting Australia

There is considerable pressure on water resources in many parts of Australia (Green and Moggridge, 2022), and to assist the management and governance of water, water accounts are written into law via the Water Act 2007⁶. Australia has a long history of collecting water resource data and has produced water accounts dating back to 1996 (Vardon et al., 2007). Since 2008–09, two national government agencies have produced water accounts; the ABS⁷ and the BoM⁸. Both agencies currently produce annual water accounts and were integrated once (ABS and BoM, 2019).

⁶ See Part 7 Water information of Water Act 2007. <https://www.legislation.gov.au/Details/C2021C00539>

⁷ See <https://www.abs.gov.au/statistics/environment/environmental-management/water-account-australia>

⁸ See <http://www.bom.gov.au/water/nwa/2021/>

A review of Australia's water reforms by the Productivity Commission (PC) (2021) found: "Water accounting is generally providing practical, credible and reliable information, but there is room for improvement. Public demand for information and timely provision of it has increased over time." The PC noted that strengthening water accounting would provide credible information and support robust institutional processes, helping to ensure that water rights holders are operating appropriately, water systems are being managed to best effect, and it would improve understanding of potential risks and planning for the future. Grafton (2019) came to similar conclusions.

Australia has recognized the potential of water accounting for water management and governance and regularly produces water accounts. The challenge is to improve the scope and coverage of water accounts and to effectively and systematically integrate them into decision-making processes.

3. Material and methods

The review for this section draws from existing protocols for systematic literature reviews (e.g., Moher et al., 2009; Woodcock et al., 2014; Sarkis-Onofre et al., 2021). Here, we employ a three-step process to find and scan water accounts (Fig. 3).

The first step was a search of the UN SEEA website⁹ and the results of the 2021 Global Assessment (which collected a wealth of information on the status and progress of implementation of the SEEA in countries). From this, a list of countries with water accounts was made. Following the links provided on the SEEA website or by searching the websites of responding institutions, the water accounts were accessed and downloaded. A similar search was expanded to other countries that reported having environmental or ecosystem accounts but not specifically water accounts. This step identified the accounts in the "grey literature" (e.g., published by governments or agencies in technical reports).

⁹ www.seea.un.org

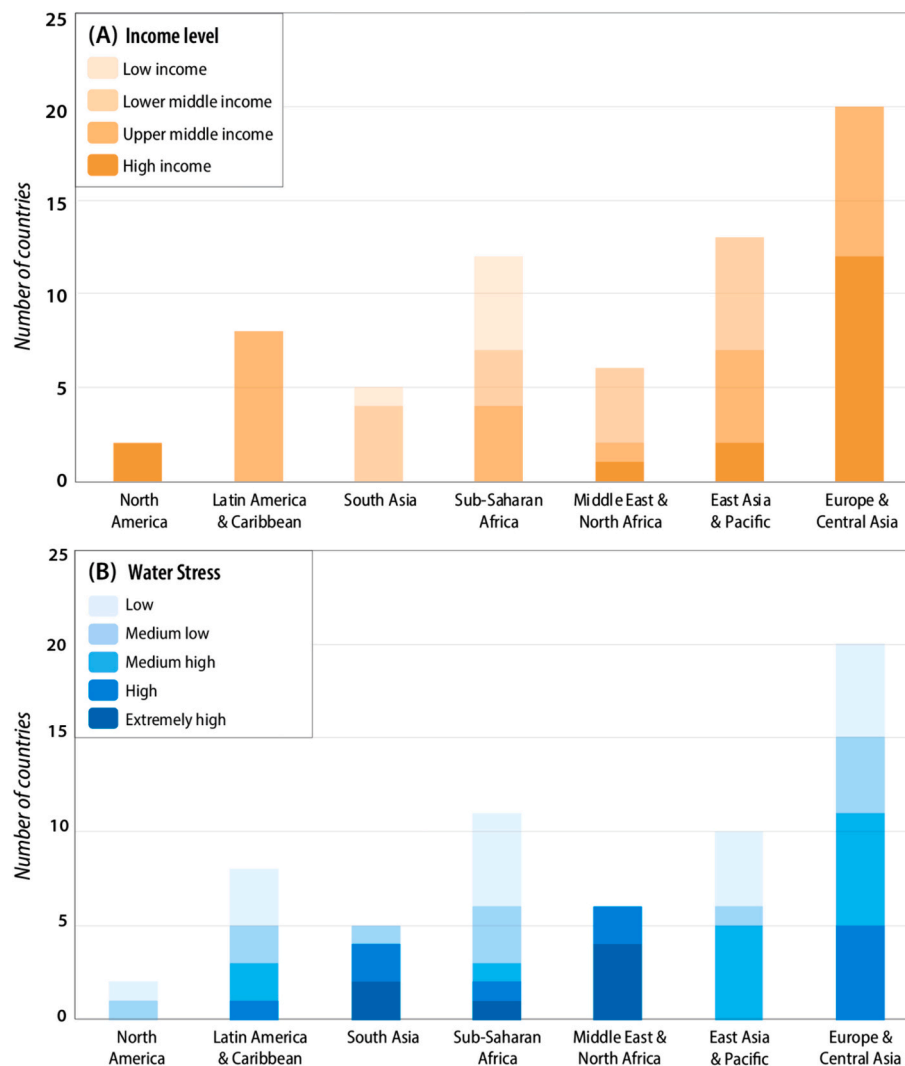


Fig. 5. Number of countries with water accounts by region, income, and water stress. In (A), the number of countries with water accounts by region and income level. In (B), the number of countries with water accounts by region and water stress level.

Some countries' websites were easier to navigate because they had separate themes for water accounts or environmental accounts. Others were more difficult to locate because water accounts were embedded in other publications or website modules or language barriers (e.g., none of the authors can read Arabic, Chinese, or Russian). To help overcome this, the SEEA website "knowledge base" was searched for related literature and project documents, including the "Natural Capital Accounting and Valuation of Ecosystem Services" (NCAVES), the Enhance Natural Capital Accounting Policy Uptake and Relevance (EnhaNCA), and Advancing Natural Capital Accounting (ANCA) projects.

Step two was a Google search for initiatives of other international organizations. This led to the knowledge base of Wealth Accounting and the Valuation of Ecosystem Services (WAVES) – a World Bank-led global partnership – and various water accounting initiatives led by the Asian Development Bank (ADB), the Food and Agriculture Organization (FAO) in cooperation with the World Water Assessment Programme (WWAP), the International Water Management Institute (IWMI), and the IHE Delft Institute for Water Education (IHE Delft). While the WAVES knowledge base provides access to project-based national water accounts, the others focus mainly on water accounts for river basins. The Google search helped to find water accounts of some countries or regions, especially those having an obvious webpage for water accounts, such as Australia and Europe. This step was complemented by the authors' own

knowledge of existing water accounts.

The final and third step was a systematic search of the Scopus database and Google Scholar to find water accounts and reviewed documents from academic and other sources. Scopus was selected as the largest global database of published documents (Kilonzi & Ota, 2019). The keywords used in the search were: "water account*", "environmental account*" + water; "environmental and economic account*" + water; "economic-environmental account*" + water, "natural capital account*" + water, "ecosystem account*" + water, "ecosystem services" + water, "water provisioning service", "SEEA" + water, "SEEA" + ecosystem. No other restrictions were set. As a result, a total of more than 1800 journals and documents of all types were found, of which approximately 200 had the keyword "water account*" in the title. These documents were scanned for references to other water accounts.

Following the identification of water accounts, a database was developed using Microsoft Access to store and classify the accounts. Supplementary Information Table S.3 contains the database's metadata. The database was structured into eight groups connected by a unique letter account code as follows:

- (i) *General information*: publishing agency, institutionalized status, search strategy, sources of water account, and review documents with links

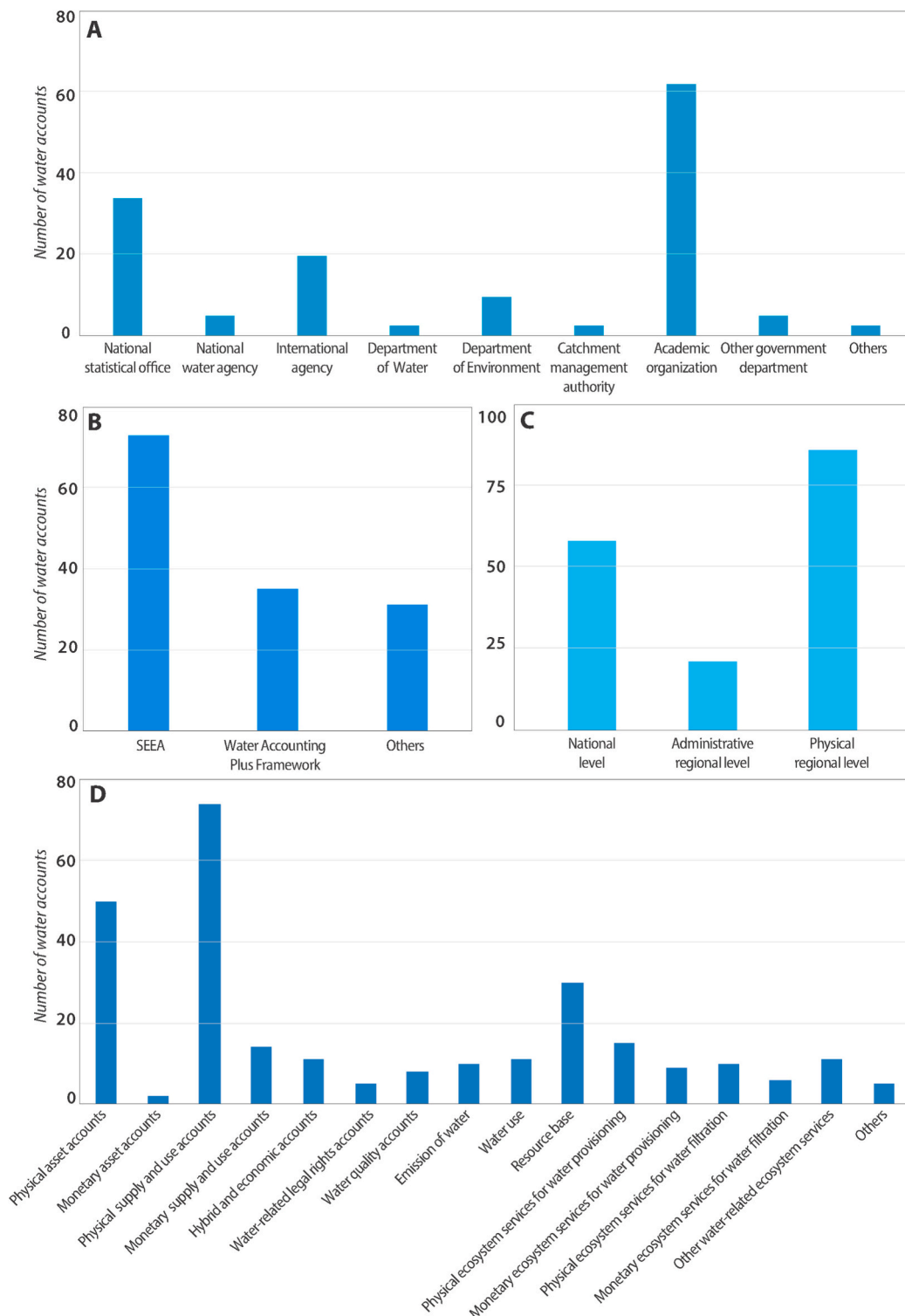


Fig. 6. Water accounts by producer, framework, scale, and type. In (A), the accounts are shown by the account producer (i.e., the agency that developed the accounts), (B) shows the accounting framework used, (C) shows the spatial output or spatial scale of the water accounts, and (D) shows the type of water accounts produced.

- (ii) *Boundaries and methodology*: type of water accounts, adopted framework and methodology, and spatial boundaries
- (iii) *Sector and industry coverage*: industries covered by ISIC classification, typical sector split shown in agriculture, energy and mining industry, and agricultural commodities covered
- (iv) *Timeframe*: the publishing year, reference year, length of the time series, and gaps

- (v) *Physical scope*: the recording of some key physical indicators, including import and export of water, water sources, losses, evaporation, flows of water within the economy, return of water and wastewater, types of produced water assets, and split shown for treated and untreated water for water treatment plants, wastewater treatment plants, and desalination plants

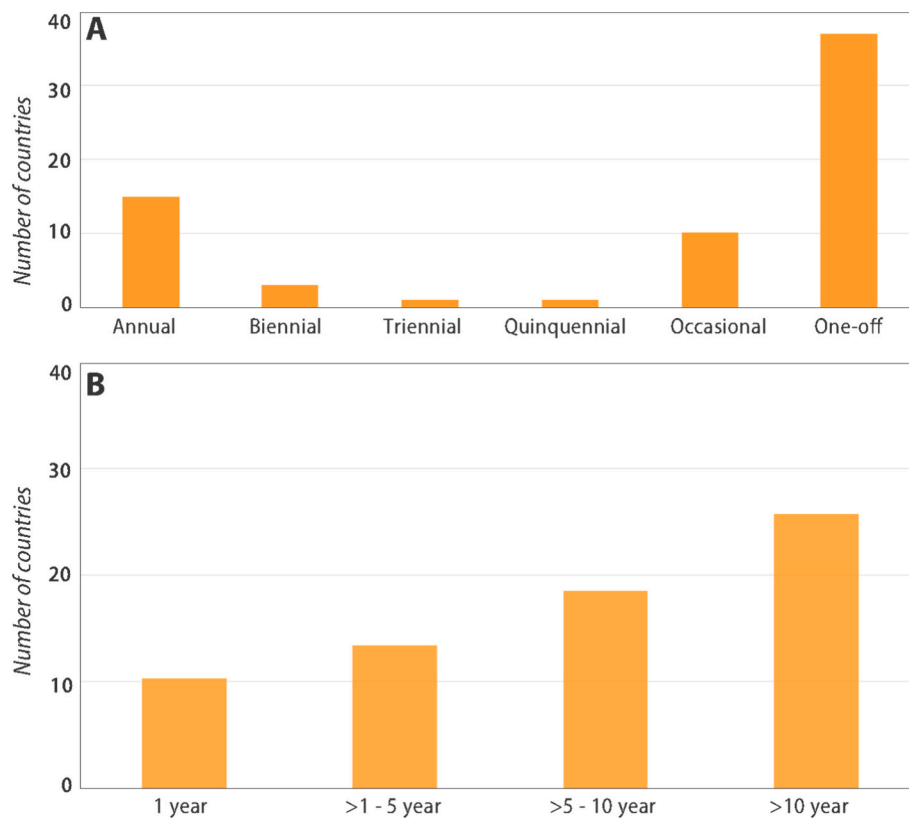


Fig. 7. Number of countries with water accounts. In (A), the production frequency of accounts by the number of countries. In (B), the timeseries of water accounts by the number of countries. Note: There are breaks in the time series of some accounts.

- (vi) *Economic scope*: the recording of some key economic indicators, including running cost of water treatment, wastewater treatment, and desalination, the value of produced water assets, and other economic information such as the value of irrigated agriculture, rain-fed agriculture, hydroelectricity, etc.
- (vii) *Region and income level*: the classification of countries by regions and income level follows the World Bank's classification 2022–2023 (WB, 2022). Accordingly, countries are divided among income groups according to 2022 Gross National Income (GNI) per capita.
- (viii) *Water stress*: the classification of water stress follows the SDG 6.4.2 water stress indicator¹⁰ based on the ratio of total water withdrawals to available renewable surface and groundwater supplies.

4. Results

A total of 271 water accounts were identified that were produced for 67 countries and four regions (Central Asia, Europe, Middle East and Sub-Saharan Africa), and for the World (Supplementary Information Tables S.4 and S.5). There were references to water accounts for another six countries, but these accounts were not discovered online, so primary documents could not be reviewed.

The 271 accounts were contained in 139 country publications. Both the number of accounting publications produced and the number of countries producing accounts increased over time (Fig. 4). The earliest water account identified was in 1991 in the Philippines for water emissions (pollution) accounts (PSA, 2018). The most recent countries to publish water accounts include Egypt, Ethiopia, Kazakhstan,

Malaysia, Mongolia, Nigeria, Turkey, and Zambia.

While the number of accounting publications produced ($n = 139$) and the number of countries ($n = 67$) producing accounts is a valuable metric, care is needed when interpreting our data (Figs. 4–7, Supplementary Information Tables S.6 to S.9). This is because some countries have more than one water account publication using different frameworks. Some publications contain more than one water account type with multiple spatial outputs. More than one agency is involved in producing water accounts, and many accounts are jointly published. For example, in Australia, accounting publications include multiple spatial outputs (national and subnational), are produced by two national (e.g., ABS, 2022; BoM, 2021) and two state government agencies (e.g. DELWP, 2022; Smith et al., 2017), accounts are jointly produced (ABS and NWC, 2006; ABS and BoM, 2019). Further, there are also academic publications on water accounting (Vardon et al., 2007; Vardon et al., 2012; Chen and Vardon, 2024) and with accounting for water-related ecosystem services (e.g. Keith et al., 2017; Vardon et al., 2019) and more than one accounting framework is used.

In our data, we found 11 water accounts for four regions, a world water account and 139 accounting publications. Because of these factors, there are different sample sizes in the results. We observed that water accounts have been produced in all regions of the world and for low- to high-income countries (Fig. 5). The greatest number of countries producing accounts was in the Europe and Central Asia region ($n = 20$ or 30 %) (Fig. 5a). This region also produced the largest number of accounts ($n = 35$ or 28 %) (Table 1). Sixty-four percent of countries producing accounts were upper-middle or high-income countries ($n = 26$ and 17, respectively) (Fig. 5a). Six low-income countries produced accounts, with five of these in Sub-Saharan Africa (Fig. 5a).

Water accounts were produced in countries of all levels of water stress (Fig. 5b). Seven of the 67 countries producing water accounts had extremely high levels of water stress. All six countries producing water accounts in the Middle East and North Africa and four of the five

¹⁰ <https://www.unwater.org/our-work/integrated-monitoring-initiative-sdg-6/indicator-642-level-water-stress-freshwater>

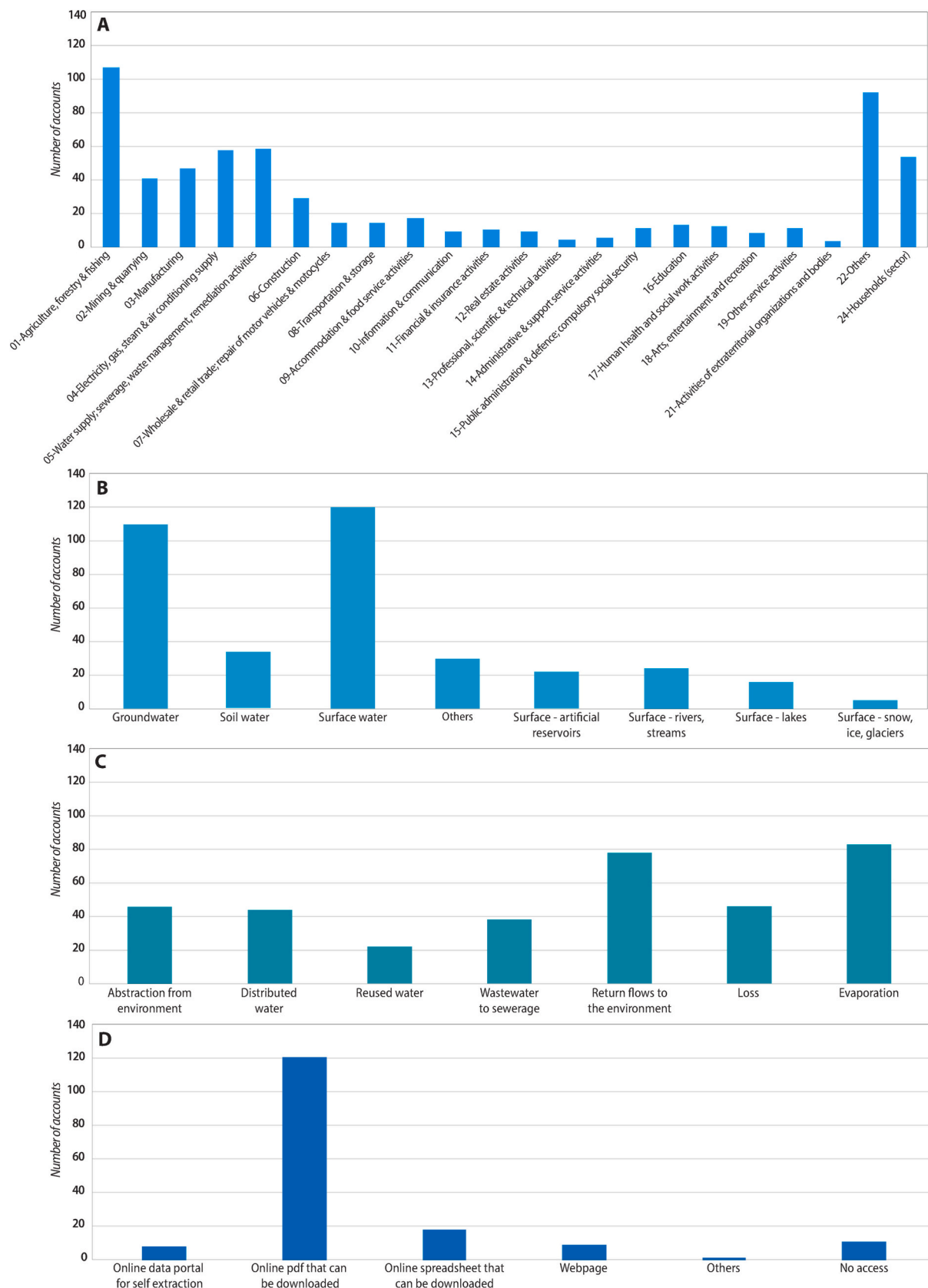


Fig. 8. Water account content and access. In (A), the industries and sectors recorded in water accounts, (B) shows the water resources recorded in accounts (Note: Others include desalinated water, rainwater tanks, and reuse water (e.g., from sewerage works), (C) shows the water flows recorded in accounts, and (D) shows access to water accounts.

Table 2
Five factoring contributing to credibility and trust in natural capital accounting.

Mandate:	Continuing high-level support for developing and using environmental-economic accounting is essential. Champions are needed, and without ongoing high-level support accounting can be stuck in an experimental phase for years and be unable to reach its potential
Engagement and communication:	Few people know environmental accounting, and even fewer understand the information accounts contain or how it can be used. Communication is needed to engage stakeholders, ensure the accounts are visible and understood, and target specific audiences.
Policy relevance:	Environmental-economic accounts must be relevant to environmental policy and management. For relevance, accounts need to be tailored, meeting the needs of specific areas, which may be from local to national levels, particular industries, or groups within society (e.g., rural poor)
Cooperation and coordination:	A process is needed effectively to organize environmental-economic accounting producers, users, and quality assurers. This has strategic and technical aspects, with high-level groups providing the former and formal working groups and a broader community of practice addressing technical aspects. The strategic and technical areas are needed for developing and using accounts, ensuring accounts' ongoing production and use, and embedding accounts in decision-making.
Continuous improvement:	Data are seldom complete or perfect, but accounts can usually be produced. Accounts can be improved over time, both in terms of increasing data quality and policy relevance.

countries in South Asia producing water accounts had high or extremely high water stress levels.

4.1. Account production and content

Accounts were produced by a range of government agencies, international organizations, and academic journals, using different accounting frameworks, multiple types of accounts, and at regional and national levels (Fig. 6). Thirty-two (23 %) of accounts were produced by two or more agencies and in two cases, the Dominican Republic (CIDECA, 2016) and Colombia (WAVES, 2016), by four types of agencies (Supplementary Information Table S.6). In the cases of joint production, the water account was included in the producer category of each agency type, hence the number of account producers (Fig. 6a) is more than the number of accounts ($n = 139$). The most common producers of water accounts were academic organizations ($n = 79$), followed by national statistical offices ($n = 43$) (Fig. 6a). Twenty-five water accounts were produced by international agencies, for example, the World Bank (e.g., the WAVES¹¹ and GPS¹² programs), the UN (e.g. NCAVES¹³), the FAO, and the Asian Development Bank (ADB). International organizations played multiple roles, supporting accounting production through technical assistance or resourcing. The SEEA was the most used water accounting framework ($n = 73$ or 53 %) and the most used by national statistical offices ($n = 33$) and academic organizations ($n = 36$) (Supplementary Information Table S3). The next most used framework was WA+ ($n = 35$) (Fig. 6b).

Most water accounts produced were at the regional level based on physical boundaries, river basins, or other hydrologically defined areas ($n = 86$) (Fig. 6c). The spatial output varied according to the account producer (Supplementary Information Table S.7). Academic institutions

Table 3
Six dimensions of data quality.

Relevance	How well the data meet the needs of users in terms of the concept (s) measured, and the population(s) represented
Accuracy	The degree to which the data correctly describe the phenomenon they were designed to measure
Timeliness	The delay between the reference period (the time to which the data pertain) and the date at which the data become available (i. e., the release date)
Accessibility	Ease of access to data by users, including the ease with which the existence of information can be ascertained, as well as the suitability of the form or medium through which information can be accessed
Interpretability Coherence	Availability of information to help provide insight into the data The internal consistency of a statistical collection, product, or release, as well as its comparability with other sources of information, within a broad analytical framework and over time

mainly produced accounts for physical regions ($n = 61$) and statistics offices for the national level ($n = 38$). Twenty-one accounts had more than one spatial output. Many different types of accounts were produced (Fig. 6d), and spatial outputs in the accounts varied (Fig. 6c). Of the 271 accounting tables identified, physical supply and use tables were the most common type of account produced ($n = 74$), closely followed by physical asset accounts ($n = 50$) (Fig. 6d). Eleven accounts reported water use but not supply. Thirty accounts were for the water resources base, which were mostly water balances that align closely with physical asset accounts (Vardon et al., 2012). The number of accounts with the ecosystem service of water provision ($n = 24$), water filtration services ($n = 16$), and other water-related ecosystem services ($n = 11$), is not an accurate reflection of the number of accounts produced, including these services as the salient word “water” is absent from the title, abstract, or keywords of many articles that produce accounts for multiple ecosystem services. Thirteen countries produced monetary supply and use tables.

4.2. Account frequency and time series length

The frequency and time series length varied (Fig. 7). The overwhelming number of accounts produced by countries were “one-offs” ($n = 37$), with just 15 countries having annual water accounts (Fig. 7a). National statistical offices produced 14 of 23 annual accounts, while academic organizations 74 of 138 one-off accounts (Supplementary Information Table S.8). The time series length ranged from 1 to >10 years, and 25 countries had timeseries >10 years (Fig. 7b).

4.3. Account content and access

The level of detail in water accounts varied in terms of the number of industries, water resources, water flows recorded, and mode of access (Fig. 8). The number of industries ranged from four (e.g., water supply, agriculture, other industries, and households), to more than 30, including subdivisions of the agricultural industry by, for example, crop types (Fig. 8a). Agriculture was the industry most often recorded ($n = 106$), and the “other” category was also large ($n = 91$) as this category is used to represent all industries other than the 20 ISICv4 industries or in accounts that do not use the ISIC classification. The water supply industry was explicit in just 57 accounts. Water use by households¹⁴ (or domestic) was reported in 52 accounts. Australia, Denmark, Guatemala, Namibia, Colombia, Finland, Guatemala, and The Netherlands had the greatest number of industries or subdivisions of industries (mainly agriculture). Surface water and groundwater were the most common water resources recorded, with surface water often split between reservoirs, rivers and streams, lakes and snow, ice and glaciers (Fig. 8b). Soil water (e.g., the water used in rainfed agriculture) was recorded in

¹¹ <https://www.wavespartnership.org/en>

¹² <https://www.worldbank.org/en/programs/global-program-on-sustainability>

¹³ <https://seea.un.org/home/Natural-Capital-Accounting-Project>

¹⁴ In the SNA and SEEA, households are a sector, not an industry

Table 4
Indicators of best practice water accounting.

Aspect	Indicator
Process	Processes are established for: stakeholder engagement, data exchange between agencies, data management, capacity building, continuous improvement, analysis of accounts, and their use in decision-making processes and tools
Relevance	Accounts have information that can be built into decision-making process. For example: water allocation, water price setting, water investment decisions, water policies, and catchment management planning.
Frequency	Accounts are produced annually to a pre-determined schedule
Timeliness	The accounts are available within a year of the reference period (e.g., if the data are for 2021, the account should be available by end of 2022)
Ongoing Coherence	Accounts have high-level support and ongoing resourcing Accounts use SEEA-based classifications and standards enabling the integration production of different types of water accounts and for water accounts to be integrated with other SEEA and SNA accounts, ecosystem accounting and a clear understanding of differences and similarities with other water data frameworks
Accuracy	Accounts are of sufficient accuracy to inform decision-making. Quantitative and qualitative measures of accuracy are equally appropriate. Accuracy should be judged by “fit-for-purpose”.
Accessibility	Accounts are easily discoverable, available online, and provide summary descriptions and graphics (not just tables)
Interpretability	Accounts are accompanied by methodological and other material that enable the information to be understood
Comprehensive	Account should be produced for: physical supply and use, physical assets, monetary supply and use, emissions, quality, water related environment protection expenditure
Water resource coverage	Accounts should include: all forms of surface water, groundwater, and soil water; where applicable, desalinated and reuse water; the product “Natural Water” (CPC 1800) and, ideally, bottled and tanked water
Industry and sector coverage	Accounts should separately identify the main water suppliers and users, including: households, water supply waste water treatment industries, agriculture (split by major commodities); mining; manufacturing (with food and beverage manufacturing separately identified); energy (with hydroelectric power generation separately identified), and; service industries (health, education, etc.)
Spatial coverage	Scalable accounts. Coverage can be built up from regional level accounts to national or multinational, or vice versa
Integration	Water accounts are integrated with other accounts and information (e.g., SNA, land accounts, ecosystem accounts)

34 accounts. Evaporation ($n = 83$) and return flows ($n = 78$) were the most recorded flows (Fig. 8c). In most asset accounts, inflows and outflows to groundwater and rivers were recorded but not stocks. Rivers were separately identified in 24 asset accounts, but the volume of water explicitly recorded in the opening and closing balances of rivers was provided in only one case (ABS and BoM, 2006).

Historically, most accounts were published as printed documents or made available via pdf files ($n = 121$). The use of PDF files is common for low- and middle-income countries that produce water accounts, like Botswana. In contrast, high-income countries like Australia and the Netherlands have dispensed with printed and PDF documents, and the text is now entirely on webpages with downloadable tables ($n = 18$) (Fig. 7d).

5. Discussion

Water account production is increasing (Fig. 4) and is feasible in a range of environmental, economic, and institutional circumstances. We found that water accounts are produced in a range of socio-economic and environmental circumstances (Fig. 5), for low- to high-income countries (e.g., Zambia and the Netherlands), in places of different

water scarcity (e.g., Botswana and the Philippines) (Fig. 5), and at different spatial scales, from river basins (e.g., Colombia) and small island states (e.g., Palau) to large countries (e.g., Australia) and by a range of institutions (Fig. 6). While data production is regular in many countries (Fig. 7) there are differences in the types and levels of information recorded in water accounts (e.g., number of industries, water sources, and water flows) (Fig. 8).

While production of water accounts is a regular activity in some countries, most water accounts are “one-off” exercises - ongoing production occurs only in a handful of countries, and many countries have short or broken time series (Fig. 7). For example, the Philippines started producing accounts in the 1990s (Angeles and Peskin, 1998), but there was long gap from these accounts to the latest accounts (PSA, 2020). Similarly, while Namibia has a time series that, with gaps, dates back to 1980 (Lange, 1997), there is a production gap until 2015 (i.e., MET, 2015), and no accounts have been produced since. This suggests a lack of capacity, resources, or high-level commitment by governments may be impeding the production of water accounts, all of which are critical factors for the successful production and use of natural capital accounts (World Bank, 2021). It is also noted that in Europe there is no mandatory reporting of water accounts although there is for other environmental accounts.

5.1. Producing water accounts

In most countries, water accounting is in an experimental phase and has yet to be embedded in the decision-making processes of water governance. This is because, one, water accounts take resources and time to produce and rely on existing water data which usually has gaps and deficiencies (Section 5.2), and, two, decision-makers have little awareness or understanding of water accounts and what they offer (Section 5.3). With resources limited and understanding lacking, there can be competition rather than the collaboration between the different agencies needed for the ongoing production of water accounts. This can also be exacerbated by misunderstandings on technical matters between disciplines (e.g., hydrologists, economists, and accountants) (Vardon et al., 2018; World Bank, 2021).

We highlight the processes to help overcome the impediments to production of water accounts (Ruijs et al., 2019) and present three modes of water account production, each of which has its strengths and weaknesses:

1. *Production led by government statistical agencies.* This generally ensures close linking with other SEEA-based accounts, the SNA and associated economic data, with a strong emphasis on integration and a focus on ongoing account production. However, accounts can take several years to produce and require substantial capacity building and technical inputs and data from a range of water and research institutions, and statistical agencies are deliberately separated from account users¹⁵.
2. *Production led by government agencies concerned with water, natural resources or environmental management and policy.* In this approach, the accounts produced suit the needs of a particular agency. This ensures close linkages to policy analysis and resource management but can also mean that water accounts do not easily integrate into other types of environmental or economic information (e.g., other SEEA or SNA accounts).
3. *Production led by research agencies* (e.g., universities). Here, the accounts are generally produced relatively quickly and use the latest knowledge and information. Interpretation and analysis are prominent, but there is no view to ongoing production unless there is ongoing funding and linkages to government agencies.

¹⁵ <https://unstats.un.org/unsd/dnss/gp/fundprinciples.aspx>

Five general factors of success for developing and using environmental-economic accounting programs have been identified by the World Bank (2021) and Ruijs et al. (2019) (Table 2). These five factors support credibility and trust in water accounts and the decisions based on water accounts and align with the processes outlined by Batchelor et al. (2016).

The United States of America (USA) released a strategic plan for environmental-economic accounting (US Department of Commerce, 2023). The strategy had a phased implementation plan with water accounts as part of the first phase. The USA's plan reflects the five factors in Table 2.

5.2. Barriers to water account production and use

Water accounts are highly-technical exercises that rely on collaboration between different agencies, the knowledge and expertise of several disciplines, and data (Sections 1 and 2). Many countries lack coordination processes, with multiple accounts being produced within countries by different agencies using different accounting systems (Section 4.1).

A common barrier to account production is data availability and data quality (Vardon et al., 2012). Most countries have some of the data needed for the production of water accounts but no country has access to all the data needed to produce the full suite of water accounts: physical and monetary supply-use tables, asset accounts, environmental protection expenditure related to water, water quality, and emissions to water. Consequently, those producing accounts rely on various estimation methods to populate different parts of the water accounts. In some cases, data may exist, but the agency or agencies producing the accounts may need help accessing the data for legal, administrative, or technical reasons (Vardon et al., 2018). This, in turn, results in few types of water accounts being produced (Fig. 6), irregular production (Fig. 7), under-coverage of water resources, and low levels of industry detail (Fig. 8).

Salminen et al. (2018) provide a detailed analysis of data quality issues in Finland. They identify two potential sources of error in Finland's water use estimates. The first is poor data coverage of some industries, resulting in unreliable estimates of the water supply and use in these industries. The second source of error is allocating the amounts of water used by industries to different water sources (e.g., self-abstracted vs. mains water or between industries). The total water supply by the water supply industry appears to be reliable but the water use by industries and households is less so, and in some cases is unknown.

Weckström et al. (2020) identified the lack of industry detail as a limitation of accounts in the analysis of the economic importance of water. Their review highlighted the lack of industry detail (Fig. 8) but this limitation could be overcome with additional data. For example, water suppliers typically have registers of customers, which could be coded to industry or sector, as has been done in Botswana by the Water Utilities Corporation (DWS, 2021). Weckström et al. (2020) also note that water accounts generally report water consumption based on incomplete data, so there is a possibility that account users may incorrectly interpret the accounts.

One barrier to expanding the use of water accounts experienced by the authors is the resistance to water accounting. In part, this resistance arises from the 'silos' across disciplines with each having established concepts, terminology, frameworks, metrics, and methods to support existing information audiences and decision-making processes. This can mean, for instance, that some hydrologists might question the need or utility for asset accounts to include river water stocks, while some economists might question the limitation of water valuation to exchange values.

Terminology is another challenge. Terms like "water consumption" are defined slightly differently in SEEA than in other frameworks. For example, for water footprints, Hoekstra et al. (2011) have a pure conceptual definition for water consumption: "The volume of freshwater used and then evaporated or incorporated into a product. It also includes

water abstracted from surface or groundwater in a catchment and returned to another catchment or the sea. It is important to distinguish the term 'water consumption' from the term 'water withdrawal' or 'water abstraction.' By contrast, the SEEA defines water consumption as the difference between supply and use and adds in practical considerations as examples: "... apparent losses due to illegal tapping as well as malfunctioning metering." Confounding the problem of interpreting water consumption is that some accounts overestimate consumption due to an underestimate of water return flows (e.g. from agricultural land).

5.2.1. Data quality assessment

Accuracy is often the main focus of data quality in water accounts. Indicators of accuracy include, for example, error bars for estimates based on sampled data or r-squared values for models. But accuracy is just one of several dimensions of data quality and data quality frameworks are available from various sources (e.g., ABS, 2009; Eurostat, 2005; IMF, 2012; OECD, 2012; Statistics Canada, 2002; Clarke et al., 2011). The frameworks from national statistical offices and international organizations typically describe six data quality dimensions (Table 3). Trade-offs between the different dimensions of data quality are usually needed for accounting, with the degree of accuracy determined by a "fit-for-purpose" test: the information supplied meets the needs of the information user.

Key challenges for water accounting are *relevance*, *coherence*, and *timeliness*. For relevance, accounts are often limited in scope, including only some water resources and using highly aggregated industry classifications. Further, valuation is uncommon, and accounts are irregularly produced. This can mean that the relevance of water accounts to decision-makers is limited. Coherence with other information sources is also not always evident. For example, non-SEEA water accounting cannot be directly linked to the information from the SNA or other environmental accounts because of different definitions or classifications. A key reason for using SEEA is to have a coherent and integrated information system, as data for the accounts is from many sources, the concepts and definitions in these sources need to be understood and clearly linked to those in SEEA. Such an approach means that data suppliers for water accounts have increased confidence that their data is being used appropriately and interpreted. For timeliness, the review found that most water accounts were published well after the reference period. Lack of timeliness reduces the relevance of water accounts for decision-making. In a world of changing water availability and increasing water demand, for accounts to be built into decision-making processes, they will need to present current (timely) and frequent (e.g., annually) information.

6. Indicators of best practice water accounting

Our global review shows that shows that water accounts can be produced and support improved water governance, but challenges remain in the production and use of water accounts. To respond to these challenges, we propose 14 indicators of best practice water accounting (Table 4). Best practice is an elusive concept, but we define it as "those practices likely to increase the quality and use of water accounting in decision-making process". The indicators of best practice we provide are intended to support the take-up and application of water accounts into decision-making practices in a way that the use of the SNA supports improved economic decision-making.

6.1. Process

A process of ongoing development, production and use of water accounts is, arguably, the most essential part of best practice. Engagement between account producers and users has previously been identified as critical to the effective use of environmental accounts (Ruijs et al., 2019; World Bank, 2021). Further, water accounting needs to evolve to incorporate new knowledge (data, methodologies, understanding, etc.)

and perspectives which requires continuous engagement across stakeholders.

Engagement processes should vary depending on countries' environmental, economic, and institutional conditions and the needs and capacities of stakeholders. The continuing evolution of the SEEA would benefit from greater engagement by hydrologists and other environmental scientists on the physical aspects of water accounting, and with economists on water valuation. The UN and other international agencies are, ultimately, responsible for promoting and improving accounting processes, but individual accounting practitioners can also play a role in fostering understanding, incorporating new knowledge and perspectives into water accounts.

One important gap, currently overlooked in SEEA's development, is that of First Nations. We endorse the recommendation of Normyle et al. (2024) to establish a working group under the auspices of the UN for this purpose. How First Nations' values can be included in environmental accounts and how First Nations might be able to use environmental accounting are two questions that have received little attention in SEEA-based accounting (Normyle et al., 2022). These questions are equally valid for water accounts as water, in its many forms, connects to places, practices and values of First Nations' (Manero et al., 2022).

6.2. Relevance

Expanding the relevance of water accounts means increasing the frequency, timeliness and detail of the accounts. Increasing the number of industries in accounts should increase their use in economic modeling (e.g., Wittwer, 2012), while adding information on physical flows allows some indicators, like water scarcity and water consumption, to be more readily derived from water accounts. As water availability is likely to become more variable with climate change (e.g., Konapala et al., 2020), sub-annual accounts and faster production of accounts could make accounts more relevant to managing short-term water demand and balancing the needs of households and industry (e.g., Grafton et al., 2020).

6.3. Accuracy

The degree of accuracy needed in accounts depends on the purposes for which accounts are used, i.e. the accounts are "fit-for-purpose". As water governance occurs at several levels, the degree of accuracy will change with who is the decision-maker. For high-level governance issues, top-down hydrological information from, for example, global data sets and models are likely to be appropriate, along with existing information from population statistics and the national accounts. For local water governance, additional data are likely to be needed for calibrating models, and for understanding the uses and users of water.

Accuracy is related to all the physical and economic data and methods used to populate the accounts (see Section 2.4). Accuracy will vary and errors may arise from many sources including in measurement, sampling bias, model assumptions, and processing errors (human and software). All data sources and methods used in accounts should be described and be publicly available. Quantitative (e.g., standard errors) or qualitative (e.g., "traffic lights") measures of accuracy should also be included as best practice. Over time, anomalies between different data source can be resolved, data gaps filled, and the accuracy of accounts improved (Vardon et al., 2018).

7. Conclusion

To improve the understanding and use of water accounts we identified and reviewed 271 water accounts from around the world. We found that account production has increased over time and has occurred in countries of all income levels and degree of water stress with SEEA the most commonly used water accounting framework. We observed that water accounting remains in a pilot phase in most countries, but 27

countries have regularly produced water accounts with a time series extending >10 years.

For water accounts to be routinely used by decision-makers for water governance several changes need to occur. A key step forward would be acknowledging data and interpretation challenges and effectively responding to these difficulties through better engagement between account producers and users to determine, for example, the type and level of detail included in accounts and acceptable levels of data quality. Based on our global review, we have proposed 14 indicators of best practice to speed the uptake and usefulness of water accounting. In our view, the uptake of these practices is urgently required. This is because of increasing water demands and the water-connected challenges of climate change which mean that decision-makers increasingly need up-to-date and relevant information to effectively (re)allocate water across competing uses.

CRedit authorship contribution statement

Michael J. Vardon: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Thi Ha Lien Le:** Investigation, Writing – original draft, Writing – review & editing. **Ricardo Martinez-Lagunes:** Writing – review & editing. **Ogopotse Batlokwa Pule:** Writing – review & editing. **Sjoerd Schenau:** Writing – review & editing. **Steve May:** Writing – review & editing. **R. Quentin Grafton:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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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Anna Normyle prepared the figures.

Appendix A. Supplementary data

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